AGARD-AG-299

AGARD-AG-299

AGARD

ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

7 RUE ANCELLE 92200 NEUILLY SUR SEINE FRANCE

AGARDograph No.299

AGARD Handbook on Advanced Casting

(Manuel AGARD des Techniques de Coulée Avancées)

NORTH ATLANTIC TREATY ORGANIZATION

DISTRIBUTION AND AVAILABILI[TY]
ON BACK COVER

AGARD-AG-299

NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARDograph No 299

AGARD Handbook on Advanced Casting

(Manuel AGARD des Techniques de Coulée Avancées)

Edited by

Dietmar Mietrach

MBB Transport und Verkehrsflugzeuge, TFB 51
Hunefeldstrasse 1–5
PO Box 107845
D-2800 Bremen 1
Germany

This AGARDograph was sponsored by the Structures and Materials Panel of AGARD

The Mission of AGARD

According to its Charter, the mission of AGARD is to bring together the leading personalities of the NATO nations in the fields of science and technology relating to aerospace for the following purposes:

— Recommending effective ways for the member nations to use their research and development capabilities for the common benefit of the NATO community;

— Providing scientific and technical advice and assistance to the Military Committee in the field of aerospace research and development (with particular regard to its military application);

— Continuously stimulating advances in the aerospace sciences relevant to strengthening the common defence posture;

— Improving the co-operation among member nations in aerospace research and development;

— Exchange of scientific and technical information;

— Providing assistance to member nations for the purpose of increasing their scientific and technical potential;

— Rendering scientific and technical assistance, as requested, to other NATO bodies and to member nations in connection with research and development problems in the aerospace field.

The highest authority within AGARD is the National Delegates Board consisting of officially appointed senior representatives from each member nation. The mission of AGARD is carried out through the Panels which are composed of experts appointed by the National Delegates, the Consultant and Exchange Programme and the Aerospace Applications Studies Programme. The results of AGARD work are reported to the member nations and the NATO Authorities through the AGARD series of publications of which this is one.

Participation in AGARD activities is by invitation only and is normally limited to citizens of the NATO nations.

Published March 1991

ISBN 92-835-0455-0

*Set and printed by Specialised Printing Services Limited
40 Chigwell Lane, Loughton, Essex IG10 3TZ*

Preface

In March 1982 a SMP Specialists' Meeting on Advanced Castings took place at Brussels. After the very successful meeting there was a general feeling in the SMP that the activities in this specific field should be continued

Progress in advanced casting technology offers an important contribution in cutting costs in military aircraft structures. But from the designer's point of view there are still some reservations and lack of confidence for the broad application of castings. This persists, in spite of the availability of mechanical data for advanced castings and first design experience of cast structural components.

Under these aspects the Structures and Materials Panel decided, in October 1983, to establish a follow-on activity in the form of a working group to prepare the publication of a "Handbook on Advanced Casting".

In the working group, specialists from foundries, research laboratories and aircraft companies held several meetings to collect and review data of casting materials which are fundamental tools for the design engineer.

The handbook comprises mechanical data of materials and informs about foundries, quality control and testing methods, and examples of application in structural components. It should be of assistance to designers and possible users of advanced castings to get detailed information about the potentia' of the materials existing today and the way to use them profitably in aircraft design work.

G Grüninger
Chairman of the Working Group

D.Mietrach
Coordinator of the Working Group

Structures and Materials Panel

Chairman: Prof. Dr-Ing. Hans Försching
Direktor der DFVLR
Institut für Aeroelastik
Bunsenstrasse 10
D-3400 Göttingen
Germany

Deputy Chairman: Mr Samuel L. Venneri
Director, Materials & Structures Division
(Code RM)
Office of Aeronautics & Space Technology
NASA HQ
Washington DC 20546
United States

WORKING GROUP MEMBERS

Chairman: Prof Dr-Ing G Grüninger
Direktor
Institut für Bauwesen und Konstruktionsforschung der
DLR
Pfaffenwaldring 38–40
D-3400 Stuttgart
Germany

SMP Members

Dr H.J G Carvalhinhos	PO
Mr D Coutsouradis	BE
Dr P Costa	FR
Dr G L.Denman	US
Prof. M Doruk	TU
Prof. J.S L.Leach	UK
Dr-Ir H P.van Leeuwen	NL
Mr W.Schoernack	GE
Col S.Signoretti	IT
Dr W Wallace	CA
Mr P.R.Wedden	UK
Mr H Zocher	GE

Working Group Coordinator

Mr D E.Mietrach GE

PANEL EXECUTIVE

Mr Murray C.McConnell UK

Mail from Europe:
AGARD OTAN
Attn: SMP Executive
7, rue Ancelle
France

Mail from US and Canada.
AGARD-NATO
Attn: SMP Executive
APO New York 09777

Telephone: 33 (1) 4738 5790 & 5792
Telex: 610176 (France)
Telefax 33 (1) 4738-5799

Acknowledgements

The Chairman and Coordinator of the Working Group on Advanced Casting would like to thank the "Invited Experts" of the Working Group for their continous willingness to contribute their knowledge and experience, their time and energy to this task, especially those colleagues who acted as authors for specific chapters:

D.Mietrach, MBB, GE:	(Chap 1: Introduction)
R.Genoux, MBB, GE:	(Chap 2 Casting Design)
	(Chap.3. Mechanical Data)
C.L.Harmsworth, AFWAL, WPAFB, US:	(Chap 4: Examples of Application)
D.Mietrach, MBB, GE.	(Chap. 5. Quality Assurance/Corros on Behaviour)
C.L.Harmsworth, AFWAL, WPAFB, US:	(Chap 6 Damage Tolerance/Casting Factor)

Special thanks to Mr Harmsworth who besides his responsibility for Chapters 4 and 6 has coordinated the US contributions for the Handbook.

From the casting industry there was strong support from:

Cercast Inc., CA (S.Kennerknecht)
Messier Fonderie d'Arudy, FR (J PMannant)
Montupet, FR (C.Planchamp)

Specifically involved in some meetings were ALCOA (US), Hitchcock (US), Honsel (GE), Howmet (US), PCC (US), TITAL (GE), TiTech (US). Additional thanks to those companies which provided examples to the Handbook.

Abstract

The need to improve aircraft performance and, simultaneously, to reduce costs has led to a re-examination of the use of casting processes in aircraft manufacture. In this volume the Structures and Materials Panel of AGARD has provided practical information about design, mechanical values, applications, quality assurance and damage tolerance.

By providing the data in this form it is hoped that the designer will be encouraged to exploit the many recent advances in casting to optimum effect.

Abrégé

La nécessité d'améliorer les performances des aeronefs et en meme temps d'en reduire les couts nous a conduit a revoir l'emploi de différents procédés de coulée dans la fabrication des aéronefs.

Le présent ouvrage, édité par le Panel des Materiaux et Structures de l'AGARD, donne des indications pratiques concernant l'étude de l'avion, les données mécaniques, les applications, l'assurance qualité et la tolérance à l'endommagement

Il est a esperer que la presentation de ces donnees sous forme de manuel incitera les concepteurs a exploiter de façon optimale les progrès considérables réalisés récemment dans le domaine des techniques de coulée

Contents

	Page
Preface	iii
Structures and Materials Panel	iv
Acknowledgements	v
Abstract/Abrégé	vi
1. Introduction	1
1.1 Foreword	1
1.2 Principle of Casting Processes	1
1.2.1 Investment Casting	1
1.2.2 Sand Casting	2
1.2.3 Titanium Casting	4
1.3 Candidate Materials	7
1.4 Application of the Handbook	7
2. Casting Design	8
2.0 Flow Diagram "Designer's Guidelines"	8
2.1 General	8
2.1.1 Introduction	8
2.1.2 Selection of Casting Method	8
2.1.3 Design to Cost	9
2.2 Design Details	11
2.2.1 Overall Dimensions	13
2.2.2 Minimum Wall Thickness	13
2.2.3 Radii	15
2.2.4 Ribs and Webs	15
2.2.5 Material Accumulation	16
2.2.6 Holes Located in Ribs and Webs	16
2.2.7 Cross-Sectional Transitions	16
2.2.8 Loft Lines	16
2.2.9 Cavities	17
2.2.10 Channels and Holes as Cast	17
2.2.11 Added Material for Machined Areas	18
2.2.12 Draft Angles	18
2.2.13 Fail-Safe Design Examples	18
2.2.14 Rivet Joints	18
2.2.15 Welded Joints	20
2.2.16 Chemical Milling	20
2.2.17 Designated/Undesignated Areas	21
2.2.18 Marking	21
2.2.19 Tooling Points	21
2.3 Tolerances	23
2.3.1 General	23
2.3.2 Commonly Used Symbols	23
2.3.3 Investment Casting Tolerances	24
2.3.4 Premium Casting	31
2.3.5 Conventional Sand Casting	31
2.3.6 Rammed Graphite Casting (Ti-Alloys)	31
2.4 Surface Roughness	32
2.5 Materials	32
2.6 Surface Protection	32
2.7 Additional Data on Workshop Drawing	32
2.8 Repair	32
2.8.1 Repair by the Foundry	32
2.8.2 "In-Service" Repair	34

	Page
3. Mechanical Data	34
3.1 General Information	34
3.1.1 International Notation and Units	34
3.1.2 Physical Data of Al- and Ti-Alloys	34
3.2 Material Data	34
3.2.1 Mechanical Properties	34
3.2.2 Strength Behaviour at High Temperatures	34
3.2.3 Fatigue Data	42
3.2.4 Crack Propagation and Fracture Toughness	91
3.3 Eye Bolt Joints	91
3.4 Riveted Joints	92
3.4.1 Static Strength of Riveted Joints in Aluminium Casting Alloys	92
3.4.2 Fatigue Behaviour of Riveted Joints in Aluminium Casting Alloys	95
3.4.3 Woehler-Diagrams of Riveted Ti 6Al4V	103
3.5 Weld Repair	110
4. Applications	112
4.0 Introduction	112
4.1 A357	112
4.1.1 Pylon Casting	112
4.1.2 Airbus A320 Cargo Bay Door	113
4.1.3 Pilot Box Structure	114
4.1.4 Landing Flap Holder	115
4.1.5 Missile Check	116
4.1.6 Antenna Bases for Military and Commercial Aircraft	117
4.1.7 Forward Support Housing	118
4.1.8 Bifurcation	119
4.1.9 Cruise Missile Fuselage Section	120
4.1.10 Bell Helicopter 406 Combat Scout's Outer Swashplate	121
4.1.11 Vertical Stabilizer Substructure	122
4.1.12 Canopy Frame	123
4.1.13 MRCA Tornado Intake Floor	124
4.1.14 MRCA Tornado NIB Centre Structure	125
4.2 D357	126
4.2.1 General Dynamics F-16 Modular Common Inlet Duct Casting	126
4.3 A201	127
4.3.1 Turbocharger Compressor Impeller	127
4.3.2 Rollover Beam for Helicopter	128
4.3.3 Engine Control Support	129
4.4 TI 6AL-4V	130
4.4.1 Optical Pointing System	130
4.4.2 Exhaust Nozzle Actuation Ring	131
4.4.3 Fan Frame	132
4.4.4 TFE 1042 Front Frame	133
5. Quality Assurance Methods/Corrosion Behaviour	134
5.1 Quality Assurance Methods	134
5.1.1 General	134
5.1.2 Specifications	134
5.1.3 Quality Assurance at the Foundry	134
5.1.4 Quality Assurance at the Buyer's	141
5.1.5 Classification of Casting/Casting-factor	141
5.2 Corrosion Behaviour	142
5.2.1 General	142
5.2.2 Aluminium-alloy A357	144
5.2.3 Aluminium-alloy A201	145
5.2.4 Summary: Al-Alloys A357 and A201	145
5.2.5 Titanium-Alloy Ti Al6V4	145
6. Damage Tolerant Design with Castings	148
6.1 Background	148
6.2 Damage Tolerant Design	148
6.2.1 Durability Design	148

Page

6.3 Initial Flaw Size	148
6.4 Crack Growth Rate	149
6.4.1 Fatigue Crack Growth Rate Data	149
6.5 Critical Flaw Size	150
6.5.1 Fracture Toughness Data	151
6.6 Metallographic Controls	152
6.7 Design Allowables	152
6.8 Casting Factors	152
6.9 References	153
Appendix	177

1. INTRODUCTION

1.1 FOREWORD

The need to cut costs has in recent years led not only to the development of new materials but also to the further development of economic manufacturing processes like "advanced casting technology". Advances in casting technology could lead to increased use of castings for the manufacture of vital aircraft components, which in turn leads to reduced cost.

Castings are favourable in terms of cost and weight and offer the possibility of combining into one casting a whole number of material-intensive machining and sheet-metal parts which were previously joined by riveting at high cost. Moreover, the process affords the design engineer greater freedom of design. It should be noted that the design should be made suitable for casting, i.e. the design engineer and foundry should get in touch as early as possible during component development. Only thus will it be possible to make maximum use of all the advantages of the process.

So far, the lack of confidence of design and stress engineers in casting has stood in the way of a more widespread use of castings for primary structures. However, today there are precise and reliable data concerning castings available. They are collected in this Handbook on "Advanced Casting" to aid engineers in the application of cost-saving castings.

1.2 PRINCIPLE OF CASTING PROCESSES

The casting processes — sand casting (conventional and premium) and investment casting — are of significance for aerospace construction. Depending on the respective technical or economic conditions for the individual components, either one or the other process will be more advantageous.

Generally, the trend is noticeable of sand casting and investment casting processes complementing one another and of both processes drawing closer to one another. For instance, investment castings are becoming ever bigger and have higher strength values due to the measures described in 1.2.1, whereas sand castings can have thinner walls and closer tolerances by applying investment casting measures (e.g. ceramic moulds) and refining sand casting techniques. These trends will grow even stronger in future.

1.2.1 Investment Casting

The investment casting process, Figure 1, is a means of creating highly complex metal structures offering the engineer almost unlimited design freedom. Typical production rates of large complex components are in the order of 25–100 units per month, with smaller castings produced in hundreds or thousands per month. This casting process makes it possible to produce thin walls typically of 1.5 mm with close tolerances (±0.15 mm). At present, components of approximately 500 mm × 800 mm × 1200 mm can be manufactured; the size being limited not by the process itself, but rather by the existing manufacturing facilities. Due to generally high mould temperatures required by the process, slightly inferior mechanical material properties may be expected in comparison to sand and premium casting. Unfavourable cooling conditions of the casting are however enhanced by casting under negative pressure or in vacuum, placement of metalic chills in the ceramic mould, use of special purpose ceramic materials, forced air convection over mould surface, etc.

The principles of investment casting are similar for both solid mould and shell processes, except for the formation of the ceramic mould. Both require a pattern, gating to a runner system, a ceramic mould (either solid plaster block or shell), removal of pattern with heat, pouring metal into the cavity left by expendable pattern, removal of ceramic material from the cast cluster, and cutting of castings from the assembly. The solid mould process is typically favoured for small ultra complex castings having tiny features. The shell process, however, accounts for the greatest majority of investment castings produced, due to superior dimensional control, ability to produce extremely large parts, and flexibility of casting parameters allowing better control of solidification conditions.

The process begins with the production of a one-piece heat disposable pattern. This pattern is usually made by injecting wax or plastic into a metal die (Fig.1.1). These dies may range from fully automatic multi-cavity tooling (for volume production of simple configurations) to large complex dies having up to 600 separate blocks and weighing as much as 2000 kg. Figure 1.2 depicts dismantling of metal tooling after injection, to yield the wax pattern.

A heat-disposable pattern is required for each casting. These disposable patterns have the exact geometry of the required finished part, but they are made slightly larger, to compensate for volumetric shrinkage (a) in the pattern production stage and (b) during solidification of metal in the ceramic mould.

The pattern carries one or more gates which are usually located at the heaviest casting section. The gate has three functions:

- to attach patterns to the riser or runner, forming a cluster;
- to provide a passage for draining out pattern material as it melts upon heating;
- to guide molten metal entering the mould cavity in the casting operation, and to ensure a sound part by feeding the casting during solidification.

Patterns are fastened by the gates to one or more runners and further assembled to form a cluster. Depending on pattern configuration and casting method used, the cluster will be composed of numerous runners, a central riser area, pouring cup and down sprue (Fig 1.3).

The ceramic shell mould process involves dipping the entire cluster into a ceramic slurry, draining away excess material, then coating it with fine ceramic sand (Figs 1.4 and 1.5). After the drying or curing of the shell coat, the procedure is repeated again and again, using progressively coarser grades of ceramic material, until a self-supporting shell has been formed (Fig 1.6). Specialized industrial robots are used almost exclusively for the shell building task to facilitate cluster manipulation, eliminate pattern distortion and considerably reduce linear casting tolerance requirements.

The coated cluster is then placed in a high temperature furnace or steam autoclave where the pattern melts and runs out through the gates, runners and pouring cup. This leaves a ceramic shell containing cavities of the casting shape desired with passages leading to them (Fig 1.7).

The ceramic shell moulds must be fired to burn out the last traces of pattern material and to pre-heat the mould in preparation for casting (usually in the range 450–800°C). Because shell moulds have relatively thin walls, they can be fired and ready to pour shortly after attaining temperature (within 1½ hours) (Fig.1.8).

The hot moulds may be poured utilizing static pressure of the molten metal heat, as is common in sand casting, or with the assistance of vacuum, pressure and/or centrifugal force. This enables the investment casting foundry to reproduce the most intricate details and extremely thin walls of an original wax or plastic pattern (Fig 1.9).

Melting equipment employed depends on the alloy For non-ferrous alloys, gas fired or electric crucible furnaces are usually used.

After the poured moulds have cooled, the ceramic mould material is removed from the casting cluster, by high pressure water jets, mechanical vibration and/or chemical cleaning (Fig 1 10). The casting(s) is then removed from the cluster by plasma torch or saw cutting, and any remaining protrusions left by gates are removed by grinding or machining (Fig.1.11).

The casting is then ready for secondary operations, heat treating, straightening, machining and whatever inspection is specified. The finished casting resembles the expendable pattern from which it was produced in every detail except for the calculated shrinkage in pattern production and metal solidification (Fig 1 12).

1.2.2 Sand Casting

Sand casting is a good casting process for manufacturing large complex components. High mechanical values can be reached with chills specially placed in the mould Sand casting can be divided into conventional and premium sand casting.

1 2.2.1 *Conventional Sand Casting*

Conventional sand casting, Figure 2, is the cheapest casting process. It makes it possible to manufacture components of 5000 × 1500 × 1500 mm. The disadvantage is that, in comparison to other casting methods, large tolerances of ±0.5 mm still exist and minimum thicknesses of only 2 5 mm are possible. Local machining or selective chemical milling offer a remedy to this problem.

In conventional sand casting moulds, cores and chills are usually used.

a) *Mould*

To maintain consistently close dimensional tolerances, sound castings, and good surface finishes, it is necessary to use a moisture-free, chemically bonded sand. In addition, close control over the design and fabrication of moulds for large castings is essential if the aforementioned characteristics are to be achieved

Experiences showed that moulding sand to be used for producing large aluminium castings should have the following specific characteristics: good flowability, permeability, tensile strength, and compressive strength, high hot strength; low retained strength; and low thermal expansion and gas evolution. Good mould and core sand should be strong enough to withstand handling and resist deterioration by the molten metal at elevated temperatures, have good permeability to allow the passage of gas, be flowable and display good compaction and surface finish characteristics, hold dimensional tolerances at elevated temperatures and provide ease in shakeout after cooling to room temperature.

The required properties of moulding sand are dependent upon binder type and amount. Because of the length of time required to construct a mould for a large aluminium casting, a binder that displays good mould properties after prolonged storage and provides flexible work and strip times is required These characteristics are displayed by an oil urethane binder

b) *Chill-Material*

The function of chills in a mould is to promote directional solidification and produce a microstructure with fine dendrite arm spacing (DAS). The influence of the chill on cooling rate is related to the volumetric heat capacity of the chill material Fine DAS (good properties) is dependent upon rapid solidification of the cast material and is typically finest in the areas adjacent to the chill. Normally, chill materials are of copper, iron, aluminium and graphite.

In summary, investigations showed that the use of chills is essential in casting aluminium parts requiring good properties. To obtain maximum properties in a cast part, a rapid solidification rate is required This is best achieved with copper chills because of the high thermal conductivity of copper. However, the cost of copper makes it economically impractical to use it for all chills Hence, a combination of copper chills in the heavy (greater than 25 mm) sections and aluminium chills in the lighter sections (5 to 25 mm) may be used to reduce costs.

Both types of chills will promote directional solidification and enhance the mechanical properties of the casting. The configuration of the chills will be dictated by the shape of the area to be chilled. Proper use and positioning of chills in the mould will reduce the possibility of casting defects such as shrinkage, misruns, and cold shuts

c) *Insulation Material*

Insulating materials such as plaster, ceramic and fibrous material are used by the casting industry to provide improved fluidity and/or decrease the solidification rate of molten aluminium These materials are commonly used to insulate risers or thin sections of aluminium sections, which are susceptible to cold shuts or misruns.

d) *Gating Techniques*

The gating technique used to get metal into the mould cavity is one of the most important contributors to the production of sound casting Improper gating practice can result in a wide variety of casting defects Right gating techniques have to be used to ensure the promotion of directional solidification, adequate mould filling, proper riser feeding, and minimum turbulence. Gating parameters are gating ratio, sprue height and shape, straining materials and riser size and location.

One of the first concerns in designing a gating system is to determine if the part should be cast vertically or horizontally. Horizontal gating is the most commonly used technique because it is generally less complicated to mould, has less hydrostatic pressure, and produces less metal turbulence. However, large, thin-wall castings are impractical to cast in a horizontal position because of non-uniform directional solidification and the potential for mould sag.

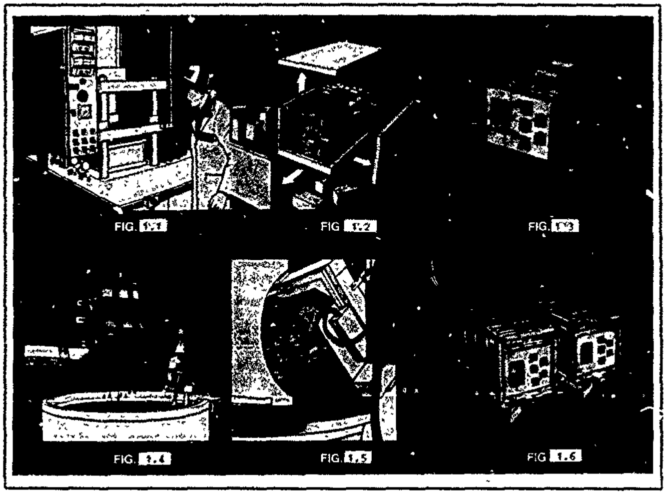


Fig 1 Principle of investment casting (a)

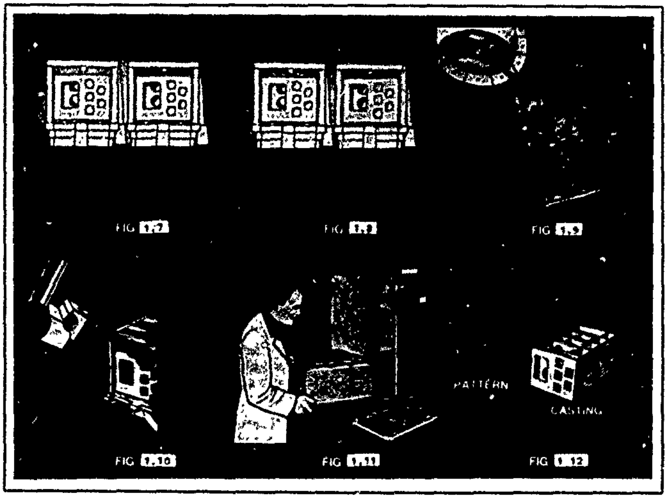


Fig 1 Principle of investment casting (b)

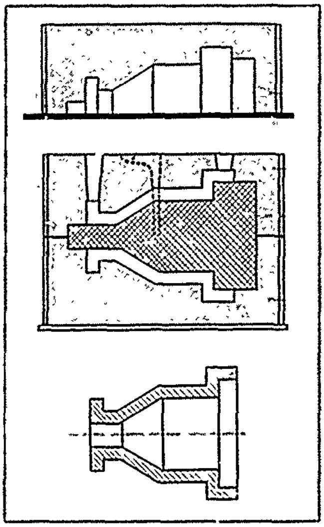


Fig 2 Principle of conventional sand casting

When parts are cast in the vertical position, directional solidification is promoted because the metal is gated into the casting only when and where metal is required. Solidification then can be controlled by judicious placement of chill, thus allowing the metal to solidify towards each riser/ingate combination The main disadvantage of vertically-gating large, thin-wall castings is a large sprue height that will cause metal turbulence if not properly designed.

1.2.2.2 *Premium Sand Casting*

Premium sand casting is more expensive than conventional sand and investment casting but makes it possible to manufacture components 3600 × 2000 × 1900 mm at minimum wall thicknesses of 1.6 mm and high tolerances (+0.4 mm − 0 2 mm). By selective, local cooling, good metallurgic properties and thus high strength values can be achieved similar to those achieved by conventional sand casting.

A special type of premium sand casting is the low-pressure sand casting process, Figure 3a. A low pressure casting machine includes:

- a tight holding furnace (a) with an inner overpressure of about 0 2 to 1.5 bar and a crucible filled with molten metal
- a filling device comprising of a cast iron dip tube (b) and an injection nozzle (c) allowing molten metal to be transferred to the mould
- a structure (d) holding the mould, with one or several pour-holes

The main casting stages are as follows, Figure 3b:

- progressive pressurization of furnace to drive the metal up through the tube
- then, in the component (from point A), with an upward motion speed directly related to this pressurization
- overpressure is applied as soon as the mould is filled up (from point B)
- this overpressure is maintained for a period corresponding at least to the component solidification range (from point C to point D)
- the release in the furnace pressure causes the non-solidified metal to go down back in the crucible through the tube and the casting nozzle.

Great care should be taken:

- for a turbulence-free filling of the mould so that oxides or blowholes are avoided
- so that mould should have all suitable venting ports to get t. best filling, yet avoiding molten metal leaks when pressurization applies
- so that solidification should occur first in the most distant parts from the gating system, then, gradually in the casting till it reaches those gates and occurs at last at the injection nozzles level which will be the seat of solidification shrinkage.

The improvements achieved by low-pressure sand casting are

1. Repeatability of casting conditions through:
   - total control of casting temperature (furnace regulation)
   - total control of filling speed (gas admission control)
   - total control of overpressure after filling (through same control system as above)
2. Control of gradient temperature
   The metal near casting gates (for they act as feeder heads) stays liquid longer in an insulating mould (sand or ceramic) while the component solidification speed can be increased using metallic denseners.
3. High feeding overpressure
   This overpressure is applied through the gating system on the component molten metal as soon as filling has ended and ranges from 300 to 500 mbar, which corresponds to a feeder head height of about 1.6 to 2.5 m.

   This high value largely increases the components density. An investment pre-coat applied on the moulds avoids molten metal penetrating into the sand.

1.2.3 Titanium Casting

The casting of titanium and its alloy presents a special problem due to the high reactivity of the material in the molten state. This requires special melting, mould-making practices and equipment to prevent alloy contamination At the same time, titanium castings present some advantages when compared to castings of other metals.

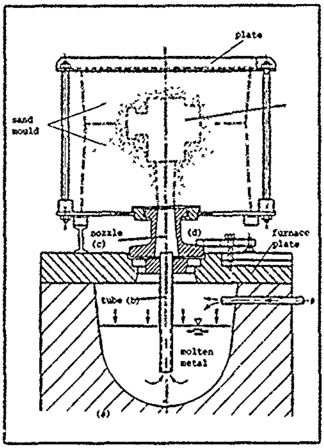


Fig 3a Principle of low-pressure sand casting

1.2.3.1 *Introduction*

The following special techniques, Figure 4, are used to cast titanium:

- Because it readily absorbs oxygen and nitrogen, it is melted and poured in a vacuum.
- To ensure purity of the metal a consumable-electrode skull process is used for melting. It is possible using electron beam melting.
- Because this melting process does not provide significant superheat, the titanium solidifies rapidly after pouring. Therefore, it is necessary to fill the moulds quickly, and a centrifugal method is often used.
- Because it reacts with normal mould materials, new materials had to be selected and developed for use.

The consumable electrodes are made from billet, bulk weldable solids (for example, rolling-mill offcuts), approved foundry revert (such as feeders and risers from previous melts) and customer-supplied material.

For small castings, moulds are packed around the inside periphery of the centrifuge, while for large centre axis castings, which may be up to 2.7 m diameter, the moulds are stacked concentrically in the centrifuge.

The complete furnace is evacuated, the arc is struck to melt the electrode progressively into the water-cooled copper crucible, and with the centrifuge spinning the crucible is tilted to pour the molten metal through the rotating runner system into the moulds.

1.2.3.2 *Casting Methods*

There are two major titanium casting methods: rammed graphite and investment casting.

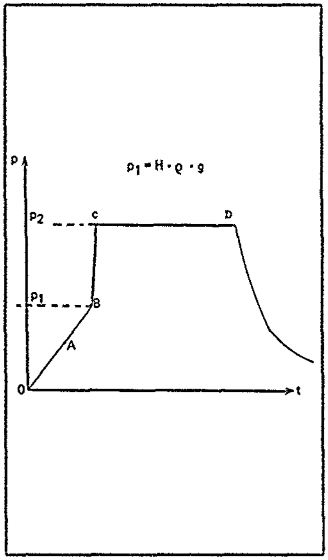


Fig 3b Low-pressure sand casting: pressure diagram

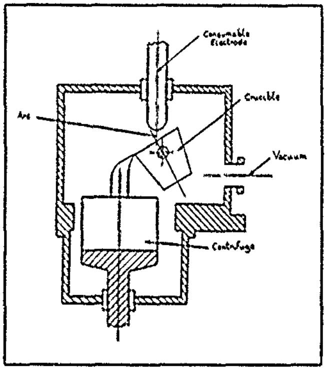


Fig 4 Principle of titanium casting

To illustrate the typical stages involved in the process of producing titanium cast parts, a manufacturing sequence for

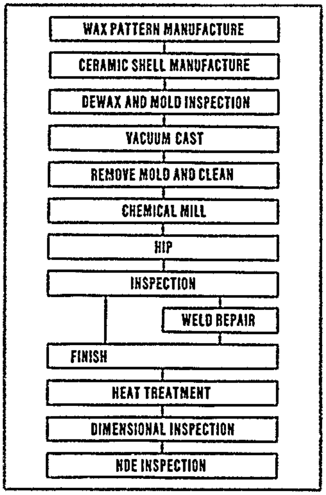


Fig 5 Process diagram of titanium investment casting

the investment casting method is shown in Figure 5 This sequence is typical for producing high integrity components for gas turbine engines and airframes. For less demanding applications, some steps, such as hot isostatic pressing (HIP'ing), weld repair, or heat treatment, can be eliminated.

a) *Rammed Graphite Mould*
Rammed graphite was the earliest commercial mould-making technique for casting titanium. Traditionally, a mixture of properly size-fractioned graphite powder, pitch, corn syrup, starch and water is rammed against a wooden or fibreglass pattern to form a mould section The corn syrup and the starch give the mould some green strength after the rammed mould has been dried in air for 24 h or for shorter periods at 200°C in a drying furnace. The mould segments are then fired under a suitable shield for 24 h at 1025°C causing all the constituents to carburize and harden. In some cases, watersoluble binders are used in the mixture, which then does not require the high firing temperature.

The minimum practical wall thickness is 5 mm. The mould ramming is a labour-intensive process which cannot be easily mechanized and automated using the traditional binder/aggregate mixture. A system of gates and risers assures proper molten metal flow during the casting process, and causes most of the shrinkage porosity to occur in the risers and the gates, which are not part of the finished product.

The graphite mould is so hard that it must be chiselled off the cast parts. The castings are then generally cleaned in an acid bath (followed by chemical-milling and weld repair if necessary) and sand blasted for good surface appearance. Care is needed to prevent hydrogen pickup during the acid operations.

In large or complicated shape castings, the mould can be assembled from as many as 30 segments In large mould segments it is sometimes difficult to control the precise shape of the mould during the drying and firing stages which limits the dimensional accuracy of the final product. The dimension tolerances of large components can be improved by using shell cores which are light, hard and accurate, or by using the ceramic moulds

b) *Ceramic Moulds*
In this method ceramic mould segments are produced from wooden patterns in a proprietary process which maintains good mould accuracy and reproducibility. This is a higher cost method than the rammed graphite technique and, in addition, the ceramic mould is more difficult to remove from the cast parts. This method is most appropriate for large components requiring accurate dimensions such as water-jet pump impellers for hydrofoil boats.

c) *Investment Casting*
In this method, a wax pattern is produced by an injection moulding technique. The oversized wax injection tooling cavity is produced with consideration of wax, ceramic shell, and titanium alloy shrinkages. The gating system pattern is added to the product wax pattern.

The pattern assembly is then dipped in ceramic slurries, stuccoed and dried. This is repeated several times to build a ceramic shell with enough strength to sustain the molten metal pressure after being hardened by firing. The wax pattern is then removed in a steam auto-clave, which leaves the mould cavity ready for casting after firing. The minimum practical wall thickness is 1.0 mm.

To improve productivity, many duplicate components can be cast in a cluster pattern. The injection mould wax pattern production, the slurry dipping process, and the cluster patterns make this method adaptable to automation and production of large-quantity runs

The ceramic shells are placed inside the mould chamber of the vacuum arc furnace. The casting can be done on a centrifugal table to assist the metal flow or, more simply, by gravity pouring which requires higher temperature preheat of the shells to increase the molten metal flow.

The ceramic shell is removed after casting, as well as the gating system. Investment casting provides very good dimensional control and is suitable for production of high-quality aerospace engine components.

1.2.3.3 *Supplementary Operations and Processes*

a) *Chemical Etching*
Although mould materials are chosen for minimal reactivity with molten titanium, there is always some reaction leaving a superficial layer of surface contamination. This is removed by chemically etching away a layer, usually 0.13 to 0.38 mm deep. The dies and patterns are made oversize so that the etched castings meet drawing dimensions. This chemical

etching method may, under some circumstances, be extended to provide somewhat thinner wall sections than can be cast

b) *Hot Isostatic Pressing (HIP)*
A heated argon-filled pressure vessel (autoclave) is used to HIP densify titanium alloy castings. If the HIPing is done properly, no residual voids will remain in the material (diffusion bonding) except for surface connected porosity. This type of porosity cannot be healed by HIPing, unless special procedures are followed, and must be weld repaired

The HIPing of Ti-6AL-4V is typically done in the temperature range 890—955°C at pressures of 700—1000 bar for 2—4 h.

In the case of titanium castings, a can or a mould is unnecessary to obtain densification, which makes it a less expensive operation than HIPing of powders. HIPing can enhance critical mechanical properties such as fatigue resistance, while causing no serious degradation in properties like fracture toughness, fatigue crack growth rate, and tensile strength. Therefore, cast parts which are fatigue-critical are HIPed, whether these be for airframe components, or engine parts.

c) *Weld Repair*
Titanium is fully weldable allowing repair or salvage operations whenever necessary Weldments have excellent tensile and fatigue properties sometimes exceeding those of the base metal.

Therefore, weld repair is a common practice for filling gas porosity shrinkage pores exposed by chemical milling, post-HIP surface depressions, or cold shuts, for applications requiring defect-free components. Inert gas tungsten arc welding is typically used.

d) *Heat Treatment*
Two types of heat treatment are generally used with titanium alloy castings. The first is a post-casting heat treatment which is primarily intended to relieve the residual stresses which result from cooling from the molten state, and the second is designed to change the cast microstructure for mechanical property improvement. This latter type is carried out at higher temperatures than the stress relieving treatment, typically close to or above the beta transus temperature.

Since titanium castings are slow-cooled in insulating moulds in a vacuum, subsequent thermal treatment is normally unnecessary since the castings are virtually 'annealed' while still in the moulds Stresses induced by welding can be relieved by a simple stress relief cycle at 650°C.

Straightening, flattening or sizing may be accomplished at the normal stress relief/anneal temperature by use of appropriate fixtures Alpha alloys are not heat treatable, but a wide range of strengths can be obtained in Alpha-Beta or Beta alloys through solution treating and ageing.

1.3. CANDIDATE MATERIALS

Preference is given to the casting alloys A357, A201 and TiAl6V4 (Table 1), for structures in aircraft, on account of the high strength values of these alloys.

The siliceous standard casting alloy A357, a further development of A356, has particularly good casting properties, producing strength values between $R_m = 310$ N/mm² (investment casting) and $R_m = 340$ N/mm² (premium casting) depending on the casting process and component geometry

The silver-alloyed and highly cupriferous material A201 is well suited when high demands are made on strength values of approx. $R_m = 420$ N/mm² but is sensitive to heat-cracking during casting.

High purity versions of A357 and A201 are now under development in an attempt to control better uniformity and reproducibility of their properties. These alloys will be known as B357 and B201.

Titanium castings are produced predominantly from the TiAl6V4 alloy and various commercially-pure titanium grades. However, a number of the other alloys have recently been cast. In almost all cases, these are simply cast versions of conventional IM alloys. For TiAl6V4 the guaranteed properties are approx. $R_m = 1000$ N/mm².

1.4 APPLICATION OF THE HANDBOOK

The Handbook should provide the user with practical

Table 1
Chemical composition of the aluminium alloys A356, A357, A201 and the titanium alloy TiAl6V4

ELEMENTS / ALLOY		Cu [%]	Ag [%]	Be [%]	Mn [%]	Mg [%]	Ti [%]	Fe [%]	Si [%]	Zn [%]	Others each [%]	Σ [%]	Al [%]	V [%]
A356 (3 2374)	from	—	—	—	—	0.20	—	—	6.50	—	—	—		—
	to	0.20	—	—	0.10	0.40	0.20	0.20	7.50	0.10	0.05	0.15	Bal	—
A357	from	—	—	0.04	—	0.40	0.10	—	6.50	—	—	—		—
	to	0.20	—	0.07	0.10	0.70	0.20	0.20	7.50	0.10	0.05	0.15	Bal	—
A201	from	4.00	0.40	—	0.20	0.15	0.15	—	—	—	—	—		—
	to	5.00	1.00	—	0.40	0.35	0.35	0.10	0.05	—	0.03	0.10	Bal	—
TiAl6V4	from	—	—	—	—	—		—	—	—	—	—	5.50	3.50
	to	—	—	—	—	—	Bal	0.25	—	—	—	—	6.75	4.50

information, i.e. design data, mechanical values and quality assurance methods, but not with manufacturing data because they are the "know-how" of the foundry. This Handbook was created to help the user with basic information for properly designing a casting. It provides specific information on design data and includes practical tips on how to prepare a drawing for a casting.

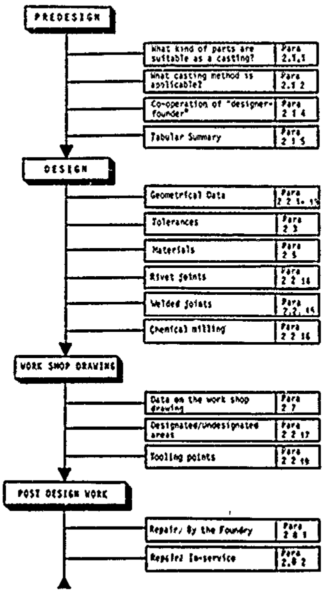
The Handbook was also designed to help the user to understand how castings can be used as reliable and cost-saving components in their products.

At the present time the Handbook will cover only aircraft structural applications and the A357, A201 and TiAl6V4 alloys.

In the next step the Handbook can include also turbine-application and other casting-alloys.

2 CASTING DESIGN

2.0 FLOW DIAGRAM "DESIGNERS GUIDELINES"



2.1 GENERAL

2.1.1 Introduction

This section deals with the geometrical aspects of the casting methods and should help to optimize casting created by the aircraft designer as well as by the casting specialist. As a first step a casting should be designed with regard to the requirements of its application.

In the rough design stage the geometrical design data and casting techniques should be taken into account, according to the chosen casting method (Investment, Premium, Sand or Conventional Sand Casting). This is the reason why the casting method has to be determined very early on by the aircraft designer. Each system has its own advantages, which will help to optimize the part with regard to stress, weight and cost.

There are some features, that can be used as a first design step to check whether a casting solution is applicable or not.

a) *Outer contour and geometry*
The more complex the shapes, the greater is the advantage of casting, because the machining expenditure is very high for spherical contours.

b) *Overall dimensions*
The overall dimensions of the component considered have to be checked with regard to feasibility by the foundries, because for each casting method there is a limit to production possibility.

c) *Wall thickness*
In general, castings can be produced with the minimum wall thickness of 1.5 to 1.8 mm. However, designs with thinner walls are possible.

d) *Tolerances*
It is indisputable that the tolerances obtained by casting are somewhat higher than those produced by machining. Thus it is very important to know whether these tolerances are acceptable with regard to the assembly or to the outer aerodynamics surface requirements. In many cases these casting tolerances may be suitable for the design without large expenditure by shimming.

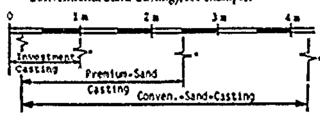
e) *Loads*
In early design, a rough calculation has to be made for the selection of the right casting material. If the normal Al-alloys (A356, A357) will not fit with the load level, the application of a Ti-alloy may be considered.

2.1.2 Selection of Casting Method

The above mentioned features have to be used for the selection of the casting method.

The following check list should help the designer to find the appropriate casting method for his design.

1. Outer Dimensions
Each casting method is determined by the maximum overall dimensions. This depends on the equipment of the foundries, i.e. the ceramic dipping tank (Investment Casting) or the heat treatment furnace (Premium-Conventional Sand Casting), for example.

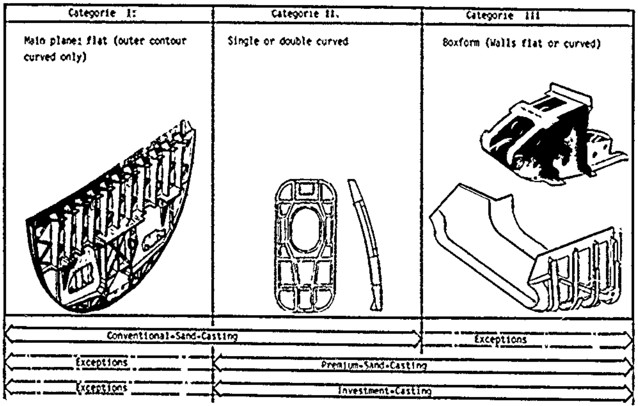


2. Tolerances
Castings are typical integral parts and therefore the size of the tolerances depends on the size of the dimensions to a higher degree than, for example, in

* The overall dimensions in this range have to be agreed by the foundries.

machined parts. *And they also differ according to the various casting methods.* So the designer has to check whether the casting allowances are suitable for the overall assembly. For additional information see para. 2.3.

3. Shape
   All shapes of aircraft parts can be divided into three main categories:



4. Wall Thickness
   Nearly the same minimum wall thickness can be produced with the casting methods:

   Investment Casting: 1.5 ± 0.15 mm

   Premium Sand Casting: $1.8 {+0.4 \atop -0.2}$ mm

   Conventional Sand Casting: 2.5 ± 0.5 mm

5. Mechanical Properties
   A further selection feature is the mechanical properties. Considering the same casting alloy for the three casting methods, different values are achievable (see Chapter 3).

6. Surface Roughness
   This point is only of concern for castings located at the outer contour of the aircraft structure or for mating surfaces which may or may not require subsequent machining. Typical surface roughness is as shown:

   – Investment Casting
     – 1.6–3.2 μm – 65–125 RMS
   – Premium Sand Casting
     – 3.2–6.4 μm – 125–250 RMS
   – Conventional Sand Casting
     – 6.4–12.5 μm – 250–500 RMS

After going over this checklist, the suitable casting method should be clear and the discussion with the foundry may start.

2.1.3 Design to Cost

2.1.3.1 *Introduction*

A primary driving factor in the utilization of castings is cost reduction. Many studies have shown that castings can be extremely cost effective for particular applications. The two primary application areas are

1. Replacement of components which involve assembly of numerous details and
2. Replacement of components requiring extensive machining

However, there is no firm fixed rule on when or where a casting should be used. The economics will be affected by the casting process selected, production volume, material and quality requirements. But most importantly the economics are affected by how good a job the designer does in designing the component to be cast. The cost of a casting can easily be doubled by factors controlled by the designer. It is highly recommended that the designer works with one or more foundries in developing his design.

The foundry should make suggestions during the conceptual design and again during detail design stages *(not after the design is complete)*. The importance of this to get cost effective high quality castings can not be over emphasized.

2.1.3.2 *Economical Casting Utilization*

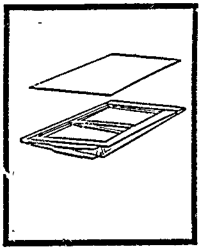
Castings are not a panacea for all aircraft components. They should be used where it makes sense to use them.

The following three figures show three different aircraft applications:

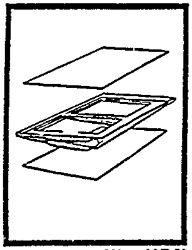
Simple configuration (2.1.3.2.a), semi-complex configuration (2.1.3.2.b), and complex configuration (2.1.3.2.c).

Assuming typical aircraft production quantities, relative non-recurring and recurring costs were developed for the

SIMPLE CONFIGURATION
MANUFACTURING COST COMPARISON
LEADING EDGE EXTENSION



HOGOUT DESIGN WITH ASSEMBLED DETAILS

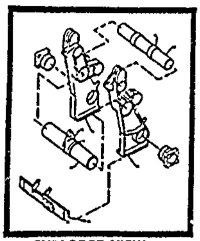


CASTING DESIGN — ALT #1 FRAMEWORK ONLY — A357—T6 ALUM ALLOY SEPARATE UPPER & LOWER ATTACHED SKINS

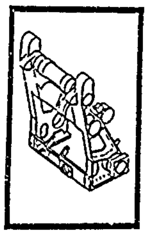
Design	NON-RECURRING	RECURRING
HOGOUT DESIGN WITH ASSEMBLED DETAILS	100	100
CASTING DESIGN — ALT #1	182	109

Fig 2.1.3.2 a

SEMI-COMPLEX CONFIGURATION
MANUFACTURING COST COMPARISON
SUPPORT CANOPY MECHANISM



EXPLODED VIEW — DETAIL BUILDUP DESIGN



A357-T6 CASTING DESIGN

Design	NON-RECURRING	RECURRING
EXPLODED VIEW — DETAIL BUILDUP DESIGN	100	100
A357-T6 CASTING DESIGN	81	85

Fig 2.1.3.2 b

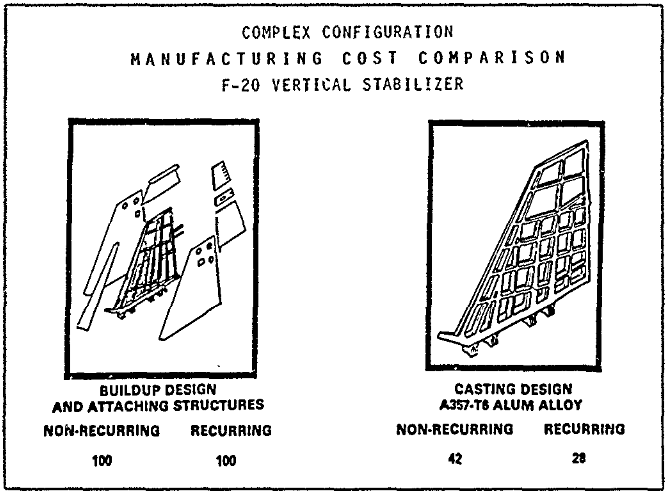


Fig 2 1 3 2.c

baseline design and for a cast replacement design

As can be seen, in the simple configuration the non-recurring costs were very high for the casting compared to the machined design In addition, the recurring costs were also higher, since the machining required on the machined design was fairly simple. In summary, this would be a poor application for castings.

The semi-complex configuration, however, is a different story It involves complex machining of details and assembly of these details. As can be seen, the casting alternate design shows 15–20% cost savings. Where castings are really advantageous, however, is in the replacement of complex configurations. This particular application involves extensive machining and the assembly of a large number of details. The casting alternate design shows a very high cost savings potential — well over 50%.

In the above cases, production quantity made no difference. In many instances, though, the non-recurring costs may be very high, but the recurring costs very low. In these instances, the production quantity becomes the determining factor in whether a casting is selected or not.

For a design comparison the following cost parameters have to be considered.

Non Recurring Costs (NRC): — Casting tooling
— Inspection jigs.
— Tooling for machining
— Transport boxes
— Prototypes

Recurring Costs (RC): — Casting price
— Inspection work
— Transport

The various cost parameters differ from casting method to casting method and from foundry to foundry Therefore all potential foundries have to be asked for an offer for every part, because it is not easy to transfer the cost from one part to another part.

2.2 DESIGN DETAILS

This section deals with the geometrical rules applicable on the mentioned casting method Some of them differ from method to method but they are mostly equal for all castings

The following features should be considered for an optimized casting:

2 2.1 Overall dimensions
2 2 2 Minimum wall thickness
2 2.3 Radii
2 2 4 Ribs and webs
2.2.5 Material accumulations
2 2 6 Holes located in ribs and webs
2.2.7 Cross section transitions
2.2.8 Loft lines
2.2.9 Cavities
2 2.10 Channels and holes as cast
2 2.11 Added material for machined areas
2 2.12 Draft angles
2 2.13 Fail-safe design examples
2 2.14 Rivet joints
2.2.15 Welded joints
2 2.16 Chemical milling
2 2.17 Designated/undesignated areas
2 2.18 Marking
2.2.19 Tooling points

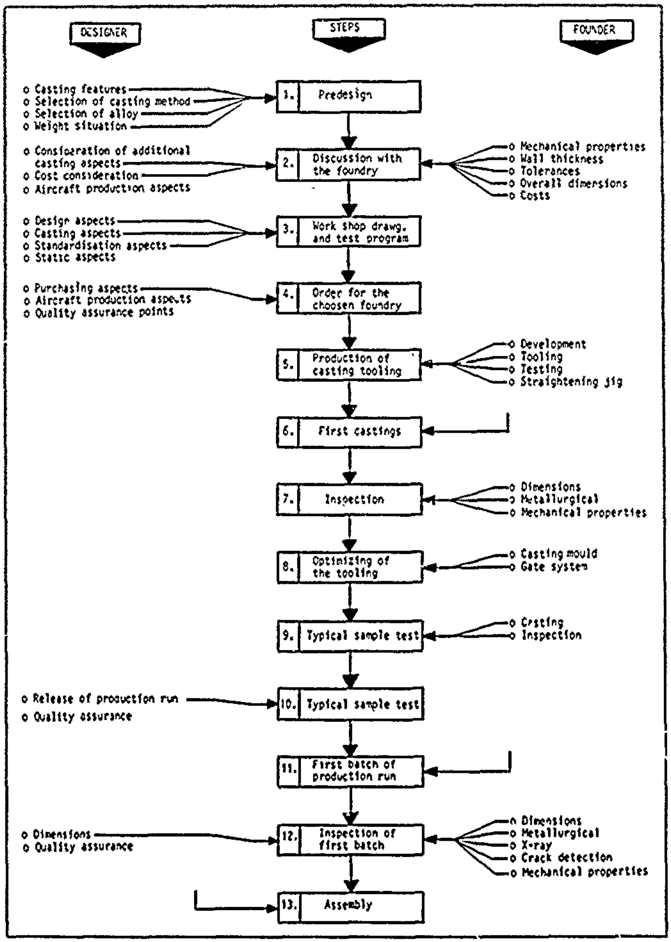


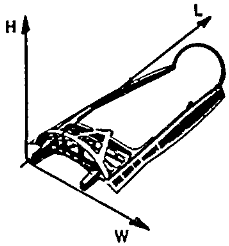
Fig 2.1.4 Flow diagram: co-operation between designer and founder

Table 2.1 5
Tabular Summary (Al-castings, only)

	Investment-Casting	Premium-Sand-Casting	Conventional-Sand-Casting
Advantages	o Small tolerances o Small wall thickness	o High mechanical properties for all wall thickness o Small wall thickness o Small tolerances	o Large dimensions o Low costs o Local high mechanical properties by local cooling
Disadvantages	o Lower mechanical properties	o Higher costs for castings and tooling	o Larger tolerances o Larger wall thickness
Part Size (Maximum overall dimensions)	1000 x 800 x 500 mm	3600 x 2000 x 1900 mm	5000 x 1500 x 1500 mm
Wall thickness, depends on: o outer dimensions o part geometry o alloy	$T_{min} = 1,5 \pm 0,15$ mm	$T_{min} = 1,8 {}^{+0,4}_{-0,2}$ mm (Local, $1,5 \pm 0,2$ mm)	$T_{min} = 2,5 \pm 0,5$ mm (Local, $2 \pm 0,5$ mm)
Tolerances D = considered dimension	According to countries standard. For example: VDG-P690 for Germany	$T_{min} = \pm (0,4 + \frac{1,5\ D}{1000})$ mm	According to countries standard. For example: DIN 1688 for Germany
Surface roughness	Ra 3 2 um	Ra 3 2 - 6,4 um	Ra 6,4 - 12 um

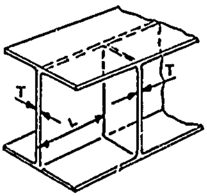
2.2.1 Overall Dimensions

In general, maximum dimensions feasible by the foundries are listed below:



	Dim.	L (mm)	W (mm)	H (mm)
Al	Investment-Casting	1000	800	500
Al	Premium-Sand-Casting	3600	2000	1900
Al	Conventional-Sand-Casting	5000	1500	1500
Ti	Investment-Casting	800	660	400
Ti	Rammed-Graphite-Casting	2100	1100	1100

2.2.2 Minimum Wall Thickness



		T (mm) -Normal-	T (mm) -Special-
Al	Investment-Casting bei L = 130	0,8	0,6
Al	Investment-Casting bei L = 600	1,6	1,4
Al	Investment-Casting bei L = 1200	3,0	1,9
Al	Premium-Sand-Casting	1,8	1,6
Al	Conventional-Sand-Casting	3,0	2,5
Ti	Investment-Casting	1,8	1,3
Ti	Rammed-Graphite-Casting	3,0	3,0

Wall Thickness (Investment Casting)
One of the significant advantages of the investment casting process is the ability to produce very thin wall thicknesses, compared to any other casting method

The infinite number of casting configurations and sizes makes it difficult to recommend general wall thicknesses The graphic illustration, Fig.2 2.2 2 is an attempt to relate wall thickness to wall area.

The incorporation of ribs enables the foundry to produce thinner walls as represented in Fig 2 2.2 1 by curve 2, as compared to curve 1 which represents the thickness limitation of walls without ribs. The ribs will improve metal feeding and enhance stiffness, and rib intersections may be used as feeding points.

Depending on design considerations, ribs may be cast in many different configurations, two examples are illustrated

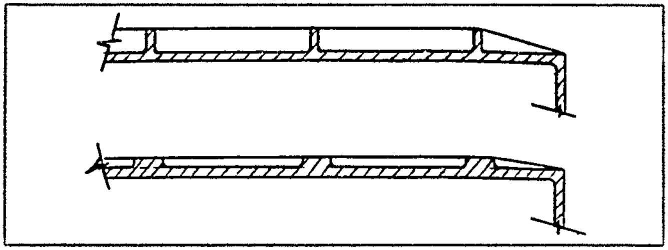


Fig 2 2 2 1

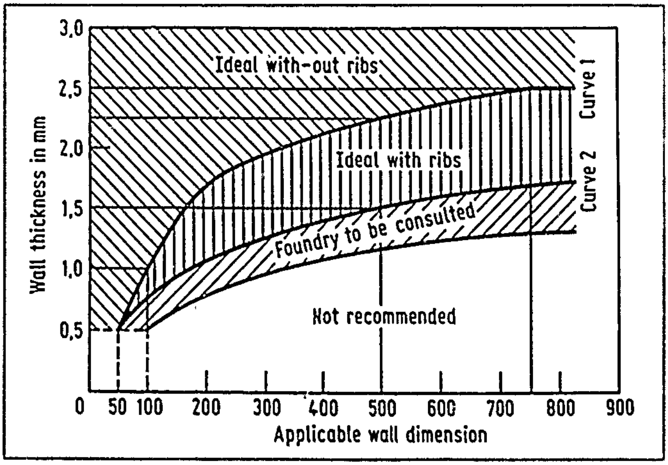
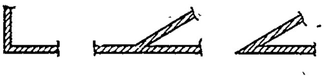


Fig 2.2.2.2

2.2.3 Radii

On principle, all fitting corners should have a radius. The reasons are to improve the material flow and to avoid crack propagation during casting and use

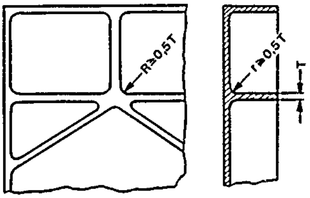
To be avoided:



Recommended:

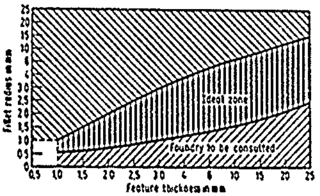
r ≈ 0.5T

Design of pocket corner radii:



Further information about fillet radii is given in the diagram below, showing the radii in dependence on the wall thickness for investment castings.

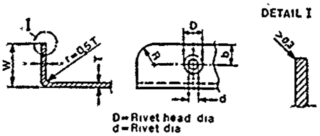
Other features may be cast sharp, such as O-ring grooves, card guides, counter bores, waveguide passages — or when functionally required.



Radii at Flanges

In many cases the flange of a web has to carry mainly shear loads, and only this determines the cross section. Then the width of the flange can be made smaller in a casting than in a machined part because of the smaller radius "r", which means less weight.

All sharp corners should be avoided, i.e. they should be radiused (see detail I). This will help to obtain a better surface protection by improving adhesion of the paint



$W = T + r + 1 + \frac{D}{2} + b$

Minimum Radii may be. 0,8 mm inside
0,5 mm outside

2.2.4 Ribs and Webs

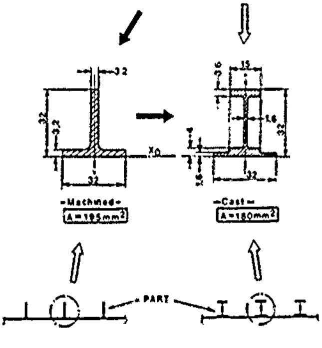
The advantage of higher mechanical properties for plate material (7075 for example) has to be compensated for when a casting is considered. The only way is to take full advantage of the production of ribs and webs possible by the casting method.

The possibility of this compensation depends in part on function and partly on collective load

From the following example it can be seen that for a statically loaded part the disadvantage of the lower mechanical properties can be eliminated, and even for a dynamically loaded part a weight advantage is possible.

1. Example (Statically loaded)

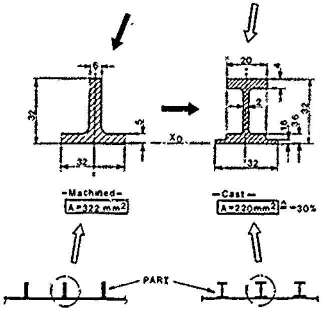
	Machined Part	Investment Casting
Bending Moment Mx	259 186 Nmm	263 120 Nmm
Rib Height	32 mm	32 mm
Material	7075 (Plate)	A357 T6
Rm (N/mm²)	470	310 *
σ (allowable) N/mm²	470 : 1.5 = 313	310 : 1.5 : 1.25 = 165



* Note For Premium-, Sand-Casting are higher mechanical properties

2. Example (Dynamically loaded)

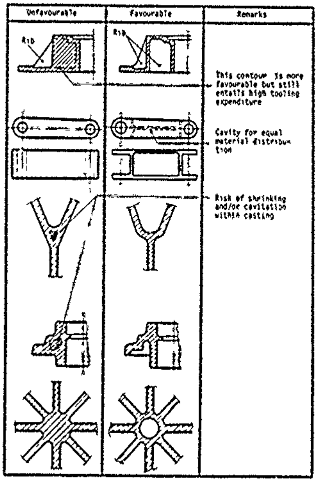
	Machined Part	Investment Casting
Bending Moment Mx	259 186 Nmm	279 510 Nmm
Rib height	32 mm	32 mm
Material	7075 (Plate)	A357 T6
σ (allowable) N/mm²	200	160 *



* Note For Premium-, Sand-Casting are higher mechanical properties

2.2.5 Material Accumulation

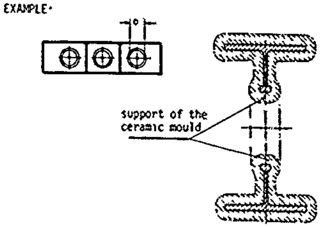
To avoid shrinking, the material thickness should be approximately equal. This measure helps to improve the weight situation, too.



2.2.6 Holes Located in Ribs and Webs

For the investment casting method it is of some advantage to provide some holes in a web within a large area. This is to support the ceramic mould.

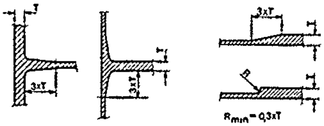
EXAMPLE:



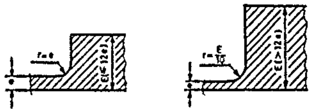
2.2.7 Cross-Sectional Transitions

If a step has to be designed (in the thickness), the transition should be carefully considered. The founder (with regard to the material flow) and the stress man (with regard to the dynamic loads) do not favour a short transition (see following example).

Examples for all casting methods



But if for any reason a large step is desired, the premium process can provide that (see example below)



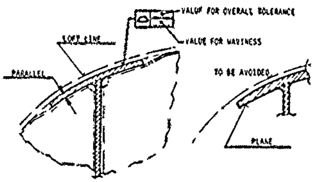
Example for premium process

2.2.8 Loft Lines

The majority of solid parts of an aircraft are in some way related to the theoretical outer contour, the loft line. This means the production of single or double curved surfaces on flanges and chord sections.

Here a casting has an advantage because spherical surfaces on the die for the mould need only to be machined once.

The inner surface of a flange should be parallel to the loft. This makes it easier to define all connection parts and in addition results in a weight reduction (see example).



This symbol should not be omitted for the definition of the loft and shows the allowable tolerance.
These resulting deviations have to be considered as an important criterion, if loft lines are produced on a casting. The importance of position and waviness tolerances and in particular their definition should be very clear to the designer and have to be discussed with the foundry. It is indispensable that both designer and founder use the same terms (for more information see chapter 2.3).

The foundry has to be provided by the designer with the suitable loft line data in the form of tables, drawings or tapes.

2.2.9 Cavities

A further advantage of casting design is the possibility of providing cavities. This will increase the degree of integration, i.e. reduce the number of parts.

It should be borne in mind that the core needed must be sufficiently supported by several bolts.

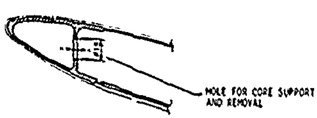
The minimum diameter of the required holes should be approximately 18 mm, but the ... and spacing of these holes for the core support has to be discussed with the founder and agreed by him, because location and number of bolts depend on the geometry of the parts and have a great influence on the tolerances.

A second purpose of these holes is to allow the removal of the lost cores from the casting.

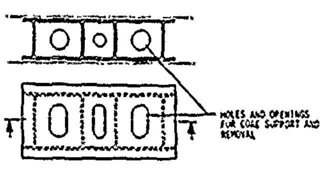
Later, in service, they can be used as inspection holes by the airlines. If they are in the outer contour and are to be closed, this can be done by riveting or welding.

Below are shown some examples of cavities on castings.

a) Lip of the "Forward Inlet" casting



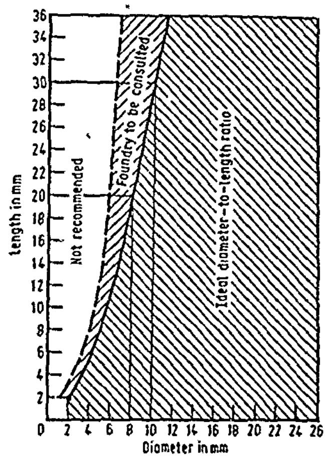
b) Holes for core support on a box-shaped casting. Size and geometry of the openings should be defined and agreed in cooperation with the stress department and the foundry.



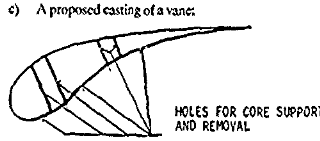
Through Holes

Almost any size of through hole can be cast, provided that certain conditions are met.

The figure below gives a graphical description of the recommended diameter to length ratio

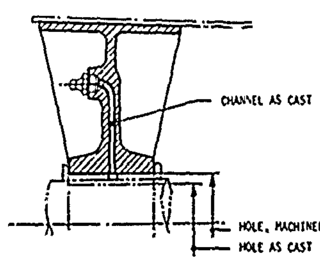


c) A proposed casting of a vane:



2.2.10 Channels and Holes as Cast

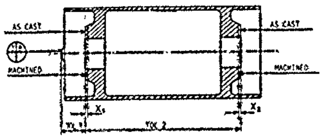
In the special case of a bearing that requires lubrication it is possible to place the grease nipple in a practical location. A channel for the grease can be provided by the founder, without complex drilling in the machine shop (see sketch below).



Where large holes are needed, for example for a bearing, a large portion of the hole can be cast and drilled later for exact bearing position and for the correct diameter for bush installation.

2.2.11 Added Material for Machined Areas

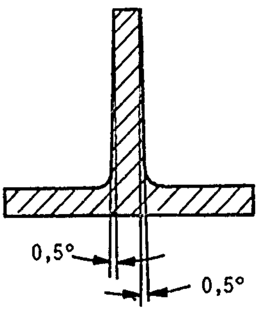
In those places where very high accuracy is required and not possible by casting, sufficient material must be provided for subsequent machining to take into account all deviations that may appear on wall thicknesses and wall positions (see sketch below).



$x_1 = 2 + TOL\ 1$
$x_2 = 2 + TOL\ 1 + TOL\ 2$

2.2.12 Draft Angles

Normally there is no need for draft angles. For casting processes using sand as the moulding material, a draft angle is needed on certain flanges. It should be taken into account that the draft angle means more weight and it is therefore necessary to minimize its use.

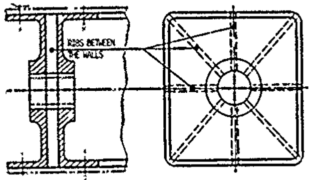


2.2.13 Fail Safe Design Examples

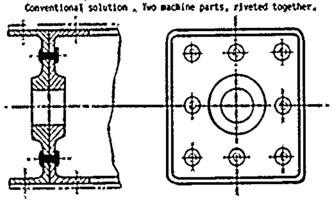
In some design cases there is a need for a second load path in primary structures.

The normal design method solves this problem by providing a second machined part riveted to the other. So if one part fails the load is carried by the other one.

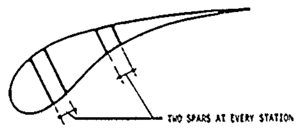
This principle can also be used for a casting. Below are shown two examples of a fail-safe construction:



Conventional solution , Two machine parts, riveted together.



Section of a vane



2.2.14 Rivet Joints

Generally this topic embraces a large range, and there is a great deal of experience of connecting metallic structures by riveting. What do these values look like for cast materials (Al/Ti)?

Questions which will concern the designer on detail design points include:

- Kind of rivet
- Rivet diameter
- Spacing
- Edge distance
- Hole fit
- Thickness of the joint member
- Rivet fracture values
- Rivet fatigue value

With regard to above mentioned questions, several tests were performed under the "Economic Structures Technology-Metals" program founded by the Federal Ministry of Defence of Germany

The conclusions of these tests are as follows:

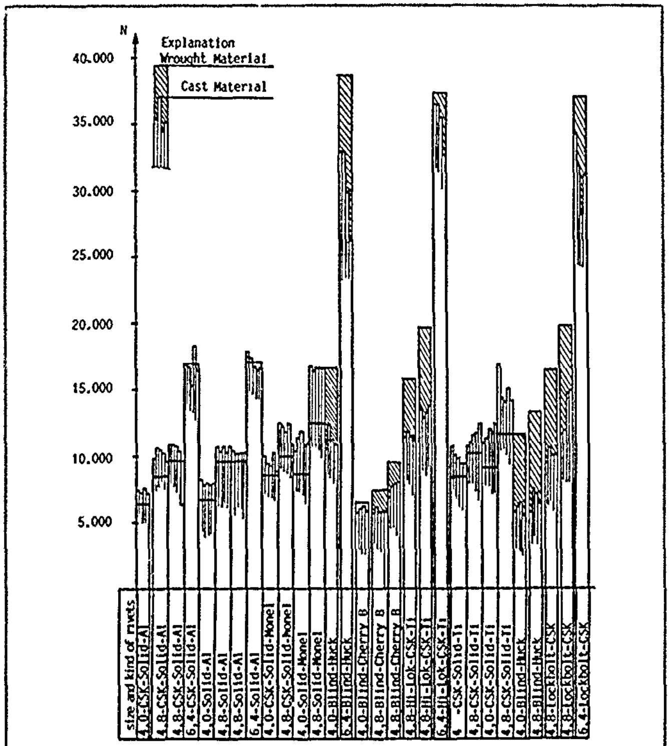
- It is possible to join Al-cast-alloy A357 without special production expenditure.
- The *static* stress behaviour of the riveted test specimen was the same when solid Al-rivets were used. But when blind or close tolerance rivets are installed the cast material has a slight disadvantage (see Fig.2 2.14.1).
- For fatigue loading the alloy A357 showed a slight advantage in smaller decrease of fatigue life (see Fig 2 2.14.2).

Several kinds of rivets (solid-Al-Monel-Ti., blind and close tolerance rivets from steel and Ti) have been considered. No fracture cracks have appeared at the joint during installation (Note the increase of the body for solid rivets).

A further point is mating of material. In future, there will be more and more Al-alloy — Carbon Fibre Reinforced Plastic and Al-alloy — Ti-alloy combinations. Also no special requirements have been found for A357-material versus wrought alloys in these combinations.

For all these aspects, the designer does not have to consider special points and alterations of his known rules with regard to the integration of castings.

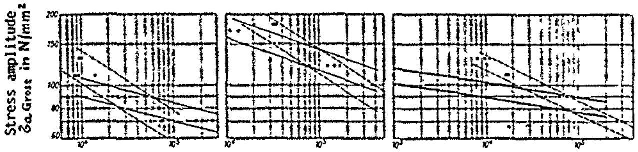
For all static and dynamic stress values see Chapter 3



- o Material of specimen: A357-T6
- o Test specimen acc. to MIL-STD.-1312
- o Calculation value = Ultimate value or 1.5 x Deformation value

- Scource: Journal "Aluminium" (Ger) 58. Edition, 1982-3
  Author: K. Hoffer, Bremen

Fig 2.2.14.1 Results of static tests



Picture a   Picture b   Picture c

- single load at specimen with low load transfer
- Rivet dia = 6,4 mm
- o Al-Alloy A357-T6 (casting)
  • Al-Alloy 3.4364 (wrought)

Stress Ratio:

- Picture a: $\frac{\sigma_u}{\sigma_o} = +0{,}1$ (Hi-Lok)
- Picture b: $\frac{\sigma_u}{\sigma_o} = -0{,}1$ (Hi-Lok)
- Picture c: $\frac{\sigma_u}{\sigma_o} = +0{,}1$ (Taper-Lok)

- Scource: Jounal "Aluminium" (Ger)
  58. Edition, 1982-3
  Author: K. Hoffer, Bremen

Fig 2.2.14.2 Fatigue life of rivet connections

2.2.15 Welded Joints

Special applications are conceivable where several castings are joined by welding. In this case, the designer has to define the welding joint according to the chosen welding process.

Some features have to be considered:

Alloy — A357: • Use base metal as filler metal.
• Notice the decrease of mechanical values in the welding zone:

Welding Process	Residual properties of the base metal A357	
	Rp02/Rm	A5
EB	95%	30%
TIG	55%	60%

- *No decrease of mechanical properties, if a heat treatment (T6) is performed after welding.*
- No higher susceptibility to corrosion
- No disadvantage for cyclic loads.

AVIOR A
K01

see same features mentioned for alloy A357, but note some differences:

- As little heat penetration as possible
- Decrease of mechanical properties in the welding zone

Welding Process	Residual properties of the base metal (Avior A)	
	Rp02/Rm	A5
EB	75%	
TIG	40%	

- Surface protection absolutely necessary, because of the high susceptibility to corrosion.

  Because of the stress corrosion, a heat treatment T7 is necessary

2.2.16 Chemical Milling

Chemical milling is a normal process for sheet and plate. It is mainly used on skins in areas where different stress levels allow various material thicknesses, which means saving of weight.

In some cases, that idea is interesting for castings, too We know of Al-alloys, like A201, that have high mechanical properties, but low castability: for example, the minimum wall thickness for A201 is about 3 mm (0.12").

This is a great disadvantage, because the normal structural parts have a *small* area for introducing high loads but in the *larger areas* there may be no reason for such a wall thickness. In that case, if a local reduction is required, the "chemical milling" process should be taken into consideration

In addition, it is possible to use the cheaper sand casting method and to reduce the higher wall thickness by chemical milling.

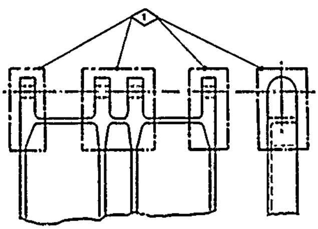
For the design the same features as used for wrought products can be transfered to castings!

2.2.17 Designated/Undesignated Areas

It is generally important to divide a casting into designated and undesignated areas. This is valid for economic as well as mechanical and geometrical reasons.

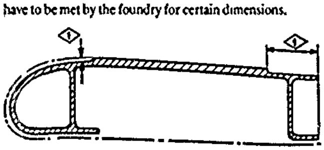
Mechanical areas:
Most structural parts have areas where higher loads have to be introduced. These areas must be marked on the drawing within a dash-dotted line. Here, the founder will provide and guarantee the higher mechanical properties and a better grade of x-ray As they will greatly influence the cost, the designated areas should be kept as small as the designer can permit.

Marking example:



1. In this zone: x-ray grade....
2. Undesignated areas: x-ray grade....

Geometrical areas.
Geometrical critical areas are zones where small tolerances have to be met by the foundry for certain dimensions.



1. Dimension with reduced tolerances

2.2.18 Marking

The necessary marking of castings has to be done by the foundry Normally they will work the identification mark into the mould so that the letters will be in raised form on the casting. For small parts and where the raised letters will not fit the assembly, a rubber stamp is possible.

The identification mark should include:

- part number (refering to the aircraft drawing numbering system)
- number of the material specification
- name of the foundry

The size of the letters and the position of the marking have to be defined on the drawing.

Further information has to be taken from the applicable aircraft standard.

2.2.19 Tooling Points

To ensure that dimensioning of drawings is consistent throughout the industry, a standard procedure has been set up to identify important points and planes for all set-ups, in the foundry, at the aircraft manufactory inspection and for machining. The system of *tooling points* and *datum planes* described here will help in the preparation of drawings and ensure the casting quality.

Cast surface irregularities may be present in any casting process. While these irregularities may be within casting tolerances, unless they are taken into consideration during setup (for both dimensional inspection and machining) acceptable surface irregularity may be interpreted erroneously as lack of casting consistency

These discontinuities may even be magnified by the setup to wrongly show a casting as out of dimensional tolerance!

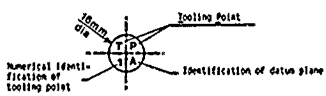
The tooling point approach eliminates this effect of cast surface variations on setup.

Specific small areas of the cast surface are designated as tooling points. Attention can then be given to these areas to assure regularity. In casting production the designated areas will be avoided where a processing operation might result in surface irregularity

Tooling points are located so as to establish three datum planes. Wherever practical, casting dimensions are taken from these three planes. By using tooling points in all setups — in the foundry, at aircraft manufactory inspection, and for machining — consistent dimensions can be ensured of the finished part.

Definition
Tooling points are specified locations on accessible surfaces of a casting which serve as points of fixture contact for inspection and subsequent machining operations. These points define three datum planes on the casting for dimensioning purposes.

Tooling Point Symbol
The following symbol should be used on drawings to indicate tooling points.



Drawing Specification

Tooling points should be indicated on drawings as shown in 2.2.19.a. The datum plane may be defined by the tooling point symbol or designated by a leader and the appropriate letter with the following note "Datum Plane A".

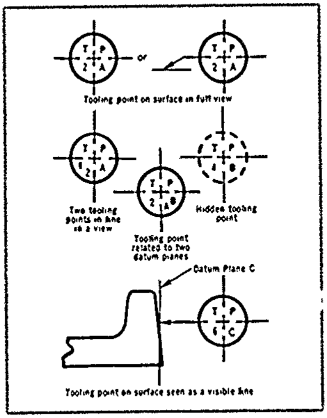


Fig 2.2.19 a

Definition of Datum Plane

Datum planes are planes of origin from which features of the casting are dimensioned

Relationship between Tooling Points and Datum Planes

The tooling points define and identify three datum planes. The datum planes are mutually perpendicular planes unless otherwise specified. In general, tooling points should be located to establish the first datum plane with three points, the second datum plane with two points and the third datum plane with one point (see 2.2.19.b).

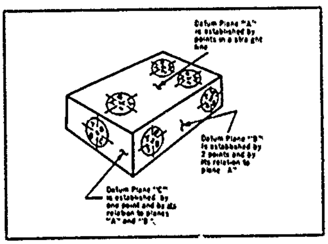


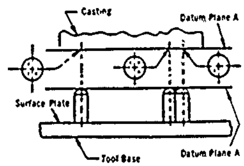
Fig 2.2.19 b

The tooling points selected should be shown and their location must be dimensioned on the drawing. After the drawing has been released for production, datum planes and tooling point location should not be changed without proper coordination between designer and founder

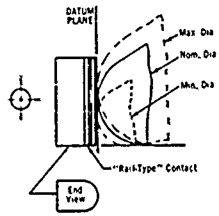
Tooling Point Contacts

Several configurations of tooling point contacts will be employed:

1. Crown type:



2. Rail type:



3. Where the tooling point contact is on a surface not normal to the datum plane, the centre of the tooling point contact should be offset as illustrated in 2.2.19 c However, where the tooling point contact radius is not greater than 12.5 mm and angle c 5°, offset may be disregarded.

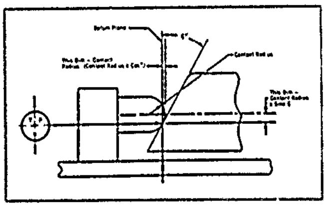


Fig 2.2.19 c

4. The third type of tooling point contact is used on spherical or multiple-curved surface castings. Here, a somewhat different approach in establishing datum planes is required. Tooling point contacts are 90° V contacts and may be either fixed or movable (see 2.2.19 d).

5. The fourth type of tooling point contact — also used on castings having circular features — is the centring device or three jaw chuck (see 2.2.19 e).

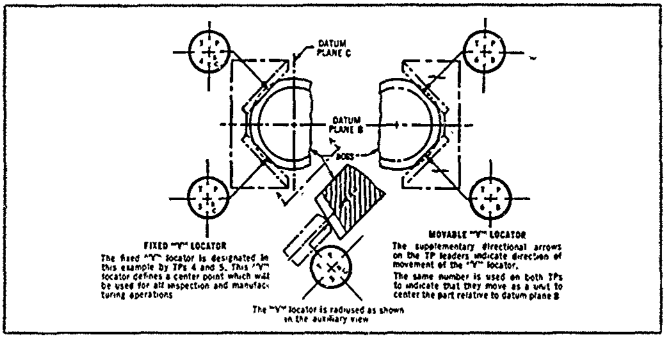


Fig 2.2.19 d

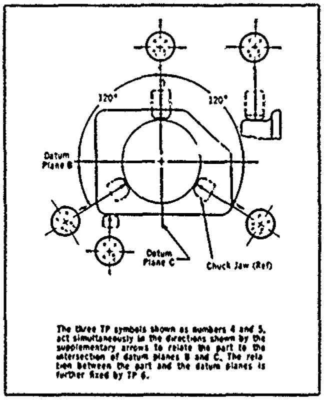


Fig 2.2.19 e

Conclusion
In most situations the tooling point contact would be a crown (spherical radius) button with the amount of crown kept to a minimum to prevent denting of the part from clamping pressure. This system can be seen in Fig.4 (Crown type) and how the datum planes are defined by tooling points.

2.3 TOLERANCES

2.3.1 General
Dimensional variation in a casting may by caused by many factors. Most of these factors are closely controlled by the foundry, but minor "lot to lot" variations do occur which result in the tolerance bands defined later in this section. While it is often true that machining tolerance on a given part may be closer than tolerance for a casting *it is also often true that critical review of a design will allow a slight backing off on tolerances,* undercut, blind holes, etc., for translation into higher production yields and *lower initial piece costs*

Or to say it in another way the cost of any casting increases in proportion to the preciseness of specification, whether on chemistry, nondestructive testing or tighter tolerance bands

2.3.2 Commonly Used Symbols
These symbols replace longhand notes on drawings for indicating forms and positions of part features

Symbol	Meaning	Note Method	Symbol Method	Interpretation
-A-	Location feature	Relative to "A"		Locate on feature -A- to establish location of other feature
⌓	Profile of any surface	Deviation of the defined surface		
⏥	Flatness	Deviation of the defined surface		
⊥	Perpendicularity	Indicated surface to be perpendicular to -A-		
∥	Parallelism	Indicated surface to be parallel to -A-		
⌯	Symmetry	Indicated dimension to be symmetric with -A-		
∠	Angularity	Indicated surface may vary angularly to -A-		
○	Roundness	Indicated dia. to be round within X		
◎	Concentricity	Locate on dia -A- indicated dia to be concentric within X		
⌖	True position	Located at true position		Centre within dia X

2.3.3 Investment Casting Tolerances

Wax or plastic temperature, pressure, die temperature, mould or shell composition back up sand, firing temperature, rate of cool, position of the part on a "tree", and heat treat temperature — all bear directly on tolerances required in the investment casting industry

The amount of tolerance required to cover each process step is dependent, basically, on the shape and size of the casting and will vary from foundry to foundry.

This is because one foundry may specialize in thin walled, highly sophisticated castings, another in mass production requirements, and yet another in high integrity aerospace or aircraft applications.

Tolerance data for Ti-Alloys only:

- Minimum Tol. (for wall thickness): ± 0.3 mm
- Flatness: ± 0.003 mm/mm
- Linear Tolerance: ± 0.005 mm/mm

Wall Thickness Tolerance (Al-Alloy)

A wall thickness in a casting is formed by two parallel ceramic walls in the mould stage which can flex if unsupported and lead to variations in wall thickness of the casting.

Therefore, since the flexing of the 2-mould wall increases with the size of the mould area, the wall thickness tolerance generally increases in relation to the size of the wall area

Therefore, any opening in the casting wall will act as a support between the mould wall, resulting in a decreased tolerance requirement. The least thickness variation occurs at or near wall supports, i.e., a tolerance of ± 0 1 around an opening can be maintained regardless of the tolerance requirement of the remaining wall.

For general wall thickness tolerances refer to Figure 2 3 3.a

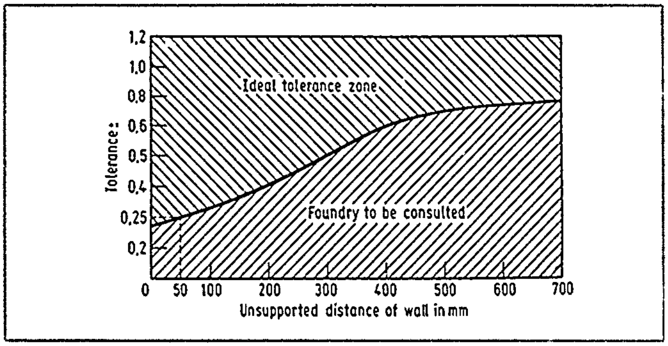
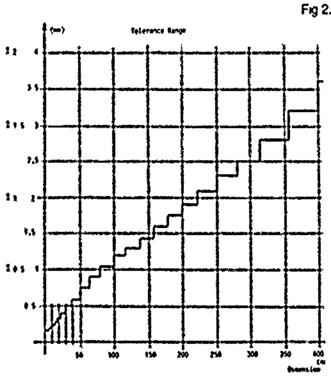
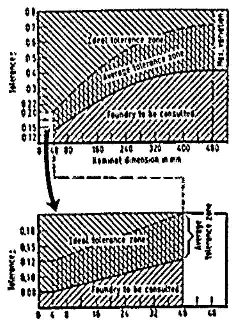


Fig 2.3 3 a



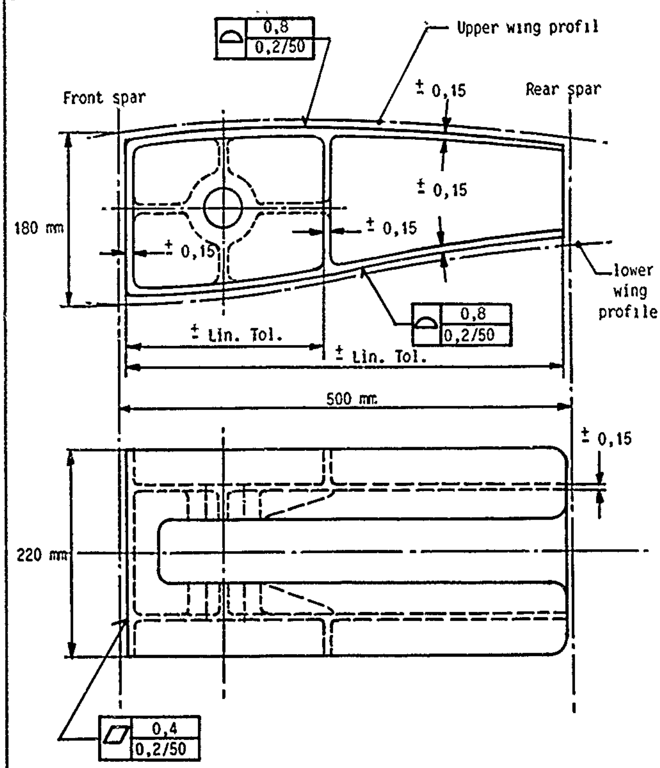
Linear Tolerances for Investment Casting (Al- und Ti-Alloys)
Source: Standard Sheet VDG-P690, Germany

These linear tolerances for Investment Casting have been taken from a foundry's Design Data Handbook.



For further tolerance information see example below A real casting made from Al-alloy is shown

It is a typical part of a wing area of a transport aircraft The tolerances mentioned have been accepted by several foundries and can be used as an example of similar parts. The main feature is the tolerance of the loft line surface with regard to its position and its waviness. It shows acceptable values for later assembly



For meaning of symbols see para 2.3.2
For values of Lin. Tol. see above shown diagram.
Values valid for Al-Castings, only

The following tolerance information for investment casting has been taken from a foundry's Design Data Handbook.

standard linear tolerances

As a general rule . . . normal linear tolerance on investment castings can be as follows: Up to 1" ± 0.010". For each additional inch thereafter, ± 0.003". Following is a chart indicating expected normal and premium tolerances:

NORMAL TOLERANCES are tolerances that can be expected for production repeatability of all casting dimensions.

PREMIUM TOLERANCES are those which require added operations at extra cost, and provide for closer tolerances on selected dimensions. In the case of premium tolerances, you can obtain even tighter tolerances than those shown on the following chart. It will depend on the alloy and configuration . . . and should be determined in close cooperation with your investment casting supplier.

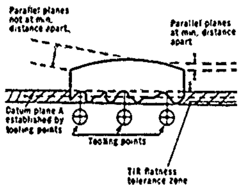
LINEAR TOLERANCE

DIMENSIONS	NORMAL	PREMIUM
up to ½"	± .007"	± .003"
up to 1"	± .010"	± .005"
up to 2"	± .013"	± .008"
up to 3"	± .016"	± .010"
up to 4"	± .019"	± .012"
up to 5"	± .022"	± .014"
up to 6"	± .025"	± .015"
up to 7"	± .028"	± .016"
up to 8"	± .031"	± .017"
up to 9"	± .034"	± .018"
up to 10"	± .037"	± .019"
maximum variation	± .040"	

An exception to the Standard Linear Tolerance exists on thin wall thickness where the tolerance must be a minimum of ± .020".

flatness (dish)

Flatness and straightness are so closely related that confusion may arise unless the foundry and the purchaser reach definite agreement prior to production. Mil Std 8 states that "a flatness tolerance is the total deviation permitted from a plane and consists of the distance between two parallel planes between which the entire surface so toleranced must lie". In measuring, the parallel planes must be the minimum distance apart.

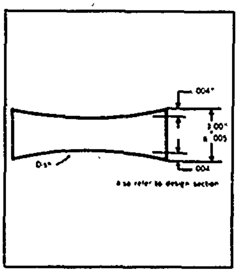


The degree of flatness exhibited in an investment casting is almost always determined by the amount of volumetric shrinkage that the wax and metal undergo during cooling. This shrinkage is usually in the center of the mass and is referred to as "dish" (shrinkage, dip, or "out of flat"). This dish can be controlled (premium) by specialized techniques, but will always be present to some extent. General flatness tolerances cannot be quoted as they vary with configuration and alloy used. The following serves as a rough guide in areas under 6 square inches.

effect of dishing

SECTION THICKNESS	POSSIBLE DISH PER FACE OF CASTING
up to ¼"	not significant
¼" to ½"	0.002"
½" to 1	0.004"
over 1"	0.006"

The amount of dishing allowed is in addition to the basic tolerance. Thus on a block of 1" ± 0.005" thick, the following would apply:

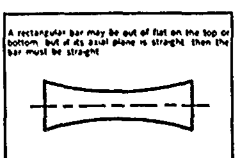


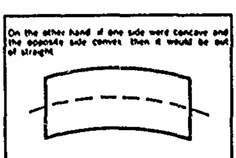
The method of measuring flatness should be specified by the purchaser. It may vary from simple surface plate and feeler gage techniques up to full layout with equalization and dial indicators (premium).

straightness

Mil Std. 8 states that "a tolerance covering the straightness of an axis is the diameter or width within which the axis must lie".

It is obvious from this that to correctly measure axial straightness of either a shaft, bar or plate, the tolerance zone (within which the axis or axial plane lies) must be measured.



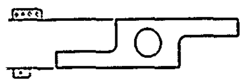


straightness tolerance

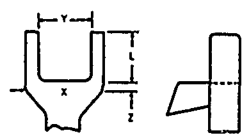
Straightness may be a real problem with certain types of castings. A relatively thin, short part may bend while a long heavy part may not. Experience tells the foundry that a given design may bend, but experience cannot say to what extent. As a rough guide, it may be said that a constant section will have an axial bow of 0.005" per inch. Ribs and gussets will inhibit warpage and will also hinder the mechanical straightening of whatever warpage has occurred.

parallelism

Casting of parts, which have parallel prongs supported only at one end, present a very specialized type of problem and should be discussed fully with the foundry prior to production.



Yoke castings also present a very specialized type of problem and should be discussed fully with the foundry prior to production.



Since point X is the thickest section, it is the ideal point to gate. It is also the area where the greatest volumetric shrinkage will occur. Dimension Y, however, will be restrained by the rigid mass of refractory. The result is that parallelism is difficult to maintain and will be 0.010" per inch of L, but can be improved by control techniques and sizing. This condition will also affect any through holes usually found in yokes. When specified, such holes should carry considerable finish stock if they are to be finished truly concentric or line reamed.

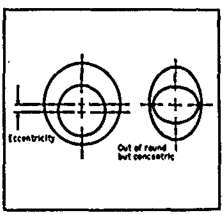
roundness or "out of round"

"Out of round" is defined as the radial difference between a true circle and a given circumference. It is the total indicator reading when the part is rotated 360° or it can be calculated by taking half the difference between the maximum and minimum condition. The latter technique is usually preferred since it takes less time. The actual method of inspection to be used, however, should be specified by the purchaser.

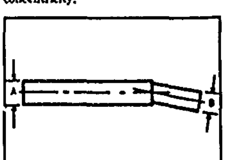
OUT OF ROUNDNESS	
Diameter	TIR or ½ difference between diameters
½"	.010"
1"	.015"
1½"	.020"
2"	.025"
On larger diameters, linear tolerances apply	

concentricity

Two cylindrical surfaces sharing a common point or axis as their center are *concentric*. Any dimensional difference in the location of one center with respect to the other is the extent of eccentricity.



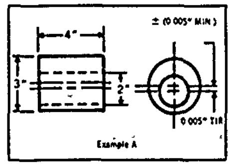
The sketch shows that out of roundness in either diameter does not affect concentricity because concentricity relates the centers or axes of the diameters. Out of roundness is their variance from a true circle. However, in a shaft or tube, straightness has a very real influence on concentricity.



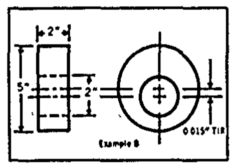
Diameters A and B may be true circles, but it is obvious that the out of straightness condition has affected concentricity.

concentricity tolerance

When the length of a bar or tube does not exceed its component diameters by a factor of more than 2 times, the component diameters will be concentric within 0.005" per inch of separation.



EXAMPLE A—3" OD x 2" ID x 4" long. 3" OD and 2" ID will be concentric within 0.005" TIR (3" OD—2" ID = 1" separation)



EXAMPLE B—5" OD x 2" ID x 2" long. 5" OD and 2" ID will be concentric within 0.015" TIR (5" OD—2" ID = 3" separation)

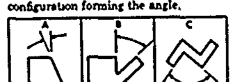
When the length exceeds the factor of two times, then the amount of out of straightness as described above should be added to the inherent eccentricity.

EXAMPLE

2" OD x 1" ID x 4" long, Separation = 1", eccentricity....... = .005" TIR
4" x .005" per inch out of straightness .... = .020" TIR
Total of deviation ..... = .025" TIR

angularity

Angular tolerance is dependent on the configuration forming the angle.

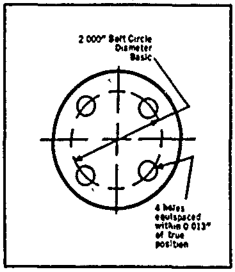


Sketch "A" cannot be sized, but in certain cases after sufficient data has been reviewed, the die can be reworked to bring the part closer to nominal dimension. Sketches "B" and "C" can be reworked to ± ½° and ± 1° respectively. Obviously, however this is dependent on the alloy and its condition.

positioning

Tolerance on the position of holes and bosses is dependent upon configuration of the parent casting. Position of holes or bosses on the periphery of examples shown under concentricity will obviously be affected by the degree of eccentricity shown. The position of holes or bosses on a flat plate will be controlled by the linear tolerances already given

A new factor enters here, however. The linear tolerances are based on volumetric shrinkage; holes and bosses disturb this shrinkage pattern. It is possible to reduce these tolerance bands by about 10% when applying them to a configuration that disturbs the shrinkage pattern. It is difficult to predict the exact amount and the foundry may wish to rework the tooling to take full advantage of these better tolerances



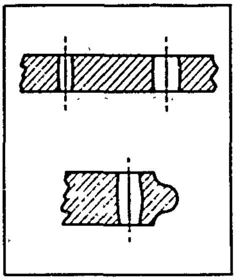
Holes and bosses on a parent diameter are affected by the degree of out of roundness exhibited by the parent diameter although the notes above concerning breakup of the shrinkage pattern are still valid.

As a rule of thumb, a bolt circle diameter carrying holes and bosses will have the same amount of out of roundness as any other diameter. Thus a 2" BCD will be round within 0 025" TIR. This is best expressed and designed for in terms of true position.

The parallelism and straightness of such holes is a function of the straightness of the parent casting and the tables already given will apply.

hole tolerance

The roundness of a cast hole is affected by the mass of surrounding metal. If an uneven mass is adjacent, the hole will be pulled out of round If the surrounding metal is symmetrical, holes up to ½" diam. can be held to ± 0 003" when checked with a plug gage. Larger holes may be affected by interior shrinkage or pulling, and the foundry should be consulted



The longer the hole or the more mass of the section around it, the more pronounced the effect. Some shrinkage concavity will be present to some extent in all castings. The openings at top and bottom of the hole will be approximately the same dimension while the center will be a larger diameter Thru holes which require clearance (this can be checked using a plug-type gage) can be held to fairly close tolerances if the larger diameter in the center is ignored. If, however, the sidewalls of the hole are used as bearing surfaces, a simple reaming operation will size the cast opening.

The lower figure shows the effect of shrinkage on a hole diameter when a heavier section is in the proximity of the hole itself. Note that the diameter is distorted due to additional mass shrinkage of the heavier section. The figure shows a graphic illustration of the distortion which will be present to a greater or lesser degree in every casting when a heavier mass affects shrinkage.

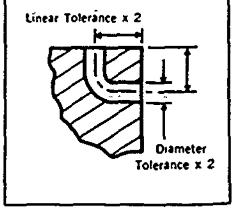
tapered holes

A. TAPERED WITHIN THEMSELVES. The notes above are applicable. We recommend that such holes be dimensioned at the lesser diameter and the angle given The angle can be held to ± ½°.

B TAPERED WITH RESPECT TO ANOTHER FEATURE. Here again the notes on holes apply. The angle from any given position will vary ± 1°.

curved holes

Since curved holes are formed by either soluble wax or preformed ceramic cores. the normal tolerance tends to be doubled. A factor of 2 times must be applied to the tolerance on all dimensions controlling such a feature. Since such holes cannot be sized, a diameter tolerance of ± 0.005" per inch also applies.



angular holes

Since these holes are usually formed by metal cores within the die, the tolerance restrictions for curved holes do not apply and normal tolerance bands are usually acceptable. If the angle formed by the two centerlines is greater than 120°, the hole can be sized, but if it is less, a diameter tolerance of ± 0.005" per inch must be used.

internal radii, fillets

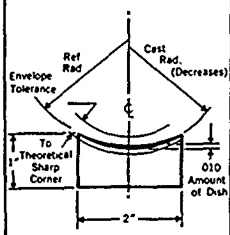
These should always be given as wide tolerance as possible. They are difficult to control and can only be checked approximately by radius gages, or at a premium by an optical comparator.

contours, radii and cams

A designer who plans to dimension a radius on a casting should understand that during the cooling process volumetric shrinkage occurs which has a disturbing effect on external radii and contours. In a flat casting, concavity is easily illustrated and understood, (refer to section on Flatness). The same concavity effects are encountered with castings that have contours, but with more dramatic results.

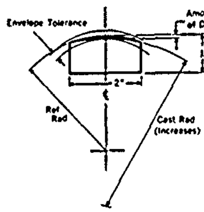
In concave radius applications, with the greatest shrinkage occurring in the center and the outer extremities fixed by the dimensions of the casting, the cast radius tends to decrease. In dimensioning a drawing for a concave radius, (see Figure 1), the designer should use a reference radius, using dimensions on the casting radius to control the basic physical size. The fit to mating configuration should be controlled by using a tolerance band on the radius itself.

Figure 1



In convex radius casting applications, with the greatest shrinkage again occurring in the center the cast radius tends to increase (see Figure 2). The drawing should be dimensioned with these considerations in mind.

Figure 2



Note Convex Radius ℄ of Envelope Tolerance would normally coincide with high point of 1" Dim (1.010)

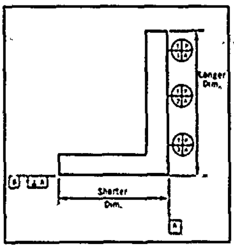
perpendicularity

When perpendicularity is specified, the reference plane should be the longer of the two planes, the datum plane to be established by 3 tooling points

In drawing of the casting at right, surface B will be perpendicular to surface A within 0.008" per 1" of length of surface B.

***Example*, Length of B = 3"**
0.008" x 3" = 0.024"

Therefore: surface B should be perpendicular to surface A within 0.024" TIR. Some improvement on tolerance can be effected by straightening.



The tolerance features above defined can also be used for the following casting processes. They differ only in their values.

2.3.4 Premium Casting

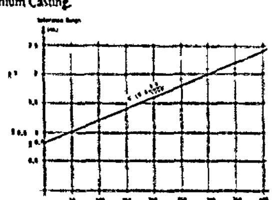
For all casting methods, tolerances depend on the material used for tooling and for the mould

Metallic tooling has a higher accuracy than tooling made of wood. Because many steps are required from the first step for the tooling up to the finished casting, the overall tolerances of a dimension are the sum of many single variations, like:

- Variation of the tooling
- Variation of the mould parts
- Variations occurring during mould assembly
- Expansion behaviour of the mould during heating
- Shrinking behaviour of the casting alloy.

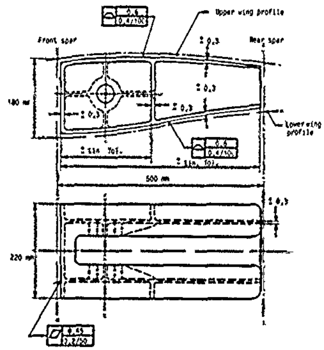
The list may not be complete, but it gives an overview of the tolerances which will arise during the casting process.

The following diagram shows linear tolerances feasible on a Premium Casting.



For further tolerance information see the example below A real casting made from Al-alloy is shown. It is a typical part of a wing area of a transport aircraft. The tolerances mentioned have been accepted by several foundries and can be used as an example of similar parts.

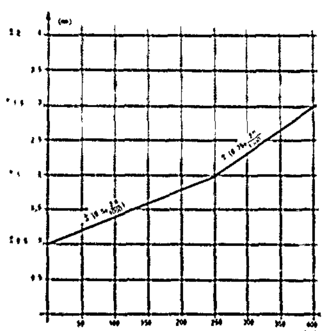
The main feature is the tolerance of the loft-line surface with regard to its position and its waviness.



For meaning of symbols see para 2.2.2
For values of lin. tol. see above diagram

2.3.5 Conventional Sand Casting

As described in Section 2.3.4, the overall tolerances for conventional Sand Casting have the same origins However, in many cases there is no need for very low tolerances, and so the conventional Sand Casting process with its cheaper tooling and mould material also has its applications.



Linear tolerances of Conventional Sand Casting

2.3.6 Rammed Graphite Casting (Ti-Alloys)

- Minimum Tol. (for wall thickness): ± 0.8 mm
- Flatness: ± 0.3 mm/mm
- Linear Tolerance: ± 0.3 mm/mm

CONCLUSION

The toler^nces shown in this chapter for Investment, Premium and Conventional Sand Casting are only meant as guidelines for the first design step, because the capabilities of the foundries differ slightly. So, after considering this chapter for the pre-design, the feasible tolerances may be determined after discussion with the foundry specialists. Another point is the fact that the geometry of the casting also has a great influence on the tolerances.

But it can be said that castings with variations acceptable for nearly every structural requirement can be produced.

2.4 SURFACE ROUGHNESS

The casting surface directly depends on the mould material used for the various casting methods.

a) *Investment Casting*
A wax model of the casting, produced in a metal tool, will be dipped in fluid ceramic material, which forms the first skin of the mould. Because of the fine-grained ceramic powder, this first coat is very smooth and very nearly reflects the surface of the wax model. For values see Table 2.4 1.

b) *Premium Sand Casting/Conventional Sand Casting/ Ti-Rammed Graphite Casting.*
Because the casting surface is a print of the casting mould, and in this case the mould is made up of sand, the surface roughness is higher than for investment casting. Careful selection of grain size and additional coating of the mould areas give the casting surface sufficient smoothness for aircraft structure application. For values see Table 2 4 1

Table 2.4 1
Surface roughness depending on the casting process

Al-Investment Casting	1,6 - 3,2 µm or 65 - 125 RMS
Al-Premium Sand Casting	6,4 µm or 250 RMS
Al-Conventional Sand Casting	12,5 µm or 500 RMS
Ti-Investment-Casting	3,2 µm or 125 RMS
Ti-Rammed Graphite Casting	6,4 µm or 250 RMS

2.5 MATERIALS

This section gives brief information on casting materials used in the aircraft industry and their mechanical properties.

The figures given will help the designer to define the necessary material and to determine roughly the wall thickness of his part in the early design stage. This is important with regard to casting method, but it has been noticed that the precise values of the mechanical properties differ from foundry to foundry and from country to country (see Chapter 3).

Another characteristic is the fact that every country has its own material specification. Therefore Figure 2.5.2 shows the "Material Specification Comparison Matrix", which explains the ꝫifferent specifications of each country for the same material composition.

2.6 SURFACE PROTECTION

Generally it can be said that all protection systems usually for Al-alloys are also applicable on casting materials (A356, A357). However, experience has shown that some treatment parameters have to be changed for the so-called chromic acid anodising process. The reason is the high proportion of Silicon (approx. 7%).

2.7 ADDITIONAL DATA ON WORKSHOP DRAWING

To assist the foundry in making an accurate cost estimate of a casting, certain information should be on the drawing in the form of notes. This is also necessary during production, while dies and tooling are being made, during casting and afterwards, for casting inspection.

The following notes should be on every casting drawing

1. Designated/undesignated areas
2. General tolerance information
3. Fillet and corner radii, if not specified on the drawing
4. Type of casting identification marking
5. Surface roughness
6. Part class
7. Material specification
8. Heat treating specification
9. Mechanical properties
10. Inspection specification
11. Final finish of part
12. Areas where no repair by welding is permitted

2.8 REPAIR

2 8.1 Repair by the Foundry

If there are defects in the casting structure it is generally permissible to repair them by welding

a) Because for simple, and especially for complex parts, welding takes place before heat treatment, there is no reduction of the mechanical properties

b) A repair specification should be prepared that shows defect sizes and geometries which allow repair by welding. This repair process has to be done by qualified workers (wit· certification).

Weld repairs, using filler material of the same composition as the casting, exhibit parent metal mechanical properties. A typical welding sequence is as follows:

SUGGESTED WELD REPAIR LIMITS

Grade	Major Dimension of Weld	Frequency in any area [illegible] in Square	Minimum Spacing
A	12,7 mm max.	Unlimited	9 5 mm
B	19 mm max.	2	12,7 mm
C	25 mm max	Unlimited	Unlimited

Table 2 5 1
Chemical Composition of Aluminium Casting Alloys A356, A357, A201

ALLOY \ ELEMENTS		Cu [%]	Ag [%]	Be [%]	Mn [%]	Mg [%]	Ti [%]	Fe [%]	Si [%]	Zn [%]	Others each [%]	Σ [%]	Al [%]
A356 (3 2374)	from	—	—	—	—	0,20	—	—	6,50	—	—	—	
	to	0,20	—	—	0,10	0,40	0,20	0,20	7,50	0,10	0,05	0,15	Bal
A357	from	—	—	—	—	0,40	0,10	—	6,50	—	—	—	
	to	0,20	—	0,07	0,10	0,70	0,20	0,20	7,50	0,10	0,05	0,15	Bal
A201	from	4,00	0,40	—	0,20	0,15	0,15	—	—	—	—	—	
	to	5,00	1,00	—	0,40	0,35	0,35	0,10	0,05	—	0,03	0,10	Bal

	Belgium	Canada	France	Germany	United Kingdom	Greece	Italy	Netherland	Norway	Spain	Turkey	USA
Al Alloy			A-S7G03	3 2374 (A356)	BS L 99		8024	S 373		L 2652		A356
				K01				K01				(K01) A201
			A S7G06	3 2384 (A357)				S 375				A357
Ti-Alloy			T-A6V	3 7264 (Ti6AL4V)								Ti6AL4V

Attention: Type of alloy (composition) is comparable, but the mechanical properties are different!

Fig 2 5 2 Designation used in material specification of the various countries

		Material Specification		Mechanical Properties (specimens cut from castings)						
				Designated Areas			Undesignated Areas			wall thickness
		Spec. No.	Short Name	UTS N/mm²	YS N/mm²	Elong. %	UTS N/mm²	YS N/mm²	Elong. %	(mm)
Al-Alloys	Investment Casting	3 2374 T6 (A356)	Al Si7 Mg 0 3	265	195	4	265	195	4	≤ 3
		3 2384 T6 (A357)	Al Si7 Mg 0 6	310	250	5	290	230	3	≤ 3
		A201 (AMS 4229)	Al Cu4,5 Ag 0,7 Mn0,3 Mg0,25 Ti 0,25	414*	345*	3*	386*	331*	1,5*	
	Premium/ Sand Casting	3 2374 T6 (A356)	Al Si7 Mg 0 3	270	200	4	230	180	2	≤ 14
		3 2384 T6 (A357)	Al Si7 Mg 0 6	330	270	5	305	240	3	≤ 20
		A201 (AMS 4229)	Al Cu4,5 Ag 0,7 Mn 0,3 Mg 0,25 Ti 0,25	414*	345*	3*	386*	331*	1,5*	
Ti-Alloys	Invest. Casting / Rammed Graphite Casting	3 7264,1	Ti 6 Al 4V	880	815	5	880	815	5	≤ 25

* : According to AMS4229

Fig 2 5 3 Mechanical properties of normally used casting alloys

1. Complete removal of the defect by grinding or machining.
2. Re-examination by radiographic and fluorescent penetrant inspection to assure the completeness of removal.
3. Degrease and chemical cleaning
4. Weld in inert atmosphere (Argon) glove box.
5. Vacuum heat treatment.
6. Fluorescent penetrant and radiographic inspection of repaired area.

2.8.2 "In Service" Repair

Parts integrated into the structure by riveting should be repaired by normal methods used generally on solid parts and in accordance with the ARM (Aircraft Repair Manual). This means mostly that re-inforcement is riveted to the casting at the defective location.

3. MECHANICAL DATA

3.1 GENERAL INFORMATION

3.1.1 International Notation and Units

Since nearly every country uses its own notation and units it is necessary to determine one system for all variables in this chapter. This system is the ISO (*I*nternational *S*tandardisation *O*rganization).

However since many sources use USA Standards, the system with its units is also tabled below

NAME	ISO NOTATION	ISO UNIT	U.S.A. MIL-HDBK 5D NOTATION	U.S.A. MIL-HDBK 5D UNIT
Stress	σ	N/mm²	F	KSI
Tensile Strength ultimate	Rm	N/mm²	F_{tu}	KSI
Tensile Yield Stress 0,2 Elong. Limit	Rp0,2	N/mm²	F_{ty}	KSI
Compression Yield Str. 0.2 Elong. Limit	$\sigma_{d0,2}$	N/mm²	F_{cy}	KSI
Bearing Strength e/d = 1.5 and e/d = 2.0	σ_{LB}	N/mm²	F_{bru}	KSI
Bearing Yield Stress e/d = 1.5 and e/d = 2.0	$\sigma_{L0,2}$	N/mm²	F_{bry}	KSI
Shear Strength	τ_{aB}	N/mm²	F_{su}	KSI
Young's Modulus (Tension)	E	N/mm²	E	KSI
Young's Modulus (Compr.)	E_c	N/mm²	E_c	KSI
Shear Modulus	G	N/mm²	G	KSI
Poisson's Ratio	ν		ν	
Elongation at Failure	A	%	e	%
Plane Strain Fracture Toughness	K_{IC}	N/mm$^{3/2}$	K_{IC}	KSI/$\sqrt{in}$
Plane Stress Fracture Toughness	K_c	N/mm$^{3/2}$	K_q	KSI/$\sqrt{in}$
Apparent Plane Stress Fracture Toughness	K_{CO}	N/mm$^{3/2}$	K_{CO}	KSI/$\sqrt{in}$
Fracture Toughness Stress Corrosion Cracking Intensity	K_{ISCC}	N/mm$^{3/2}$	K_{ISCC}	KSI/$\sqrt{in}$
Crack Propagation Rate	$\frac{dl}{dn}$	mm/cycle	$\frac{da}{dn}$	in/cycle
Density		g/mm³		lb/in³

(1 N/mm² ≙ 1 MPa)
(1 N/mm$^{3/2}$ = 31,62 MPa$\sqrt{m}$)

3.1.2 Physical Data of Al- and Ti-Alloys

		Material A357-T6	Material A201 T7	Material Ti-6Al-4V
Density	kg/dm³	2 68	2 8	4 51
	lb/in³	0 097	0 101	0,163
Coefficient of Thermal Expansion	x 10^{-6} cm/cm/°C	20,5-21 5 [1)]	22 [1)]	9 0 - 11
	x 10^{-6} in/in/°F	12 [1)]	12 2 [1)]	5 0 - 6 09
Specific Heat	KJ/Kg/°C	0 96 [7)]	0 92 [8)]	0 57 [9)]
	BTU/lb/°F	0,23 [2)]	0 22 [2)]	0,135 [4)]
Thermal Conductivity	W/m x k	152 [5)]	135 160 [6)]	15
	BTU x ft/hr/ft²/°F	88 [3)]	70 [3)]	8

1) at 20° - 100°C (68° - 212°F)
2) at 100°C (212°F)
3) at 25°C (77°F)
4) at 21°C (70°F)
5) 88 x 0,144228 x 12 = 152
6) at 20° C (68°F)
7) $0\ 23 \times 2{,}326 \times \frac{9}{5}$
8) $0\ 22 \times 2{,}326 \times \frac{9}{5}$
9) $0\ 135 \times 2\ 326 \times \frac{9}{5}$

3.2 MATERIAL DATA

This section contains variables of the aluminium alloys A357, A201 and the titanium alloy Ti-6Al-4V. These alloys are suitable for aircraft structure application.

For comparison of the material specifications and chemical composition of the mentioned alloys see Section 2.5

All variables shown for Rm, Rp0,2 are specification values, not A- and B-design allowables. Actual guaranteed values should be established for each casting by agreement between the user and the foundry. It is advisable to define all descriptive data on a special data sheet, for example position of test bars, type of test bars, Rm, Rp0,2, A and so on, and to obtain agreement about all points with the foundry. This agreement has to be part of the contract between the foundry and the user

With the casting methods it is better to control the mechanical properties of a part rather than the process method. This fact should be used by the designers, for *cost reduction* if a lowering of mechanical properties is allowable

3.2.1 Mechanical Properties

Table 3.2.1 shows the mechanical properties which the foundries can achieve. These data have been extracted from many documents, literature, foundry brochures etc. Some values are not available, because no information was in hand or because tests have not yet been done.

3.2.2 Strength Behaviour at High Temperatures

All metallic materials show a certain loss of tensile strength under the influence of elevated temperatures. This amount differs from material to material, but there are also some other aspects that influence the decrease in strength.

a) Time of exposure to elevated temperatures
b) Alloy composition
c) Heat treatment conditions
d) Wall thickness of the casting

The following diagrams can be used only as examples to show the tendencies.

Table 3 2.1

Material	Alloy	Casting Process	Rm (N/mm²) Ftu (KSI) Design. Area	Rm Remain. Area	Rp0,2 (N/mm²) Fty (KSI) Design Area	Rp0,2 Remain. Area	A (%) e (%) D A	A (%) e (%) R A	σd0,2 (N/mm²) Fcy(KSI)	τaB (N/mm²) Fsu(KSI)	σLB (N/mm²) Fbru (KSI) L/D = 1.5	σLB L/D = 2.0	σL0,2 (N/mm²) Fbry (KSI) L/D = 1.5	σL0,2 L/D = 2.0	E (N/mm²) (KSI)	E_c (N/mm²) (KSI)	G (N/mm²) (KSI)	Hardness HB HV HR
Aluminum	A357-T6	Investm.	310 45	285 41	250 36	230 33	5	3	290 42	200 29	435 63	560 81	385 56	435 63	71,700 10,400	72,400 10,500	26,900 3,900	HRE ≥ 80
		Premium	345 50	310 45	275 40	240 35	5	3	275 40	240 35	595 86	740 107	435 63	520 75	71 705 10,400	72,395 10,500	26,890 3,900	HRE ≥ 90
		Conv. Sand	330 48	305 44	270 39	240 35	5	3	215 31	200 29	435 63	560 81	385 56	435 63	71 700 10,400	72,400 10,500	26,900 3,900	HRE ≥ 90
	A201-T7	Investm.	2) 415 60		2) 345 50		3	3	420 61	282 41	1)	1)	1)	1)	1)	1)	1)	HRB 70
		Premium	460 67	400 58	390 57	360 52	4	2	352 51	248 36	655 95	841 122	510 74	600 87	72,015 10,300	73,775 10,700	27,580 4,000	HRB ≥ 70
Titanium	Ti-6Al-4V	Investm.	2) 930 135		2) 830 120		2) 5		795 115	500 72	1160 168	1495 216	990 143	1220 176	110,000 16,000	120,000 17,400	45,000 6,500	HR ≥ 39
		Ram. Graph	2) 930 135		2) 830 120		2) 5		795 115	500 72	1160 168	1495 216	990 143	1220 176	110,000 16,000	120,000 17,400	45,000 6,500	HR ≥ 39

1) Values not yet available.
2) Values are valid for designated and remaining areas

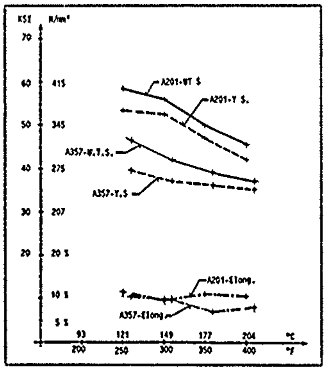


Fig 3 2 2 Diagram for Al-alloys

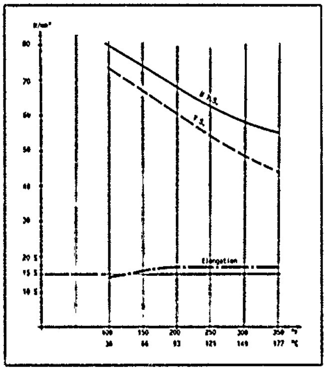


Fig 3 2 3 Diagram for Ti-6Al-4V

In addition to the above diagrams some foundrys' test results are given in the following tables:

Table 3 2 4
Alloy A357-T6 (Source; Alcoa, USA). Typical mechanical properties at various temperatures

Temperature	Time At Temp. (hr)	Tensile Properties: At Temperature Indicated: Tensile Strength (psi)	Yield Strength (psi)	Elong in 4D (percent)	Modulus of Elasticity(1) (million psi)	At Room Temperature After Heating: Tensile Strength (psi)	Yield Strength (psi)	Elong. in 4D (percent)
452°F								
−423°F								
−320°F		62,000	48,000	6				
−112°F		55,000	45,000	6				
− 18°F		54,000	44,000	6				
75°F		52,000	42,000	8	10.4	52,000	42,000	8
212°F	½	46,000	39,000	10		46,000	39,000	6
	10	46,000	39,000	10		50,000	42,000	6
	100	46,000	39,000	10		50 000	45,000	6
	1,000	46,000	40,000	8		47,000	42,000	6
	10,000	48,000	45,000	6				
300°F	½	39,000	35,000	10				
	10	41,000	37,000	9				
	100	42,000	40,000	7				
	1,000	38,000	36,000	7				
	10,000	23 000	21,000	20				
350°F	½	37,000	34,000	7				
	10	40,000	38,000	6				
	100	35,000	33,000	7				
	1,000	22,000	20,000	19				
	10,000	13,000	11,000	35				
400°F	½	36,000	35,000	6		52,000	45,000	6
	10	30,000	28,000	7		44,000	38,000	7
	100	23,000	21,000	23		35,000	27,000	9
	1,000	12,000	10,000	40				
	10,000	10,000	7,500	50				
450°F	½	31,000	30,000	9				
	10	19,000	18,000	13				
	100	14,000	13,000	45				
	1,000							
	10,000							
500°F	½	23,000	22,000	16				
	10	12,000	11,000	23				
	100	8,000	7,000	55				
	1,000							
	10,000							
600°F	½	10,000	9,500	35				
	10							
	100							
	1,000							
	10,000							

(1) The modulus of elasticity in compression is about 2 percent greater than in tension.

Table 3.2.5
Alloy A357-T6 (Source: Alcoa, USA)

Temperature	Time Under Stress (hr)	Stress Rupture and Creep Properties — Stress for Rupture and Creep in Time Indicated (psi): Rupture	1.0% Creep	0.5% Creep	0.2% Creep	0.1% creep	Fatigue Properties[1]: No of Cycles	Stress (psi)
75°F	0.1						10^4	41,000
	1						10^5	31,000
	10						10^6	22,500
	100						10^7	16,000
	1,000						10^8	14,000
							5×10^8	13,000
212°F	0.1						10^4	
	1						10^5	
	10						10^6	
	100						10^7	
	1,000						10^8	
							5×10^8	
300°F	0.1						10^4	
	1						10^5	
	10						10^6	
	100						10^7	
	1,000						10^8	
							5×10^8	
350°F	0.1	36,000	35,000	35,000	32,000	31,000	10^4	
	1	35,000	34,000	34,000	31,000	30,000	10^5	
	10	33,000	32,000	31,000	29,000	26,000	10^6	
	100	25,000	25,000	24,000	20,000		10^7	
	1,000	16,000	16,000	16,000			10^8	
							5×10^8	
400°F	0.1						10^4	
	1						10^5	
	10						10^6	
	100						10^7	
	1,000						10^8	
							5×10^8	
500°F	0.1						10^4	
	1						10^5	
	10						10^6	
	100						10^7	
	1,000						10^8	
							5×10^8	
600°F	0.1						10^4	
	1						10^5	
	10						10^6	
	100						10^7	
	1,000						10^8	
							5×10^8	

(1) Based on the results of rotating beam tests at room temperature and cantilever beam (rotating load) tests at elevated temperatures.

Table 3 2 6
Alloy A201-T7 (Source: Alcoa, USA) Typical mechanical properties at various temperatures

Temperature	Time At Temp. (hr)	Tensile Properties: At Temperature Indicated				At Room Temperature After Heating		
		Tensile Strength (psi)	Yield Strength (psi)	Elong. in 4D (percent)	Modulus of Elasticity[1] (million psi)	Tensile Strength (psi)	Yield Strength (psi)	Elong in 4D (percent)
−452°F		93,000	81,000	7				
−423°F		93,000	79,000	8				
−320°F		89,000	75,000	8				
−112°F		77,000	70,000	6				
− 18°F		74,000	67,000	6				
75°F		72,000	65,000	6	10.3	72,000	65,000	6 5
212°F	½							
	10							
	100							
	1,000							
	10,000							
300°F	½							
	10							
	100	64,000	57,000	9		72,000	65,000	6
	1,000	60,000	54,000	10		70,000	61,000	6
	10,000	58,000	52,000	6		68,000	58,000	4
350°F	½							
	10							
	100	54,000	49,000	10		68,000	61,000	4
	1,000	51,000	46,000	8		63,000	57,000	4
	10,000	43,000	37,000	9		58,000	45,000	6
400°F	½							
	10							
	100	48,000	42,000	10		66,000	58,000	5
	1,000	39,000	33,000	16		55,000	44,000	4
	10,000	24,000	18,000	25		41,000	22,000	12
450°F	½							
	10							
	100							
	1,000	22,000	15,000	25		41,000	22,000	12
	10,000	19,000	13,000	25		37,000	18,000	13
500°F	½							
	10							
	100							
	1,000	16,000	13,000	25		38,000	20,000	12
	10,000	14,000	10,000	32		34,000	17,000	11
600°F	½							
	10							
	100							
	1,000	9,000	8,000	48		34,000	14,000	12
	10,000	8,000	6,000	51		29,000	11,000	13

(1) The modulus in elasticity in compression is about 2 percent greater than in tension.

Table 3 2.7
Alloy A201-T7 (Source. Alcoa, USA)

Temperature	Time Under Stress (hr)	Stress Rupture and Creep Properties: Stress for Rupture and Creep in Time Indicated (psi)					Fatigue Properties(1)	
		Rupture	1.0% Creep	0 5% Creep	0 2% Creep	0 1% Creep	No of Cycles	Stress (psi)
75°F	0 1						10^4	
	1						10^5	
	10						10^6	
	100						10^7	
	1,000						10^8	
							5×10^8	
212°F	0.1							
	1							
	10							
	100							
	1,000							
300°F	0 1						10^4	
	1						10^5	
	10	57,000	56,000	56,000	53,000	52,000	10^6	
	100	51,000	51,000	50,000	49,000	47,000	10^7	
	1,000	45,000	45,000	45,000	44,000	41,000	10^8	
							5×10^5	
350°F	0 1						10^4	
	1				50,000	48,000	10^5	
	10	48,000	47,000	46,000	45,000	43,000	10^6	
	100	42,000	42,000	41,000	39,000	38,000	10^7	
	1,000	35,000	35,000	35,000	34,000		10^8	
							5×10^8	
400°F	0 1						10^4	
	1	42,000	42,000	41,000	40,000	39,000	10^5	
	10	39,000	38,000	38,000	36,000	32,000	10^6	
	100	33,000	33,000	32,000	30,000	25,000	10^7	
	1,000	25,000	25,000	25,000			10^8	
							5×10^8	
450°F	0 1						10^4	
	1						10^5	
	10				27,000	24,000	10^6	
	100	24,000	24,000	23,000			10^7	
	1,000						10^8	
							5×10^8	
500°F	0 1						10^4	
	1					21,000	10^5	
	10	21,000	20,000	20,000	18,000		10^6	
	100						10^7	
	1,000						10^8	
							5×10^8	
600°F	0.1						10^4	
	1						10^5	
	10						10^6	
	100						10^7	
	1,000						10^8	
							5×10^8	

(1) Based on the results of rotating beam tests at room temperature and cantilever beam (rotating load) tests at elevated temperatures.

Table 3 2 8
Alloy A201-T7 (Source: Montupet, France) Tensile strength at various temperatures

Test temperature	Temperature maintenance time (hours)	Tensile Properties: at the temperature shown: UTS MPs	TS 0 2 MPs	Z_1 %	Elasticity module MPs	at room temperature after preheating: UTS MPs	TS 0 2 MPs	Z_1 %
−244°C		641	558	7				
−217°C		641	545	8				
−160°C		614	517	8				
− 44°C		531	433	6				
− 8°C		510	462	6				
24°C		496	448	6	71,000	496	448	6 5
149°C	100	441	393	9		496	448	6
	1,000	414	372	10		483	421	6
	10,000	400	359	6		469	400	6
177°C	100	372	338	10		449	421	6
	1,000	352	317	8		434	393	6
	10,000	296	255	9		400	310	6
204°C	100	331	290	10		455	400	5
	1,000	269	228	16		379	303	4
	10,000	165	124	25		233	152	12
232°C	100							
	1,000	152	103	25		253	152	12
	10,000	131	90	25		255	124	13
260°C	100							
	1,000	110	90	25		262	139	12
	10,000	97	69	32		234	117	11
316°C	100							
	1,000	62	55	48		234	97	12
	10,000	55	41	51		200	76	13

1 MPa = 1 N/mm²

Table 3.29
Alloy A201-T7 (Source, Montupet, France) Ultimate strength properties and creep deformation

test temperature	Exposure (in hours)	Ultimate strength properties and creep deformation				
		Ultimate strength stress and creep deformation with regard to the exposure time				
		Ultimate strength stress	creeping 1.0 %	creeping 0.5 %	creeping 0.2 %	creeping 0.1 %
149°C	0.1					
	1					
	10	393	386	386	365	359
	100	352	352	345	338	324
	1,000	310	310	310	303	283
177°C	0.1					
	1				345	331
	10	331	324	317	310	296
	100	290	290	283	264	262
	1,000	241	241	241	234	
204°C	0.1					
	1	290	290	283	276	269
	10	269	262	262	248	221
	100	228	228	221	207	172
	1,000	172	172	172		
232°C	0.1					
	1					
	10				186	165
	100	165	165	159		
	1,000					
260°C	0.1					
	1					145
	10	145	139	139	124	
	100					
	1,000					

Investment Cast Ti-6Al-4V
Source: Howmet Turbine Components Corp., Ti-Cast. Div.

Room and elevated temperature tensile properties are summarized in Figure 3.2.10. Cast strength is in good agreement with wrought behaviour. Ductility, while lower than the wrought form, has been enhanced by HIP processing and is not compromised by the transverse property considerations that are anticipated in forgings.

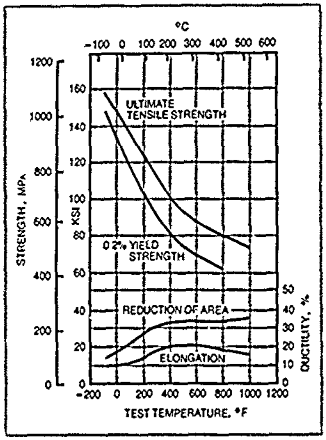


Fig 3.2.10

3.2.3 Fatigue Data

With the increasing use of castings in aircraft structures there is a strong need for fatigue data beyond the normal values of the mechanical properties. The data shown originate from the various programs of different countries or they are taken from foundry specifications. All the references are listed at the end of the section.

Generalities about fatigue:
Aluminium does not exhibit the sharply defined fatigue limit typically shown by low-carbon steel in S-N tests. For smooth or notched coupon tests, where lifetime is governed primarily by crack initiation, the fatigue resistance is expressed as a fatigue strength (stress) for a given number of cycles. In tests where fatigue crack growth is of interest, the performance of aluminium is measured by recording the crack growth rate (da/dN) as a function of stress intensity range (ΔK). *See Chapter 6.*

It is generally known that alloying or heat treatment that improves tensile strength also tends to increase the fatigue strength of aluminium. However, the design of aluminium alloys to resist failure by fatigue mechanisms has not proceeded to the same extent as for fracture toughness.

The effect of large constituent particles on the fatigue behaviour of high-strength aluminium alloys is highly dependent upon the type of fatigue test or stress regime chosen for the evaluation. Reduced iron and silicon contents (for A201) do not always result in improved fatigue resistance commensurate with the previously described improvement in fracture toughness. Increased purity level does not, for instance, produce any appreciable improvement in notched or smooth S-N fatigue strength.

FATIGUE DATA FOR THE ALLOY A357-T6

Fatigue Properties Report (acc. to 1) (MBB-Report)
The figures 3.2.12 to 3.2.45 show the results of fatigue tests specimens of the alloy A357-T6. There are diagrams of the alloy A357-T6 with tests made from investment- and conventional sand castings. In Figure 3.2.11 are pictured the test bars used for the different "Kt"-factors. The fatigue data are given in Haigh and Woehler diagrams. After each Haigh-figure follows the Woehler-lines belonging to it. The following values have been considered:

Al alloy A357-T6 Investment Casting
- Kt = 1.0 Figure 3.2.12 – 3.2.15
- Kt = 2.5: Figure 3.2.16 – 3.2.19
- Kt = 3.6: Figure 3.2.20 – 3.2.22

Al alloy A357-T6 Conv. Sand Casting
- Kt = 1.0: Figure 3.2.23 – 3.2.27
- Kt = 2.5: Figure 3.2.28 – 3.2.31
- Kt = 3.6: Figure 3.2.32 – 3.2.34

Al alloy A357-T6 Premium Casting
- Kt = 1.0: Figure 3.2.35 – 3.2.38
- Kt = 2.5: Figure 3.2.39 – 3.2.42
- Kt = 3.6: Figure 3.2.43 – 3.2.45

Of further interest is the matter of fatigue behaviour of casting in comparison with that of normal wrought materials. The Figures 3.2.46 to 3.2.48 show this for the already mentioned notch factors Kt = 1.0, 2.5 and 3.6. The stress ratio for all three diagrams was the same R = 0.1.

Additional fatigue test data for alloy A357 were provided by Cercast and Alcoa (Figures 3.2.49 and 3.2.50).

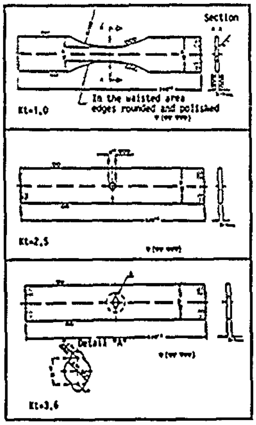


Fig 3.2.11 Test specimen according to Report TM61/71, LBF

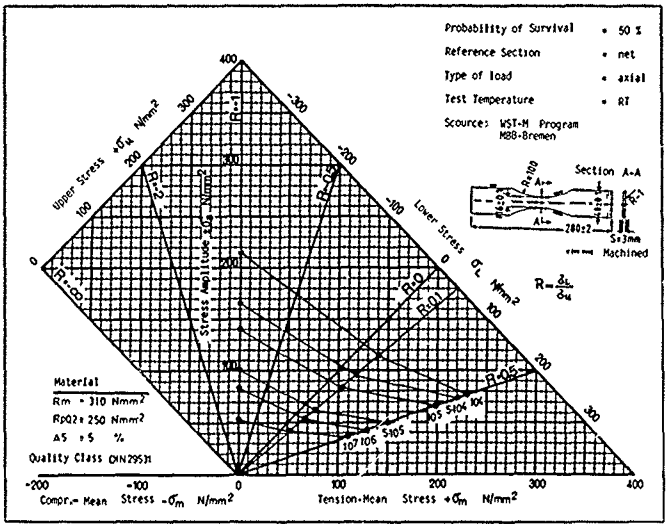


Fig 3 2 12 Haigh Diagram
Material A357-T6/Investment Casting
Stress concentration factor $K_t = 1\,0$

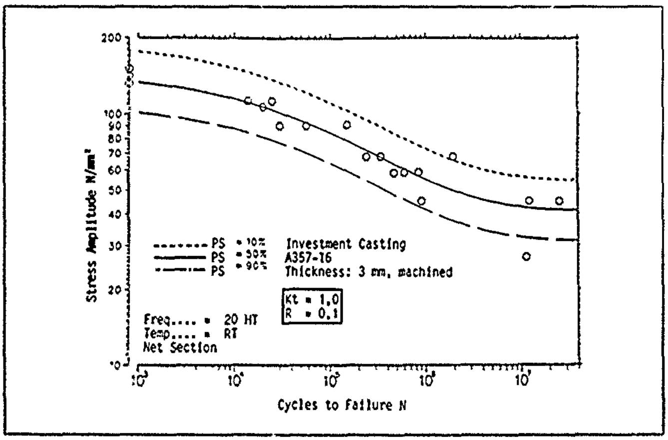


Fig 3 2 13

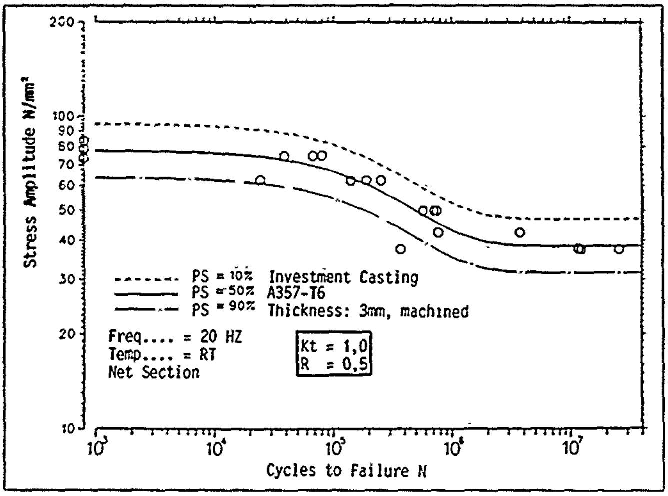


Fig 3 2.14

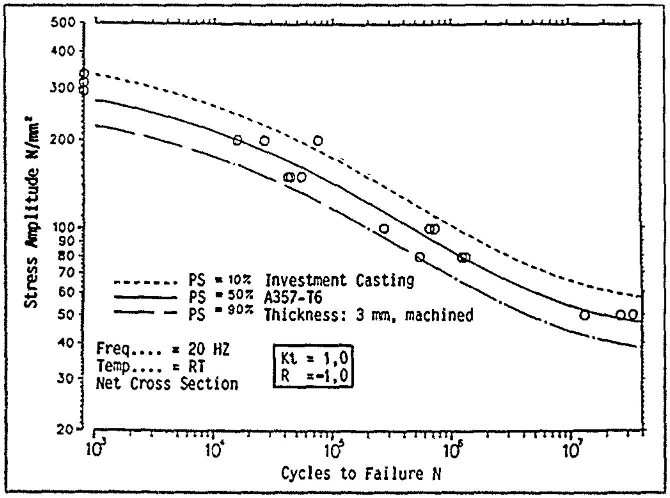


Fig 3 2 15

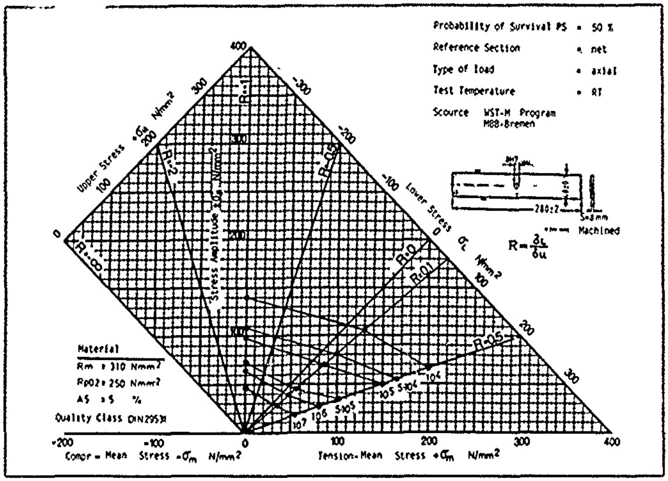


Fig 3 2.16 Haigh Diagram
Material: A357-T6/Investment Casting
Concentration Factor $K_t = 2.5$

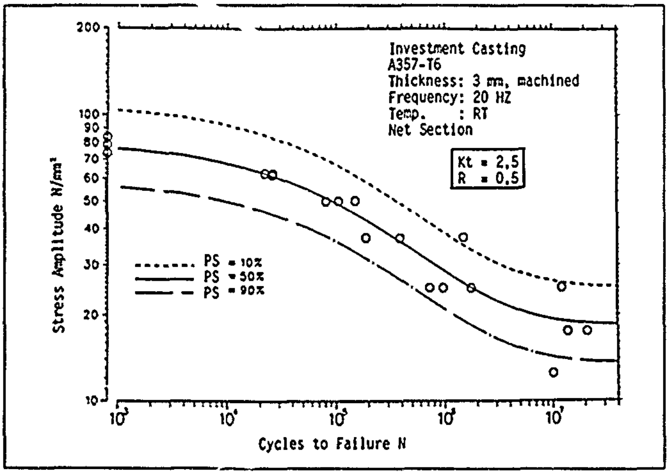


Fig 3 2 17

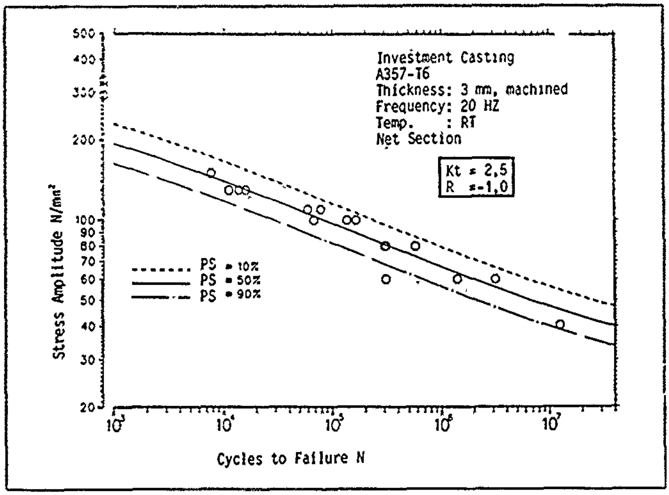


Fig 3 2 18

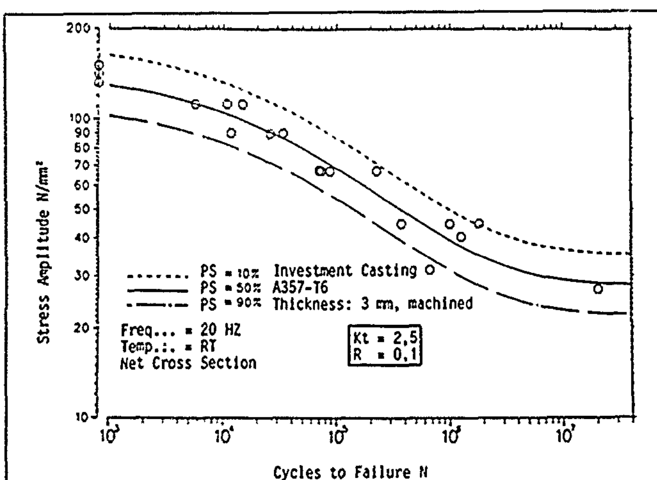


Fig 3 2 19

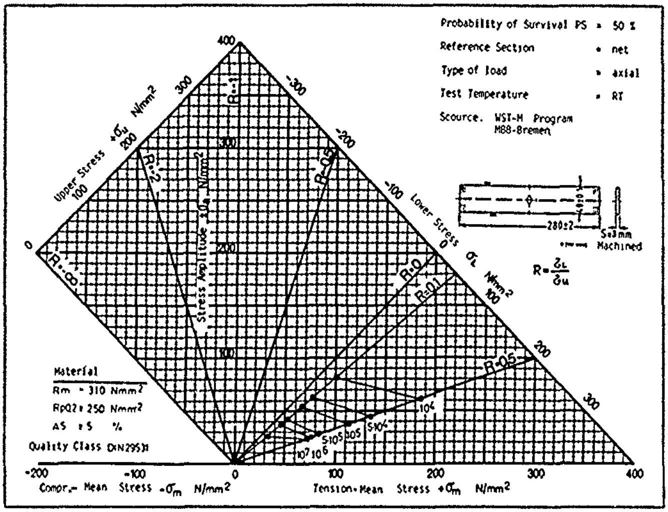


Fig 3 2 20 Haigh Diagram
Material: A357-T6/Investment Casting
Concentration Factor: K_t = 3 6

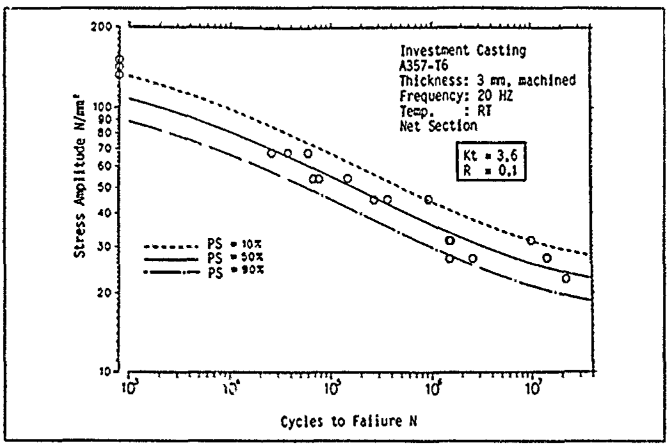


Fig 3 2 21

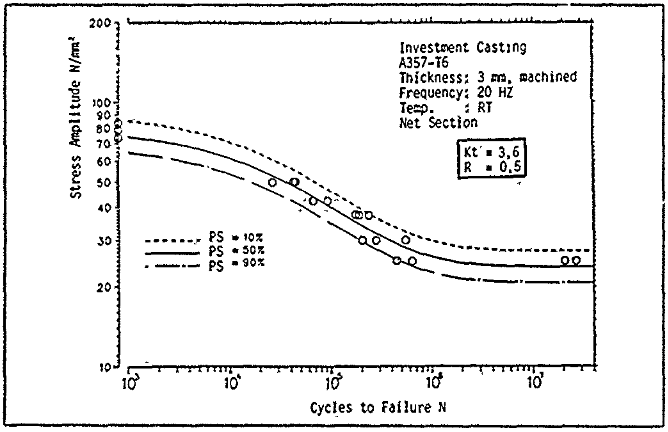


Fig 3 2 22

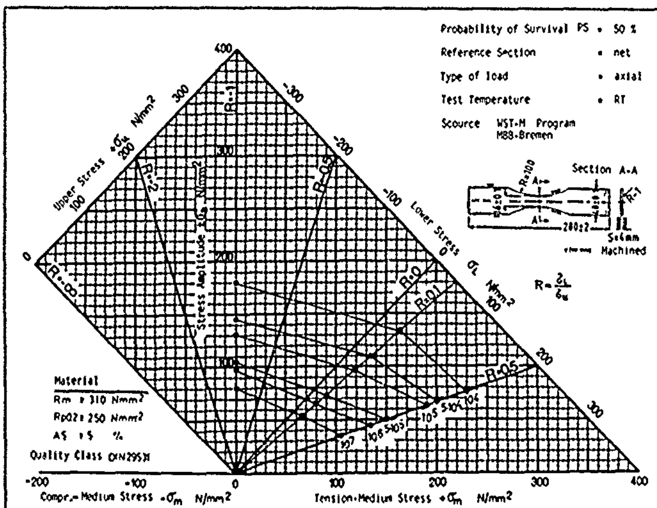


Fig 3 2 23 Haigh Diagram
Material: A357-T6/Conv. Sand Casting
Concentration Factor: K_t = 1 0

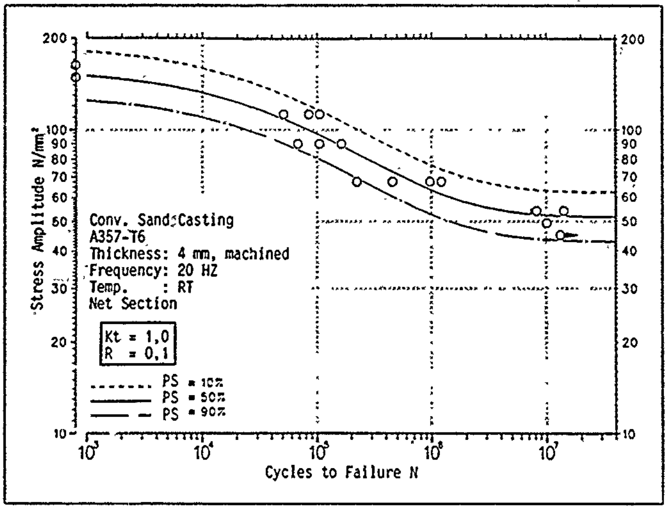


Fig 3 2 24

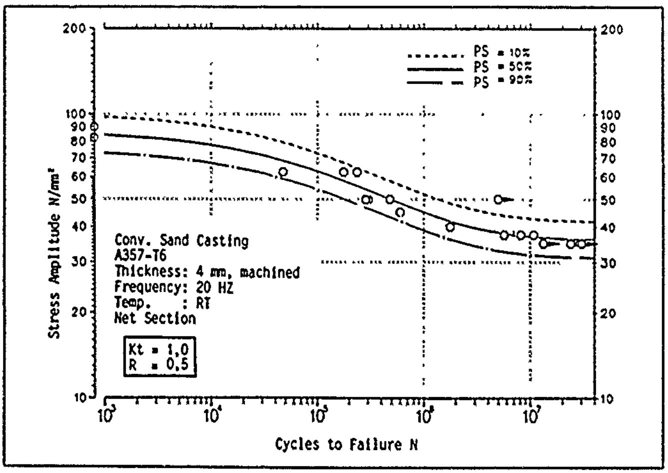


Fig 3 2 25

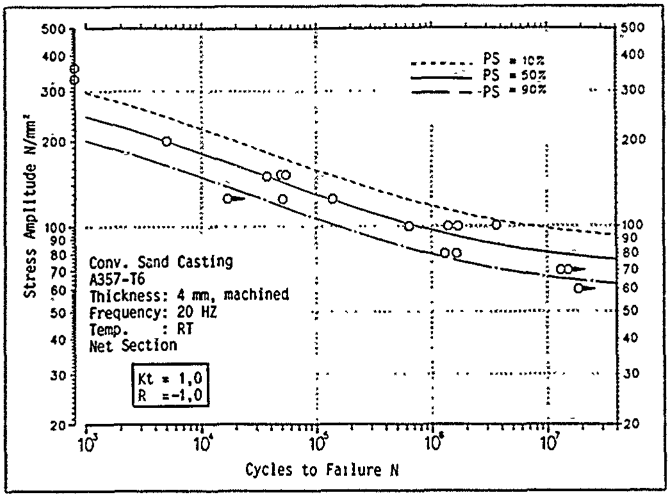


Fig 3 2 26

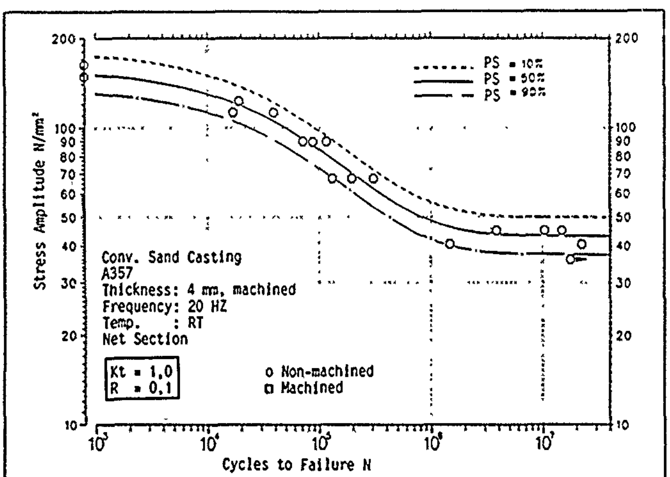


Fig 3 2 27

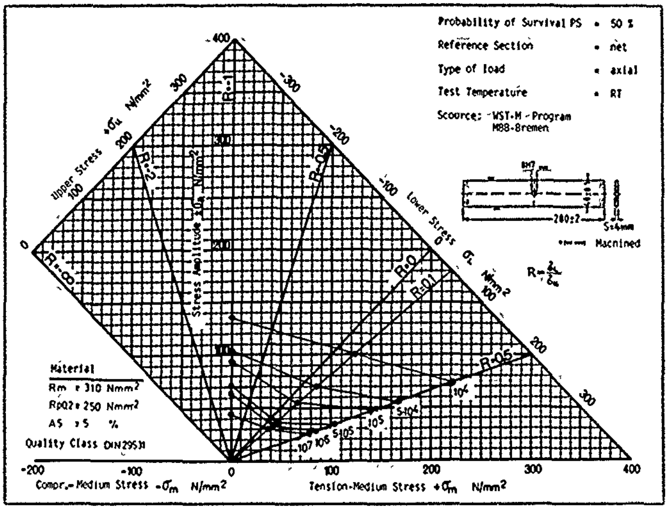


Fig 3 2 28 Haigh Diagram
Material, A357-T6/Conv. Sand Casting
Concentration Factor, $K_t = 2.5$

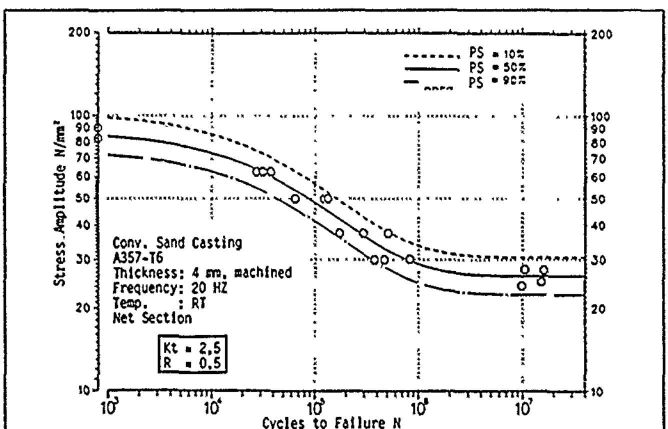


Fig 3 2 29

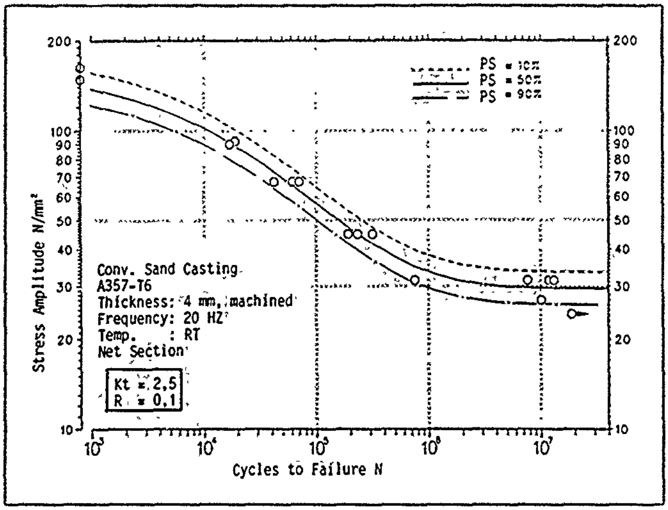


Fig 3 2 30

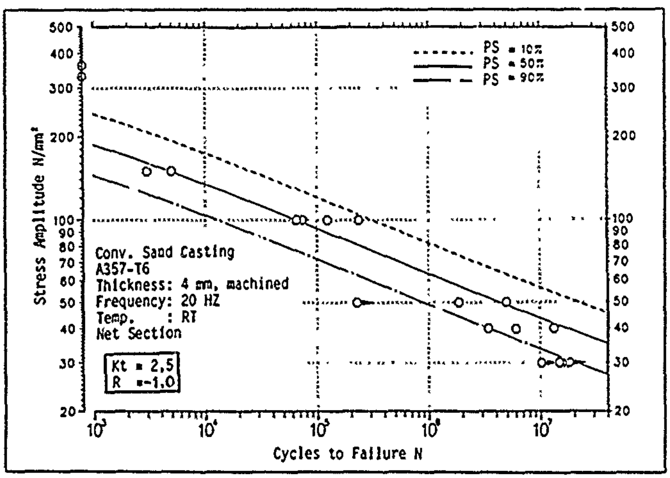


Fig 3 2 31

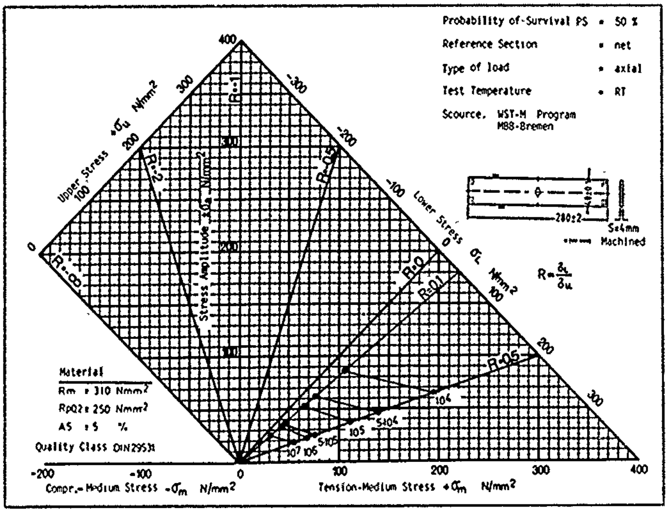


Fig 3.2.32 Haigh Diagram
Material A357-T6/Conv Sand Casting
Concentration Factor: K_t = 3.6

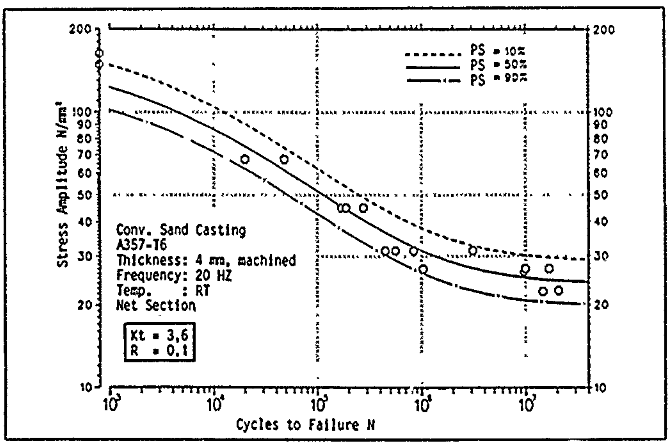


Fig 3.2.33

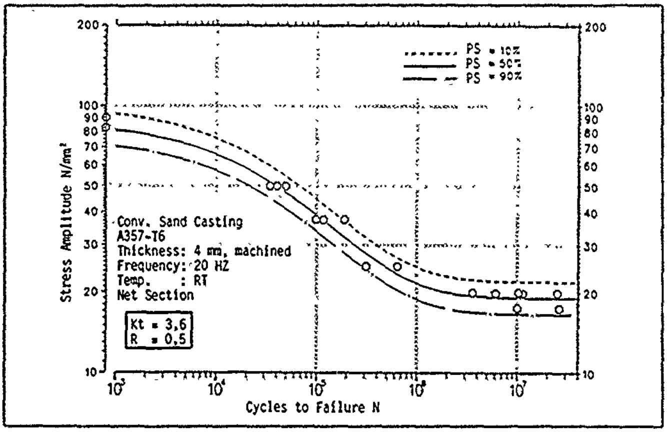


Fig. 3.2.34

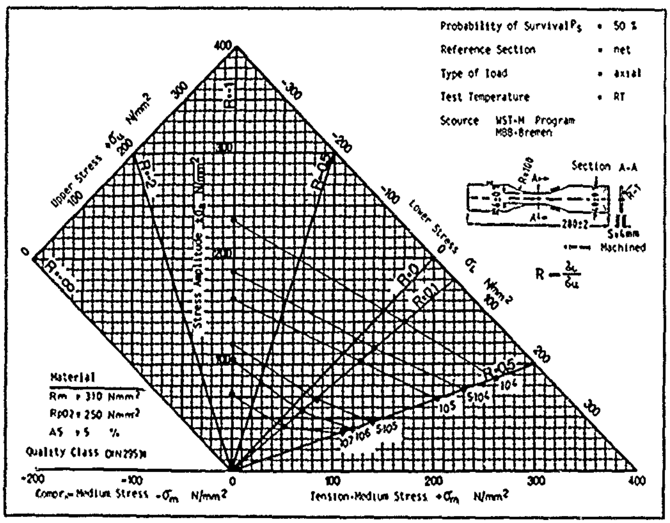


Fig 3.2.35 Haigh Diagram
Material: A357-T6/Premium Casting
Concentration Factor: $K_t = 1.0$

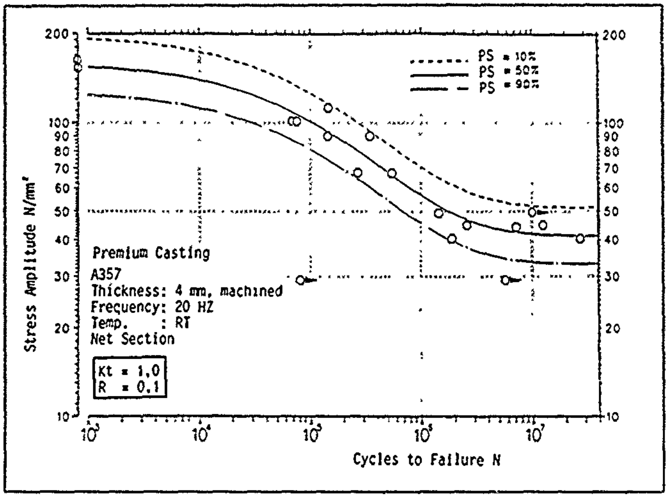


Fig 3.2.36

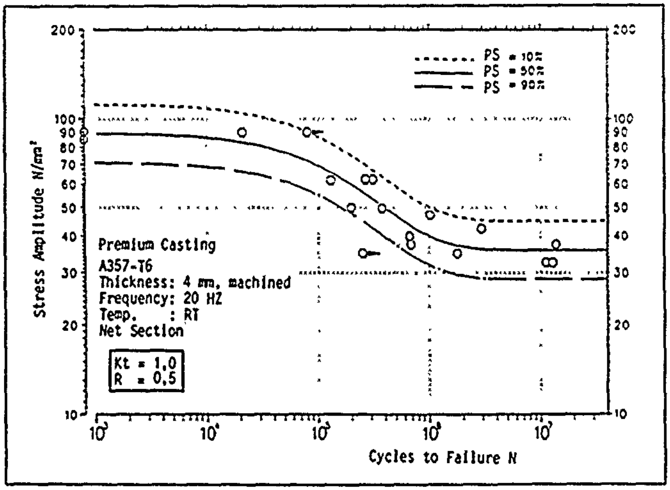


Fig 3.2.37

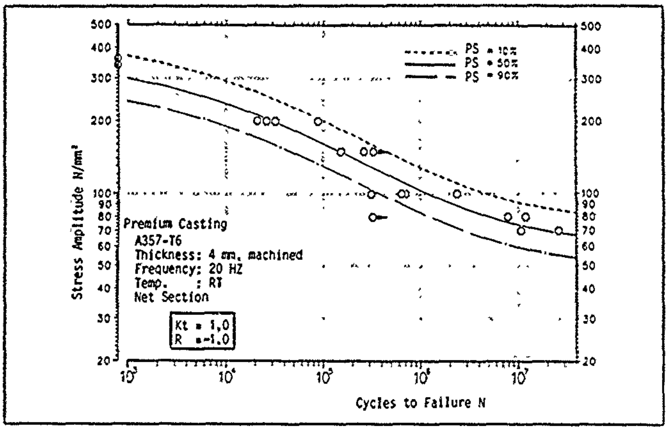


Fig 3 2 38

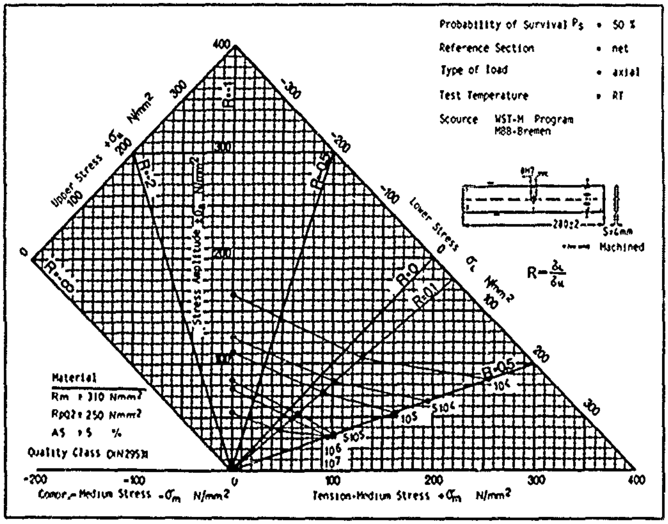


Fig 3 2 39 Haigh Diagram
Material: A357-T6/Premium Casting
Concentration Factor: $K_t = 2.5$

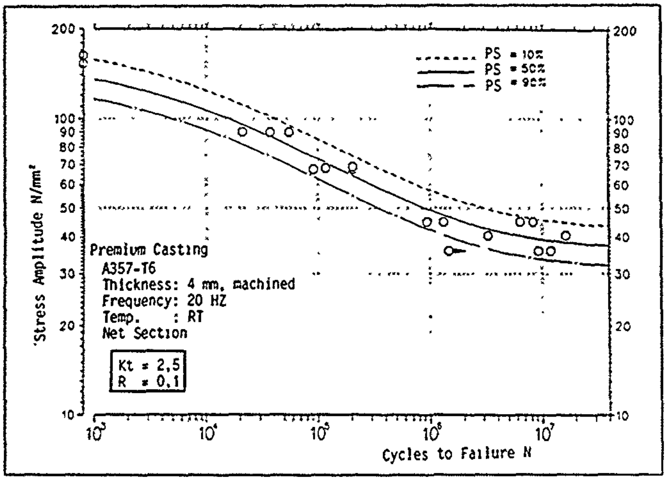


Fig 3.2.40

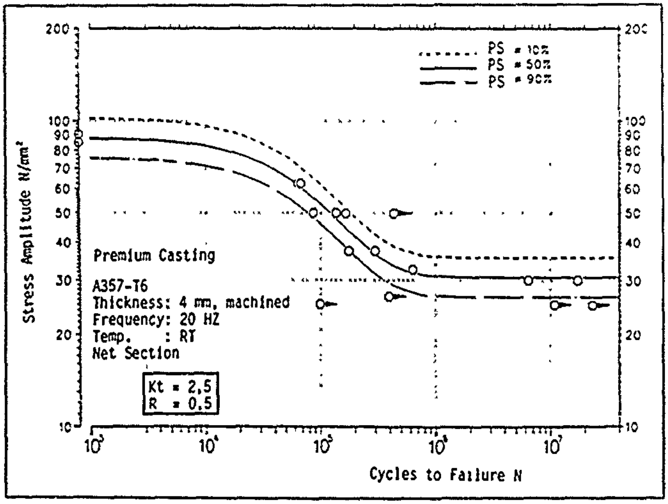


Fig 3.2.41

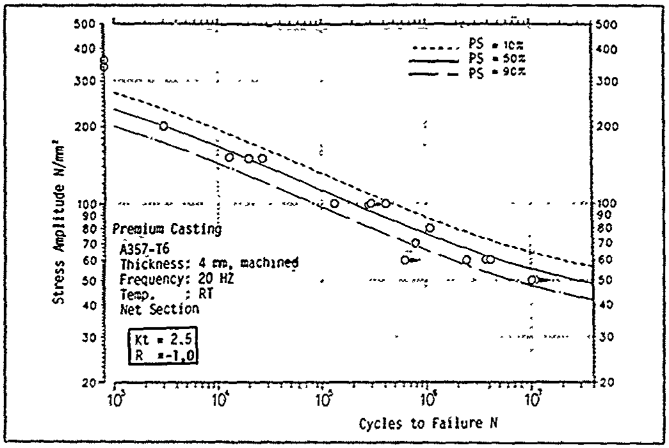


Fig 3 2.42

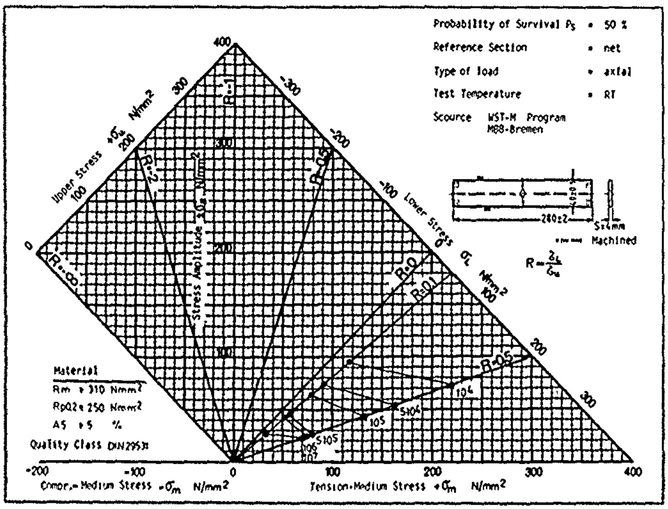


Fig 3 2.43 Haigh Diagram
Material: A357-T6/Premium Casting
Concentration Factor: $K_t = 3.6$

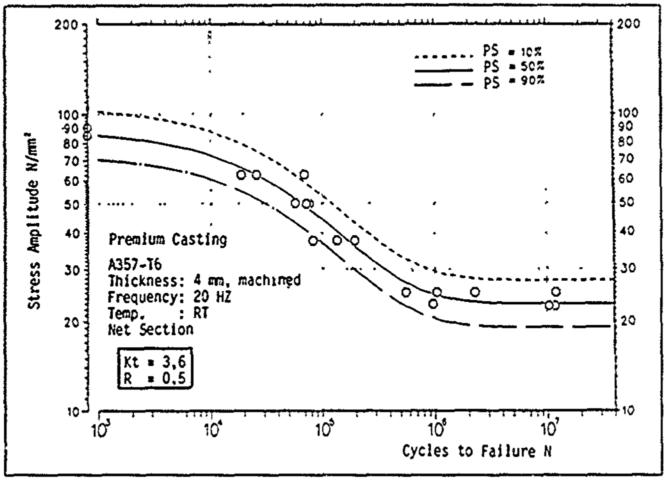


Fig 3.2.44

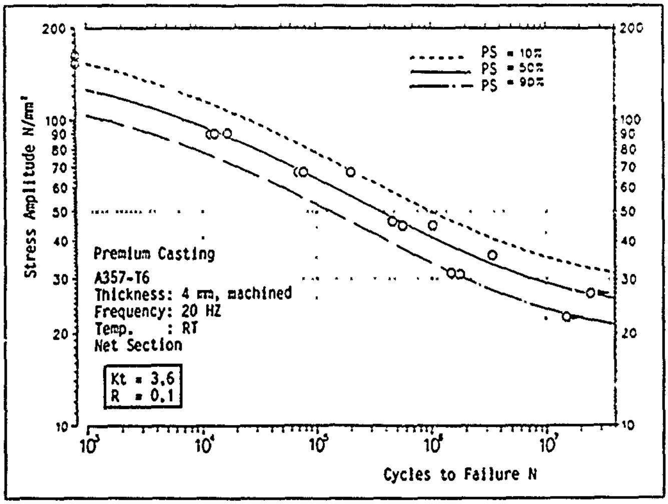


Fig 3.2.45

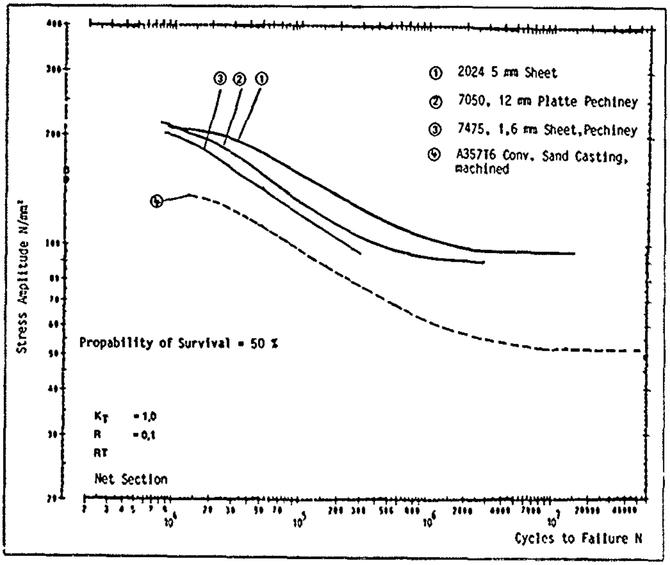


Fig 3 2 46 Stress Cycle Investigation
Comparison of Casting Alloy A357-T6 with Normal
Wrought Materials (Kt = 1 0)

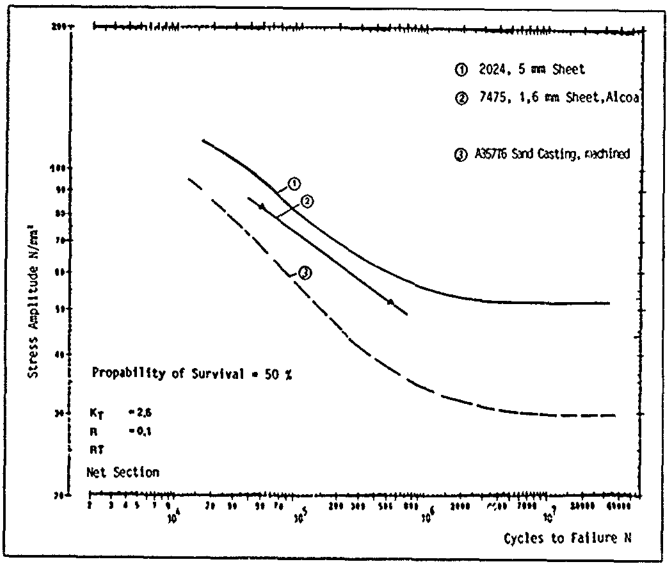


Fig 3 2.47 Stress Cycle Investigation
Comparison of Casting Alloy A357-T6 with Normal
Wrought Materials (Kt = 2 5)

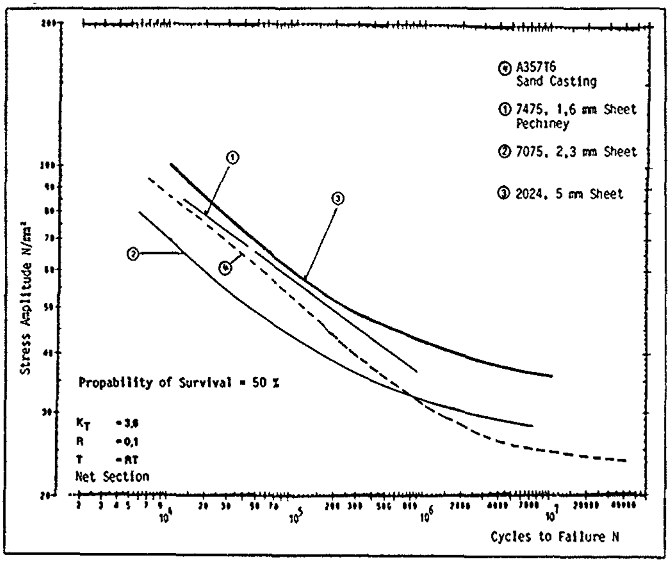


Fig 3 2 48 Stress Cycle Investigation
Comparison of Casting Alloy A357-T6 with Normal
Wrought Materials (Kt = 3 6)

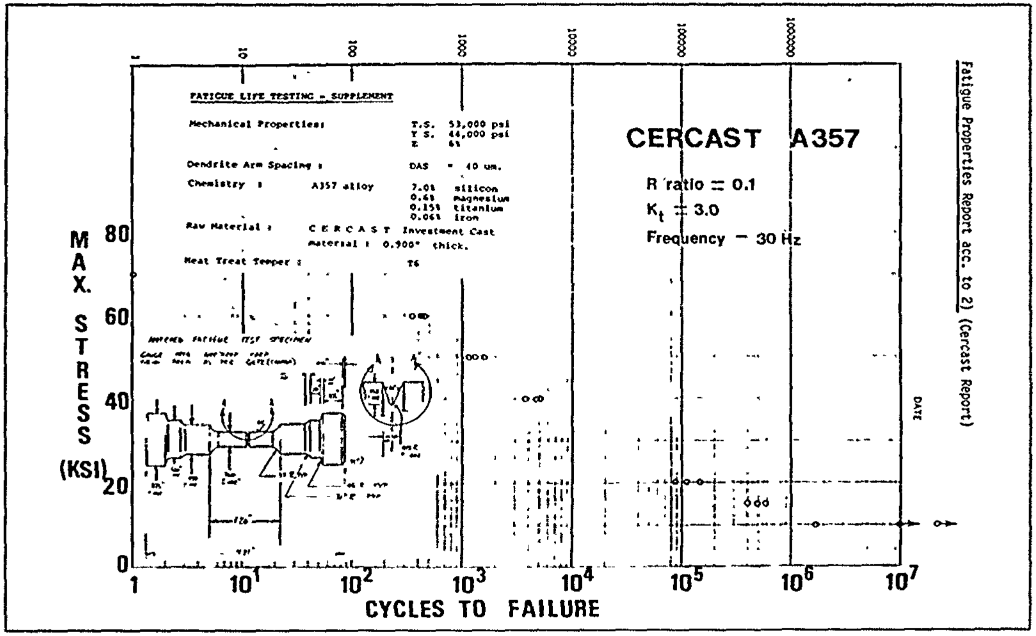


Fig 3 2.49 Fatigue Life Diagram

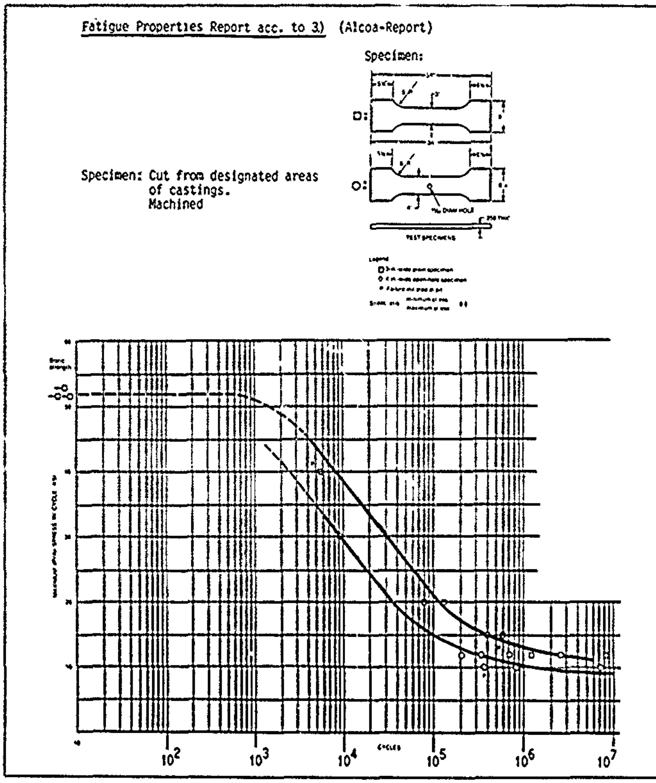


Fig 3 2 50 Fatigue Life Diagram of A357-T6 Alloy

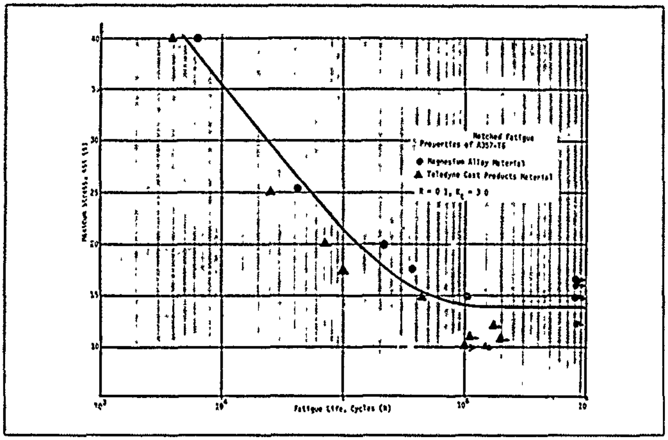


Fig 3 2 51 Fatigue Life Diagram of A357-T6 Alloy in Comparison with a Magnesium Alloy

FATIGUE DATA
FOR THE ALLOY A201-T7

Fatigue Properties Report (acc. to 5) (Northrop-Report)

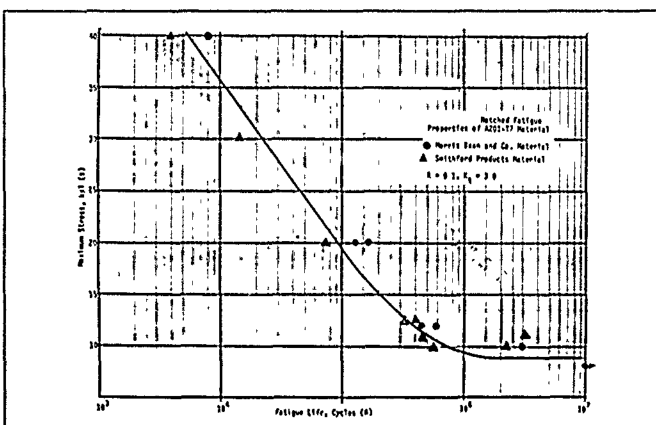


Fig 3 2 52 Fatigue Life Diagram of A201-T7 Alloy

Fatigue Properties Report (acc. to 5) (Northrop Report)
Figure 3 2.52 compares the fatigue life of alloy A201-T7 of two different material suppliers Both sets of data agree well

Fatigue Properties Report (acc. to 6)
(Report from L.B Hallowell)

The fatigue limit for A201 alloy is considered a little lower than some of the other alloys.

The fatigue resistance however is affected by factors such as microporosity (microshrinkage or gas porosity) and this indicates the importance of controlled casting practices for premium castings.

The fatigue resistance is also affected by the secondary dendrite arm spacing or cooling rates and the larger dendrite arm spacing with slower cooling rates reduces the life.

Work conducted indicates the endurance limit is not reached at 10^6 cycles in axial fatigue, either tension-tension or tension-compression, either with or without notches.

Additional work has shown that the notched fatigue behaviour of A201 in either the T6 or T7 condition is similar to other aluminium alloys such as 357 in the T6 condition

Tentative fatigue properties of Alloy A201 are indicated in the constant-life diagrams of Figures 3 2.54 (for smooth specimens) and 3 2.55 (for notched specimens)

Figure 3 2.53 shows the spproximate fatigue limit of A201 to be 14 ksi (9 84 kg/mm²) at room temperature and 10 to 12 ksi (7 to 8 4 kg/mm²) at 400°F (204°C) The fatigue limit being determined at 5×10^8 cycles

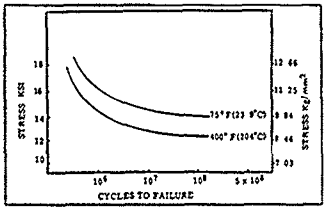


Fig 3 2 53 S-N Fatigue curves for A201 reversed bending

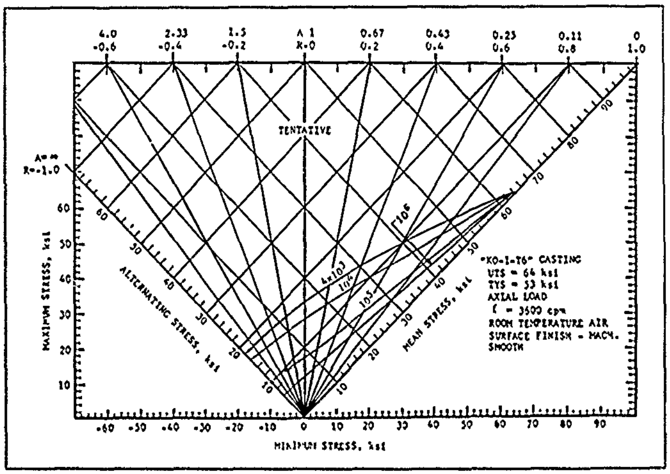


Fig 3 2.54 Tentative typical constant life diagram for fatigue behaviour of A201-T6 aluminium alloy casting

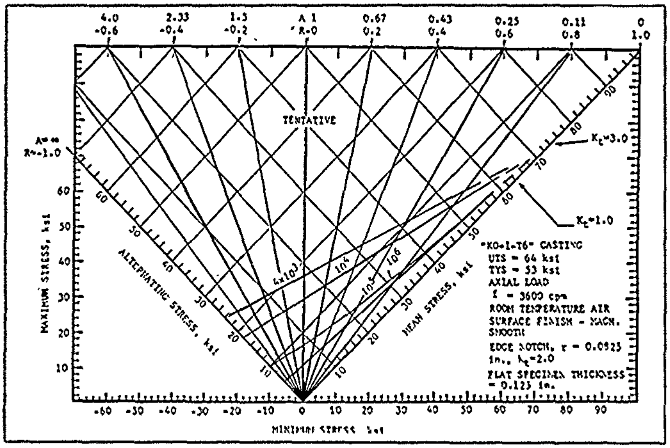


Fig 3 2 55 Tentative typical constant life diagram for fatigue behaviour of notched A201-T6 aluminium alloy casting

Fatigue Properties Report (acc. to 7) (Northrop-Report) Influence of HIP (Hot Isostatic Pressing) on A201-Investment Casting

INTRODUCTION

Most aluminium sand castings for airframe structural applications are cast using chills (in composite sand moulds) because chills are necessary to control solidification and thereby obtain high properties. With composite sand moulding the minimum as-cast thickness is greater than desired for many aircraft structural components. Thinner sections and tighter dimensional tolerances are possible with the investment mould technique; however, high properties in large, complex components are difficult to achieve because chills cannot generally be used to control solidification directionality and rates. Since hot isostatic pressing (HIP) has been shown to improve the properties of A201 aluminium sand castings, this IRAD effort was performed under the above referenced program to evaluate the effect of HIP on investment cast material. Comparisons are made to a similar evaluation performed previously for sand cast plates.[1]

PROGRAMME

Cercast, Inc. supplied investment cast plates in four thicknesses (Table 3.2.57). A sample was removed from each plate and heat treated to the T7 condition (see footnote "a", Table 3 2.61) and tensile tests performed on the samples to qualify the material. Then half of the plates of each thickness were HIP at 950F at 15 ksi for 3 hours (parameters successful with sand cast material). All the plates were then heat treated to the T7 condition Testing (Table 3 2.57) was performed on specimens removed from the plates. Metallography and fractography were also performed.

RESULTS AND DISCUSSION

The improvements by HIP of investment material are summarized in Table 3 2 58 The properties of investment and sand cast HIP material are compared in Table 3 2.59 the properties of HIP investment cast and (unHIP) sand cast material are compared in Table 3 2.60. The comparisons in these tables are based on a limited number of tests, therefore only trends are indicated with no pretense as to the statistical significance. The results are presented and discussed in more detail below.

Casting Parameters and Chemistry

Table 3 2.56 lists the mould temperatures and casting temperature for the various plates. Cercast selected the minimum mould temperature to assure a successful casting

The chemistry meets NAI-1304[2] and MIL-A-21180[3] requirements (Table 3.2.56).

Tension

The results are presented in Table 3 2.61. The minimum requirements of 53 ksi yield strength, 60 ksi ultimate strength, and 3 percent elongation of NAI-1304 for high stress areas (and the less stringent requirements of MIL-A-21180) were met except for the 1.5 in. thick plates for which the ultimate strength for both HIP+T7 and T7 material was as much as 3 ksi below the requirements and the elongation of one T7 specimen was 2 percent. A thickness of 1.5 in. is not representative of most applications, but is necessary to obtain valid fracture toughness values. This compares with the results for sand cast plates for which the properties exceeded the requirements for all thicknesses.

HIP had little effect on the tensile properties, increasing the yield and ultimate strength by about 1 ksi and increasing average elongation by one percent from 5.3 to 6.4 percent, but HIP had no effect on the minimum or maximum values. This compares with the sand cast material for which similarly HIP had little effect on strength (no change), but HIP increased the average elongation from 5.5 to 11 1 percent, increased the minimum from 4 to 11 percent, and increased the maximum from 8 to 12 percent.

Sharp-Notch Tension

The results are listed in Table 3 2 62 Sections A and B HIP increased the sharp-notch tensile strength (SNS) and notch strength ratio (NSR) somewhat for both the 0.5 and 1.5 in. thick plates and both SNS and NSR were slightly higher for the 0.5-in. thick material compared to that of the 1.5 in. thick plates. The results are similar to those obtained for sand cast material.

Fracture Toughness

Fracture toughness of 1.5 in. thick plates was the same for the HIP+T7 and T7 material, an average of 38 ksi√in (Table 3 2.62, 3 2.63). This is intermediate to the averages obtained for sand cast HIP+T7 and T7 material (46 and 32 ksi√in. respectively) All fracture toughness values were not valid per E399, nevertheless the trends indicated are meaningful

S/N Fatigue – Notched

The results for S/N fatigue of HIP+T7 specimens with a K_t of 3 0 are shown in Figure 3 2 64 along with results for sand cast HIP+T7 and T7 Only HIP+T7 investment material was tested as the results for T7 material were expected to be similar. Overall the results for the three conditions are similar, although at higher stresses the sand cast material had slightly longer fatigue life, while at lower stresses the investment cast material had slightly longer fatigue life. There were no significant differences between the results for the various thicknesses for the investment cast material.

Strain-Life Fatigue

Strain-life fatigue results for 0.5 in. thick plates for HIP+T7 and T7 are plotted in Figure 3 2.65 with results for sand cast HIP+T7 material also shown. The HIP+T7 investment cast material had better fatigue behaviour than that for the T7 investment material while the HIP+T7 sand cast material had better fatigue behaviour than both investment cast conditions.* Cyclic stress-strain curves obtained from the strain-life fatigue testing are presented in Figure 3 2.66.

Fatigue-Crack Growth Rate

The results for HIP+T7 investment cast and HIP+T7 sand cast material showed specimen differences, but no consistent differences among the various thicknesses. The sand cast material had better fatigue-crack growth behaviour than that of the investment material (results not shown).

Two tests were performed for T7 investment material from the 1.5 in. thick plate and the results were the same as for the 1.5 in. thick HIP+T7 material (results not shown).

---

* The overall result (as shown by the curve in Figure 3 2.65) for the T7 investment material is lowered by one test result with a life of 109 cycles at a strain amplitude of 0.005. This specimen was evaluated and compared to other fatigue samples to determine if this result should be considered representative of the investment material. It was found that the fatigue crack initiated at an inclusion, however, the fatigue crack in one HIP+T7 specimen initiated from a similar inclusion without substantially lowering the fatigue life (234, 129 cycles at a strain amplitude of 0 002). Therefore the low result for the T7 material was taken to be a valid result, because a similar inclusion did not lower the life in all cases; however, there are insufficent fatigue test results to reach a general conclusion of the effects of this type of inclusion on T7 and HIP+T7 fatigue results.

Metallography

Micrographs of T7 and HIP+T7 samples (Figure 3 2 67) show that HIP was effective in eliminating microshrinkage porosity Micrographs of tensile samples of T7 material are shown in Figure 3 2 68. There are very low amounts of undesirable inclusions (iron rich needles, titanium rich inclusions and undissolved copper-rich phase). Grain size was determined for two samples each from plates of each thickness (Table 3 2.63). The samples located one end of the plate had average grain diameters from 130 to 210 µm, while the trend for larger grain size for the thicker plates and those away from the ends, had average grain diameters of from 100 to 130 µm with little difference between the various thicknesses.

Fractography

All tensile and fatigue samples were examined optically and several were examined in the scanning electron microscope equipped with an energy dispersive analyzer. Many specimens had elongated inclusions up to 1.5 mm long, although typically 0 2 mm long. This was discussed in the Strain-Life Fatigue section These inclusions are probably aluminium oxide. There was porosity on most of the T7 fracture surfaces Porosity was seen on only one HIP+T7 fracture surface, however, the surface was lightly oxidized indicating that the porosity was surface connected and therefore could not be closed by HIP (Figure 3 2.69).

SUMMARY AND CONCLUSIONS

The strength and ductility requirements of NAI-1304[2] and MIL-A-21180[3] were met by both HIP+T7 and T7 material (except as noted for the 1.5 in. thick material). HIP did not improve the ductility of the investment material as it did for sand cast material S/N fatigue (notched), fracture toughness, and fatigue crack growth properties are reported HIP improved the strain-life fatigue behaviour

The properties of the investment cast material were generally slightly below those for the sand cast material From this limited comparison, no conclusion can be drawn as to whether this reflects differences between the sand and investment processes or other variables such as minor differences in chemical composition or heat treatment These same differences may explain the differences in response to the HIP. It should be noted that sand casting permits the use of chills which should allow more control of the properties.

This data does not suggest that investment cast A201 should not continue to be considered for components which are capable of being produced by this process. HIP should be considered for applications that require improved crack initiation resistance, however, additional evaluation would be required to confirm this improvement.

FATIGUE DATA FOR THE ALLOY TI-6AL-4V

Fatigue Properties Report (acc. to 8) (MBB-Report)

A great number of publications described the fatigue properties on Ti-6Al-4V alloy and the positive influence of the HIP-process. The collected figures shown in this section have different sources, so that the real origin is nominated in the appendix "Sources for Section 3.2.3" (see source 8).

Table 3 2 56
A201 Investment cast plates from Cercast

A *Material Supplied*			
Quantity	Size (inches)	Melt Number	Mould Temperature[a]
2 plates	0 125 × 3 × 12	5960	1100F
2 plates	0 25 × 4 × 12	5960	1000F
4 plates	0.5 × 4 × 12	5960	900F
2 plates	1.5 × 4 × 10	6016	250F

B *Melt Compositions.*

	Weight Percent										
Melt No.	Cu	Ag	Mn	Mg	Ti	B	Si	Fe	Zn	Cr	Ni
5960	4 68	0 50	0.308	0 268	0 217	0 013	0 034	0 026	0 008	0 003	0 004
6016	4 74	0 49	0.304	0 237	0 249	0 016	0 048	0.031	0 008	0 002	0 006
NAI-1304	4.0–5 0	0 4–1.00	0 20–0 40	0 15–0.35	0 15–0.35	b	<0 05	<0 10	b	b	b

[a] Casting temperature was 1365F, and no chills were used   [b] other elements 0 03 max each, 0 10 max total

Table 3 2 57
Test matrix for A201 investment cast plates

	Number of specimens								
	Condition	T7				HIP+T7			
TEST	THICKNESS (in.)	0 13	0 25	0.5	1.5	0 13	0 25	0 5	1 5
Tension		6	6	8	6	4	4	4	4
Sharp-Notch Tension		–	–	2	2	–	–	2	2
Fracture Toughness		–	–	–	2	–	–	2	2
S/N Fatigue-Notched		–	–	–	–	3	3	4	4
Strain-Life Fatigue		–	–	11	–	–	–	10	–
Cyclic Stress Strain		–	–	2	–	–	–	2	–
Fatigue-Crack Growth		–	–	–	2	1	1	1	2

Table 3 2 58
Improvements by HIP of investment cast A201-T7

0 13–0.5 inch thick except as noted		
Property	Improvement by HIP Minimum[a]	Average
Tension		
Ultimate Strength	2 ksi (4%) increase	1 ksi (2%) increase
Yield Strength	No change	1 ksi (2%) increase
Elongation	No change	1% (17%) increase
Sharp-Notch Tension (0.5 in.)		
Strength	6 ksi (7%) increase	5 ksi (6%) increase
Notch Strength Ratio	0.07 (5%) increase	0.06 (4%) increase
Fracture Toughness (1.5 in)	0.3 ksi√in (1%) increase	0.1 ksi√in (0%) increase
Strain-Life Fatigue	Insufficient Data	Life Doubled (100%)
Fatigue Crack Growth	No change	No change
Microstructure	Porosity Eliminated	Porosity Eliminated

[a] Comparison of lowest values obtained

Table 3.2.59
Comparison of HIP sand cast and HIP investment cast A201-T7

Property	Advantage of Sand over Investment[a] Minimum[b]	Average
Tension		
Ultimate Strength	3 ksi (5%)	3 ksi (4%)
Yield Strength	3 ksi (5%)	[illegible] ksi (5%)
Elongation	6% (150%)	4% (60%)
Sharp-Notch Tension		
Strength	7 ksi (8%)	7 ksi (8%)
Notch Strength Ratio	−0.07 (−1%)	−0.005 (0%)
Fracture Toughness	5 ksi √in (12%)	6 ksi √in (17%)
S/N Fatigue-Notched	Insufficient Data	Similar (see text)
Strain-Life Fatigue	Insufficient Data	30% Life
Fatigue Crack Growth	0–40% slower rate (20%)	40–200% slower rate (120%)

[a] Comparisons are on the thicknesses tested up to 0.5 inch — see text for detailed results
[b] Comparison of lower values obtained

Table 3.2.60
Comparison of HIP investment cast and (unHIP) sand cast A201-T7

Property	Advantage of HIP Investment over (unHIP) Sand[a] Minimum[b]	Average
Tension		
Ultimate Strength	−1 ksi (−2%)	−2 ksi (−3%)
Yield Strength	−2 ksi (−4%)	−4 ksi (−6%)
Elongation	0% (0%)	2% (30%)
Sharp-Notch Tension		
Strength	1 ksi (3%)	2 ksi (2%)
Notch Strength Ratio	0.12 (9%)	−0.11 (8%)
Fracture Toughness	5 ksi √in (15%)	5 ksi √in (16%)
S/N Fatigue-Notched	Insufficient Data	Similar (see text)
Fatigue Crack Growth	Twice as fast at low ΔK (−100%)	Similar

[a] Comparisons are on the thicknesses tested up to 0.5 inch — see text for detailed results
[b] Comparison of lower values obtained

Table 3 2 61
Tension test results for A201-T7 investment cast plates

Condition[a]	ID	YS (ksi)	UTS (ksi)	%e	AVERAGE[b] YS (ksi)	AVERAGE[b] UTS (ksi)	AVERAGE[b] %e
A Coupons excised from 0.13 in. thick plates							
HIP+T7	3HIT-1	58	66	7			
	3HIT 2	57	65	7			
	3HIT-3	57	65	8			
	3HIT-4	56	65	9	57	65	8
T7	3A1T-1	56	64	6			
	3A1T-2	56	65	6			
	3A1T-3	56	64	8			
	3A1T-4	56	65	9	56	64	7
	3A1T-A[b]	55	63	8			
	3A2T-B[b]	54	62	8			
B Coupons excised from 0.25 in. thick plates							
HIP+T7	6HIT-1	59	66	7			
	6HIT-3	59	66	7			
	6HIT-3	59	64	5			
	6HIT 4	59	64	4	59	65	6
T7	6A1T 1	59	65	5			
	6A1T-2	58	65	5			
	6A1T-3	58	62	3			
	6A1T 4	59	62	4	58	64	4
	6A1T A[b]	56	64	9			
	6A1T B[b]	c	64	8			
C Coupons excised from 0.5 in. thick plates							
HIP+T7	13HIT-2	59	65	6			
	13HIT 3	59	67	8			
	13H2T-2	59	66	7			
	13H2T-3	58	65	6	59	66	7
T7	13A1T-2	58	63	5			
	13A1T 3	58	64	5			
	13A2T-2	58	65	6			
	13A2T-3	58	64	4	58	64	5
	13A1T1 A[b]	59	65	6			
	13A2T1 B[b]	59	66	6			
	13A3T1-C[b]	60	67	OSG			
	13A4T1-D[b]	59	66	6			
D Coupons excised from 0.13 in. thick plates							
HIP+T7	38HIT-1	56	63	6			
	38HIT-2	55	63	OSG[c]			
	38HIT-3	55	59	5			
	38HIT-4	55	62	6	55	62	6
T7	38AT-1	54	60	5			
	38AT-2	54	60	5			
	38AT-3	53	57	4			
	38AT-4	53	59	5	54	59	5
	38A1T1 B[b]	55	58	2			
	38A2T1 B[b]	55	61	4			

[a] HIP = 950F at 15 ksi for 3 hours
T7 = 940F/1 hr + 960F/1 hr + 980F/15 hr/Water quench + 370F/5 hr

[b] Some bars (footnoted "b" in ID column) were heat treated separately and were not used to compute the averages, so that direct comparisons can be made between HIP+T7 and T7

[c] OSG = Fractured outside gauge length.

Table 3 2 62
Fracture toughness and sharp-notch tension results for A201 investment cast plates

A. SHARP-NOTCH TENSION

Coupons excised from 0.5 in thick plates
0.5 in nominal diameter specimens per ASTM E602

Condition[a]	ID	SNS[b] (ksi)	NSR[b]
HIP+T7	TN13H-1	87	1 49
	TN13H-2	87	1 48
T7	TN13A-1	81	1 41
	TN13A-2	83	1 44

B FRACTURE TOUGHNESS AND SHARP-NOTCH TENSION

Fracture toughness specimen excised from 1.5 in thick plates with notched tensile specimens excised from tested fracture toughness specimens

		Fracture Toughness				Sharp-Notched Tension	
Condition	ID	B(in)	R_c	K_{max} (ksi in)	K_Q[c] (ksi in)	SNS[b] (ksi)	NSR[b]
HIP+T7	38HFT-1	1 469	1 01	40.5	38 8	79	1 42
	38HFT-2	1 468	0 93	38.3	37 5	78	1 41
T7	38AFT-1	1 469	1 07	40 7	39 2	73	1 35
	38AFT-2	1 469	1 01	38 8	37 2	74	1 41

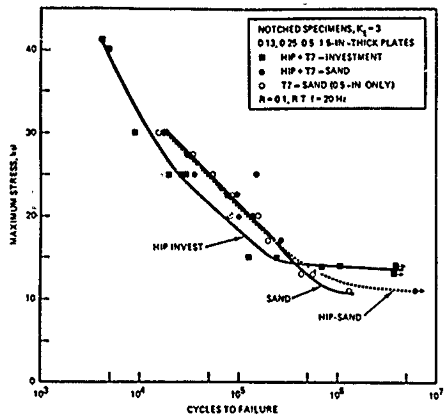
[a] HIP – 950F at 15 ksi for 3 hours
T7 – 950F/1 hr + 960F/1 hr + 980F/15 hr/Water quench + 370F/5 hr

[b] SNS – Sharp notch strength, NSR – Sharp-notch strength (SNS) to yield strength ratio

[c] Results not valid K_{Ic} because cracks were too long (a/w between 0 587 and 0 620 in.) and asymmetry of crack fronts

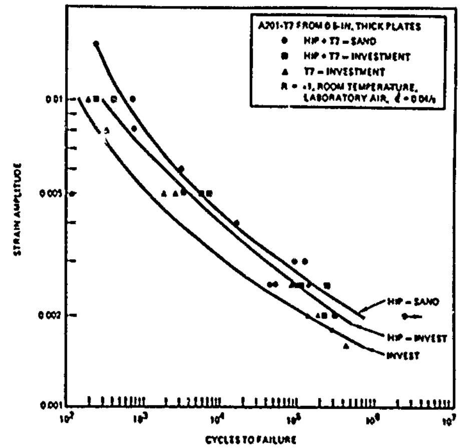
Table 3 2 63
Grain size measurements for investment cast plates

Plate Thickness, In	Grain Size, µm End of Plate	Center of Plate
0 13	100	100
0 25	160	130
0.5	130	110
1.5	210	130



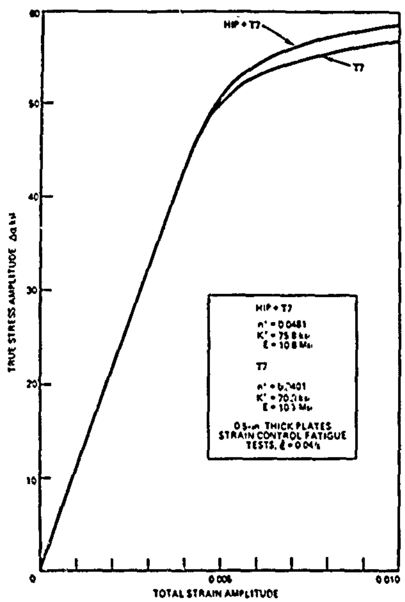
S/N FATIGUE OF A201

Fig.3 2 64



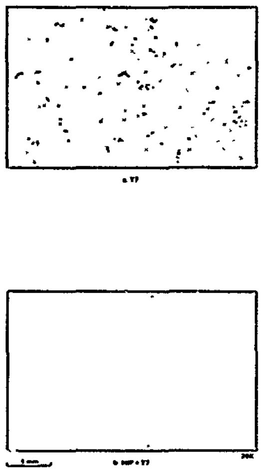
STRAIN LIFE FATIGUE OF A201-T7

Fig 3 2.65



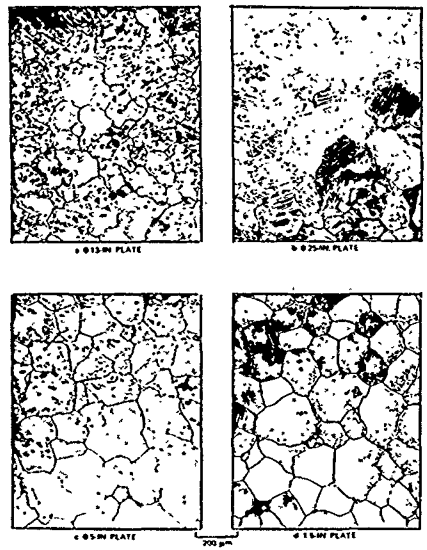
CYCLIC STRESS-STRAIN CURVES FOR
INVESTMENT CAST A201

Fig 3 2 66



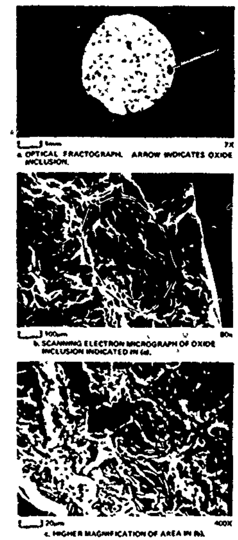
MICROGRAPHS OF UNETCHED SAMPLES SHOWING EFFECT OF HIP ON POROSITY BOTH SAMPLES FROM 0.25-IN PLATE

Fig 3.2.67



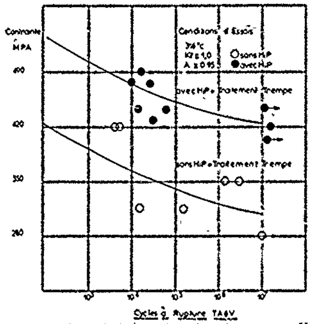
MICROGRAPHS OF TENSILE SPECIMENS FROM INVESTMENT CAST PLATES (100X, KELLERS ETCH)

Fig 3.2.68



OXIDE INCLUSION ON FRACTURE SURFACE OF A FATIGUE SPECIMEN FROM 0.5-IN.-THICK PLATE IN T7 CONDITION (NO HIP). STRAIN AMPLITUDE = 0.005, LIFE = 109 CYCLES.

Fig 3.2.69



Limite de fatigue TA 6 V — Avec et sans HIP.

Fig 3 2.70

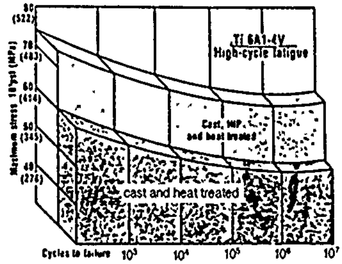
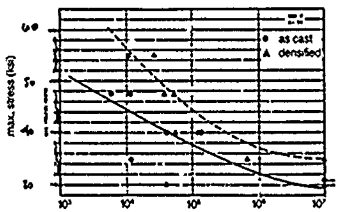


Fig 3 2 71



Ti-6Al-4V High Cycle Fatigue Results

Fig 3 2.72

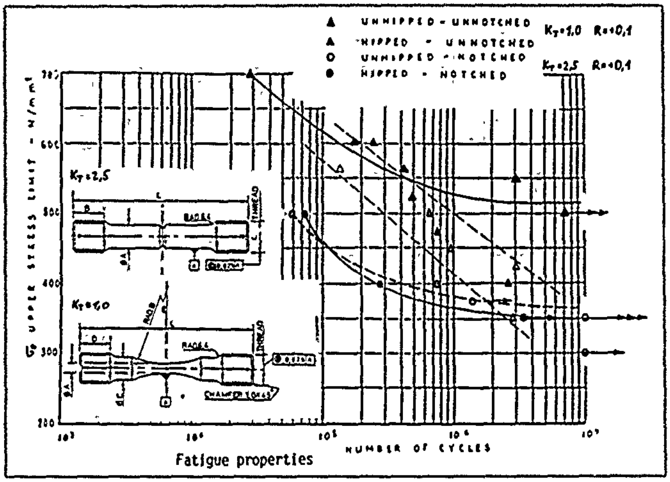


Fig 3 2.73

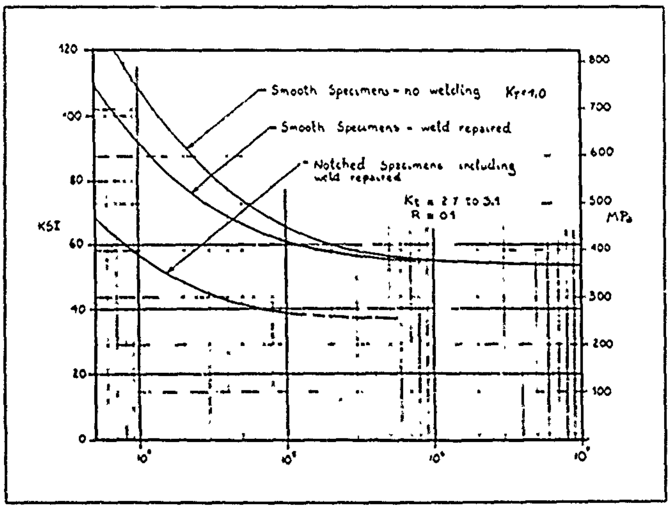
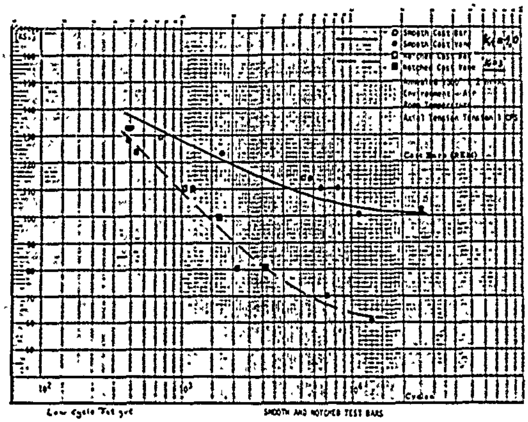
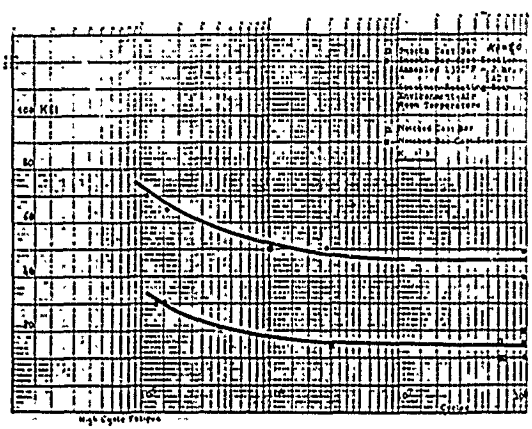


Fig 3 2.74



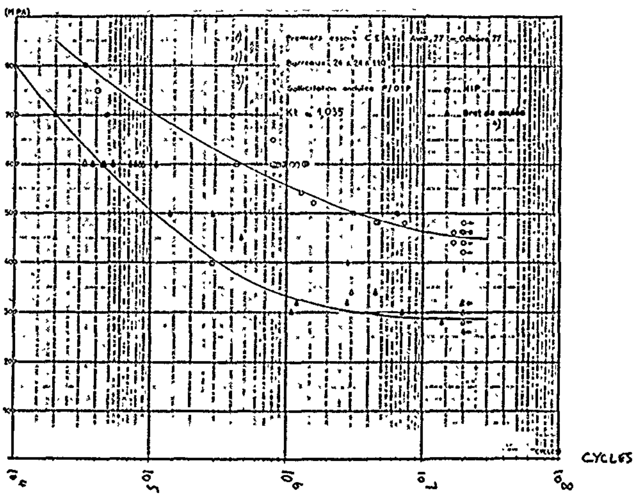
Fatigue Properties of Ti-6Al-4V, kt=3,0/kt=1,0

Fig 3 2.75



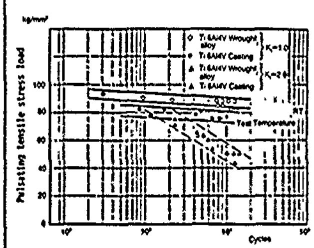
Fatigue Properties of Ti-6Al-4V Kt=3,0/Kt=1,0

Fig 3 2.76



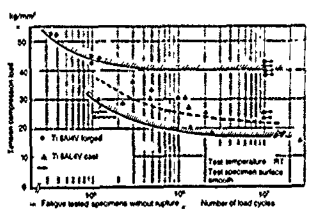
Fatigue properties, comparison of the conditions "AS Cast and HIP for Ti Ramm.Graph Casting

Fig 3 2 77



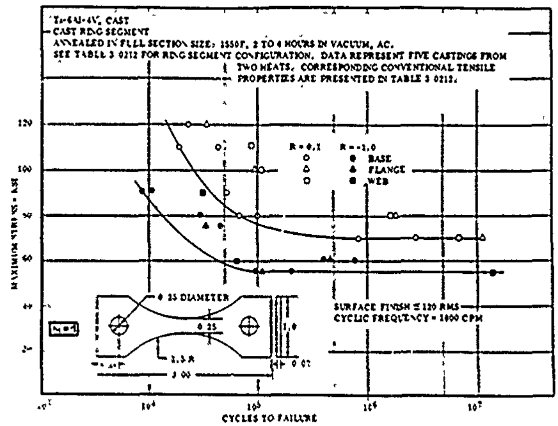
HCF-Behavior of smooth Specimen made from forged and cast alloy Ti-6AL-4V at R.T.

Fig 3 2 78



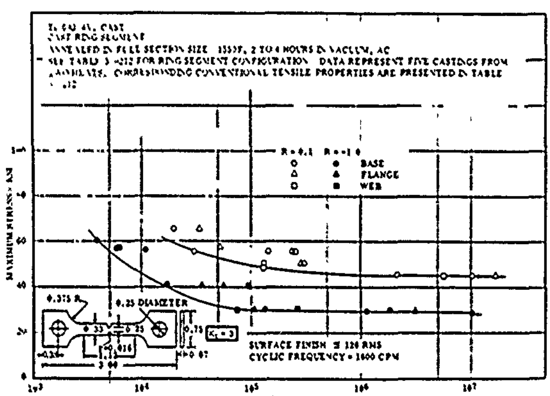
HCF-Behavior of smooth Specimen made from forged and cast alloy Ti-6AL-4V at R.T.

Fig 3 2 79



ROOM TEMPERATURE AXIAL LOAD FATIGUE PROPERTIES OF SMOOTH SPECIMENS FROM FIVE ANNEALED CAST RING SEGMENTS FROM TWO HEATS.

Fig 3.2.80



ROOM TEMPERATURE AXIAL LOAD FATIGUE PROPERTIES OF MILD-NOTCH SPECIMENS FROM FIVE ANNEALED CAST RING SEGMENTS FROM TWO HEATS.

Fig 3.2.81

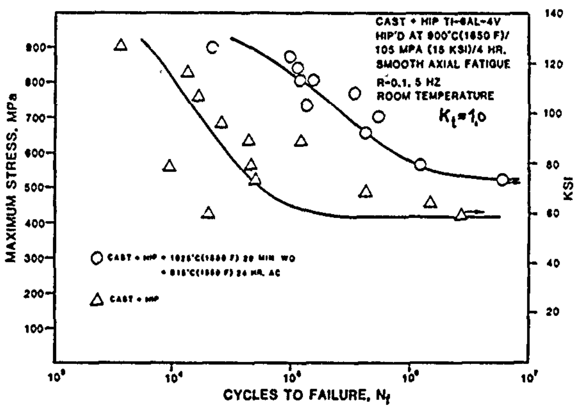
Fatigue Properties Report (acc. to 9) (Journal report)
Fatigue properties can be significantly improved by heat treatment. This is illustrated by Figure 3.2 82, which shows the improvement in smooth fatigue life versus maximum cyclic stress of beta heat treated and annealed cast Ti-6Al-4V alloy compared to the same alloy in the as-cast + Hip-Condition.

Fatigue Properties Report (acc. to 10)

Effect of Processing on Fatigue Life of Ti-6Al-4V Castings
The recent surge of interest in titanium alloys by both the Aerospace[1] and the Energy[2] industries coupled with a recent world-wide availability problem has greatly increased the interest in net shape technologies[3,4]. Although net shape technologies can contribute significantly to cost saving, titanium products are inherently expensive[1] and a process which can combine effective material use with relatively low cost, such as casting, is highly desirable. Metal casting is the most ancient net-shape technology which, in spite of being 5,000 years old, is still very effective for space age materials such as nickel, aluminium and titanium base alloys. When properties of cast titanium alloys are measured against wrought material, the biggest deficiency is in the high cycle fatigue strength[5,6,7]. The lower fatigue strength is the result of casting defects and the inherent cast microstructure, both of which contribute to early fatigue crack initiation[5]. This problem can be partially corrected by Hot Isostatically Pressing (HIP) which closes the casting pores. Experience has shown that even after HIPing, the fatigue strength of castings is lower than that of wrought products[6].

However, there are many non-fatigue critical applications for titanium components for which castings provide a low-cost alternative. It is the purpose of the present work to investigate possibilities of improving the fatigue life of castings allowing use in components with more stringent mechanical property requirements. The approach used was to heat treat both straight castings and HIP'd castings to different microstructural conditions. Generally, the cast structure of alpha/beta titanium alloys consists of a coarse transformed beta structure. It typically exhibits large beta grains separated by grain boundary alpha phase and colonies of similarly aligned and crystallographically-oriented alpha plates within the beta grains[9]. The microstructure is known to produce early fatigue crack initiation[9,10] by a mechanism of intense shear band formation across the colonies[11,12]. In essence it was the goal of this work to modify the microstructure of cast and cast+HIP material so that the propensity to produce the cross-colony shear would be reduced. An attempt was also made to break-up the continuous alpha/beta interface along the prior beta grain boundary alpha phase since previous works[6,13] showed that these can also be locations for early crack initiation.

The microstructure are shown in Figure 3 2 83 a to f. The objective of both heat treatment B and C was to break up the large colony structure by significantly reducing the amount of alpha present at the solutioning temperatures, 960°C (1760°F) and 1005°C (1840°F) followed by water quench to prevent further alpha colony formation.



Influence of Heat Treatment on Fatigue properties of Ti-6Al-4V

Fig3 2.82

EXPERIMENTAL PROCEDURES AND RESULTS

Material

The castings used in this work were divided into two main groups: those which were cast and those which were HIP'd after casting. All micro-structural modifications and tests were made simultaneously on these two groups.

The chemical analysis of the castings was as follows (Wt. Pct.):

	Al	V	Fe	C	N_2	O_2	N_2
Cast	6 2	4 0	.15	.03	032	.227	0028
Cast+HIP	6.3	4 0	14	.02	.032	.242	0031

Due to the high oxygen level, the beta transus temperature was estimated to be at 1010°C (1850°F).

The Cast and Cast+HIP material were tested in three conditions:

A. As received
B. 960°C (1760°F)/1 hr/WQ + 760°C (1400°F)/4 hrs/ AC—Condition 1
C. 1005°C (1840°F(/1 hr/WQ + 760°C (1400°F)/4 hrs/ AC—Condition C3

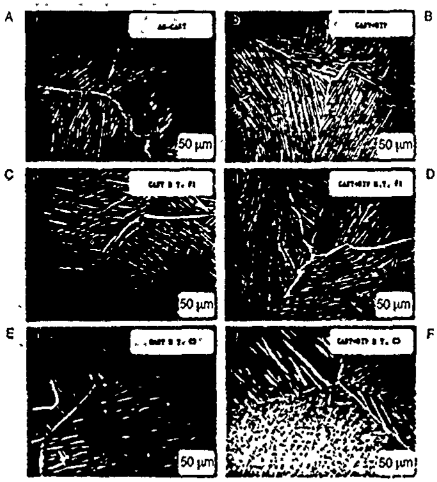
Testing

From the Cast and Cast+HIP bars, cylindrical tensile/ fatigue specimens were machined. Gauge area dimensions were 5mm (.2 inches) diameter × 50mm (2 inches) length and the total specimen length was 75mm (3 inches) with 12.5mm (.5 inches) thread diameter. Those specimens were used both for tensile and fatigue testing.

Tensile tests were performed on an Instron machine with the crosshead speed of 0 05 in./min.$^{-1}$. The tensile test results are shown in Table 3 2.84.

Fatigue tests were performed on an MTS Servohydraulic Test Machine. Triangular waveform cyclic load was used at 5Hz with R = 0 1 (R = minimum load/maximum load)

The fatigue S-N curves for all six test conditions are shown in Figures 3 2 85 through 3 2.90. These curves show all the individual data points as well as the boundaries of the scatterband. Figure 3.2 91 shows the summary plot of average fatigue curves for all six conditions.



Microstructures of Conditions Used in This Work:

a) As-Cast
b) Cast+HIP
c) Cast+960°C (1760°F) Solution Treatment
d) Cast+HIP+960°C (1760°F) Solution Treatment
e) Cast+1005°C (1840°F) Solution Treatment
f) Cast+HIP+1005°C (1840°F) Solution Treatment

Fig. 3 2 83

Table 3 2 84
Tensile Test Results of Material Used in this Work

	Y.S		U.T.S.		El	RA	Number Of Specimens Tested
	MN/m²	(Ksi)	MN/m²	(Ksi)	Pct.	Pct.	
As-Cast	895	(130)	1000	(145)	8	16	2
Cast+HIP	890	(129)	395	(136)	5	16	2
Cast+960°C (1760°F)	990	(144)	1025	(149)	4	8	3
Cast+HIP+960°C (1760°F)	1020	(148)	1040	(151)	4	13	2
Cast+1005°C (1840°F)	935	(136)	970	(141)	1	11	2
Cast+HIP+1005°C (1840°F)	725	(105)	880	(128)	1	5	2

Discussion

As expected from previous work, the Cast+HIP alloy exhibited better fatigue lives than the Cast material[5,6]. The fatigue limit (5×10^6) for As-Cast material was 275 MN/m² (40 Ksi), while that for the Cast+HIP was 415 MN/m² (60 Ksi).

The heat treatment work was successful in reducing the amount of primary alpha plates of the original Cast or Cast+HIP colony structure (Figure 3.2 83) with increasing solution treatment temperature. However, by examining the fatigue curves and especially the summary curve of the average fatigue lives, it seems that only in the case of As-Cast material has an improved fatigue life been attained.

The Cast C3 condition with the smallest amount of primary alpha, has the best average high cycle fatigue life, with a curve very close to the Cast+HIP condition. At the same time, condition No.1 shows better average fatigue life in the low cycle region (below 10^5 cycles), with average values approaching those of the Cast+HIP the two heat treatments lowered the average fatigue lives.

Based on previous works on fatigue crack initiation in Cast[5] and Cast+HIP[6] Ti-6Al-4V, it is known that the prior grain boundary alpha is one of the major contributors to early fatigue crack initiation[13]. It is evident from the microstructures shown in Figure 3 2.83 that grain boundary alpha plates still exist in the microstructure even in the 1005°C solution-treated material Future work will be directed toward eliminating these microstructural features through a beta solution treatment.

Acknowledgement

The authors wish to acknowledge Mr Glenn Lovell from Metcut for his assistance in the fatigue testing Parts of this work were done under USAF Contract #F33615-79-C-5152.

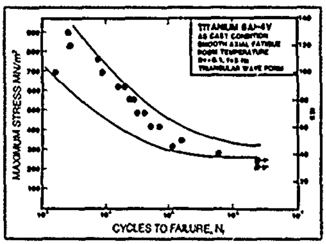


Fig 3 2 85

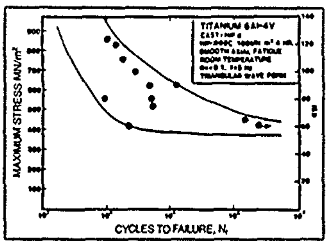


Fig 3 2 86

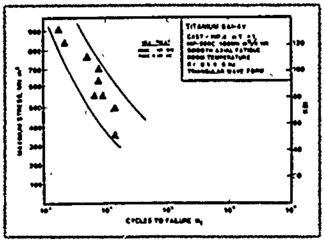


Fig 3 2 87

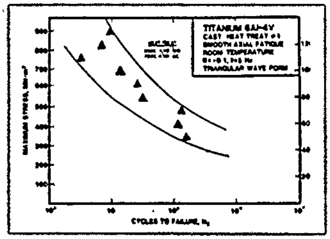


Fig 3 2 88

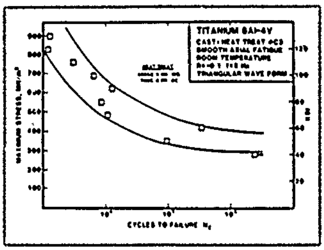


Fig 3 2 89

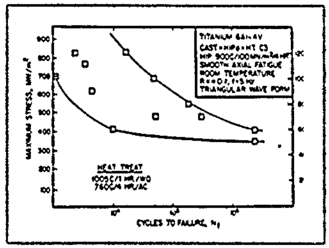


Fig 3 2 90

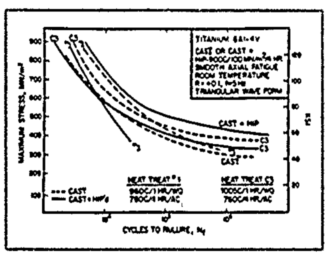


Fig 3 2 91

References (mentioned in Report 10)

1. Jaffee RI
"An Overview on Titanium Development and Application", *Ti '80 Science and Technology*, Ed. by H Kimura and O Izumi, TMS-AIME Publication, Warrendale, PA, 1980, pp.53–74.

2. *Titanium for Energy and Industrial Applications*, Ed. D.Eylon, to be published in 1982 by TMS-AIME.

3. Eylon D, Field M, Froes FH, Eichelman GE
"Manufacture of Cost-Affordable High Performance Titanium Components for Advanced Air Force Systems", Proceedings of the 26th National SAMPE Symposium, April 1981, pp.356–367, also SAMPE Quarterly, April 1981, pp.19–25.

4. Tupper NG, Elbaum JK, Burte HM
"Opportunities of Cost-Affordable Titanium Aerospace Structures", *Journal of Metals*, Vol 30, (1978), pp 7–13.

5. Eylon D, Strope B
"Fatigue-Crack Initiation in Ti-6Al-4V Castings", *Journal of Material Science, 14*, (1979), pp.345–353

6. Eylon D
"Fatigue Crack Initiation in Hot Isostatically-Pressed Ti-6Al-4V Castings", *Journal of Materials Science, 14*, (1979), pp 1914–1922.

7. Froes FH, Eylon D, Eichelman GE, Burte HM
"Developments in Titanium Powder Metallurgy", *Journal of Metals, 32*, February (1980), pp. 47–54.

8. Kelto CA, Kosmal BA, Eylon D, Froes FH
"Titanium Powder Metallurgy – A Perspective", *Powder Metallurgy of Titanium Alloys*, TMS–AIME Publications, (1980), pp 1–19.

9. Eylon D
"Faceted Fracture in Beta-Annealed Titanium Alloys", Metallurgical Transactions A, 10A (1979), pp.311–317.

10. Eylon D, Bania PJ
"Fatigue Cracking Characteristics of Beta-Annealed Large Colony Ti-11 Alloys", Metallurgical Transactions A, 9A (1978), pp 1273–1279.

11. Shechtman D, Eylon D
"On the Unstable Shear in Fatigue Beta-Annealed Ti-11 and IMI-685 Alloys", Metallurgical Transactions A, 9A (1978), pp 1018–1020.

12. Davidson DL, Eylon D
"Titanium Alloy Fatigue Fracture Facet Investigation by Selected Area Electron Channeling", Metallurgical Transaction A, 11A (1980), pp 837–843

13. Eylon D, Kerr WR
"The Fractographic and Metallographic Morphology of Fatigue Initiation Sites", ASTM STP 645, *Fractography in Failure Analysis*, ASTM Publication, Philadelphia, PA, (1978), pp 235–248.

Fatigue Properties Report (acc. to 11) (Howmet Report)
Fatigue Properties are of increasing interest as cast titanium is specified in many fatigue-sensitive applications. Figures 3 2.92 through 3 2 94 show high cycle fatigue properties as influenced by HIP, stress ratio and test temperature. Low cycle fatigue results (Figure 3 2.95) also show the benefits of HIP. Note in this figure the dramatic reduction of scatter in the test results from HIP'd material

Reports of decreased fatigue strength attributed to HIP usually result from tests of defect-free specimens which have been HIP'd or exposed to thermal cycling to simulate the HIP cycle. These specimens are comprised of less coarse microstructure than material which has been HIP'd and could exhibit greater fatigue endurance because of the microstructural difference. However, test programs which evaluate porosity-containing non-HIP samples and fully dense HIP material demonstrate improved endurance limits and reduction in scatter of data for the HIP-processed material (Figure 3 2.96 through 3.2.101).

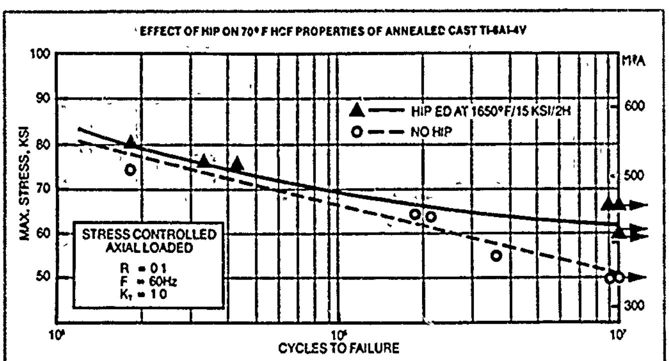


Fig 3 2.92

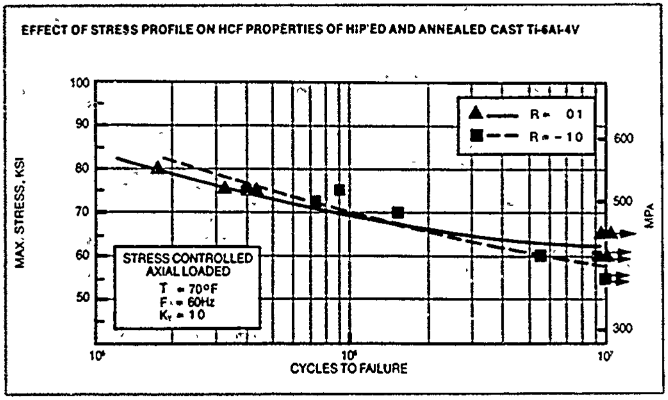


Fig 3 2 93

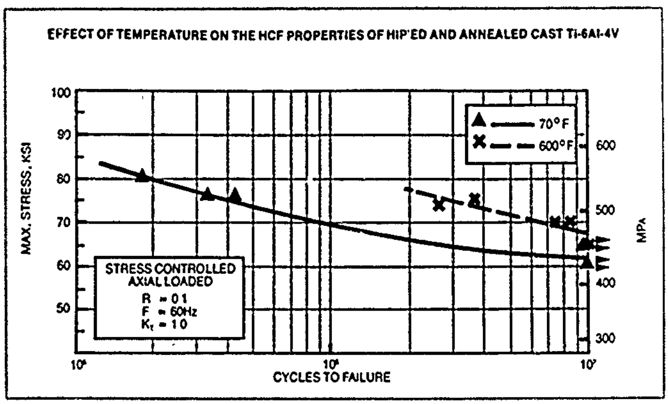


Fig 3 2 94

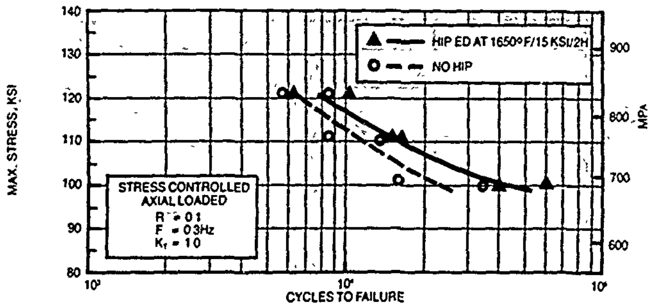


Fig 3 2 95

STATISTICAL ANALYSIS OF FATIGUE DATA.

In order to prepare a probability analysis from a set of fatigue data, the data is manipulated mathematically to extrapolate each individual result to an "equivalent stress at 10^7 cycles". The linear least squares fit through all data points in a set of fatigue data is determined. This slope is maintained constant, and used to extrapolate each individual data point to 10^7 cycles. Treating each data point in this manner develops a set of values for stress at 10^7 cycles which can then be used to develop the probability plot shown in Figure

LINEAR REGRESSION ANALYSIS

$$Y = mX + b$$

$Y = \log_{10}\sigma$

$X = \log_{10} Nf$

$$m = \frac{\Sigma xy - \frac{\Sigma x \Sigma y}{n}}{\Sigma x^2 - \frac{(\Sigma x)^2}{n}}$$

$$b = \frac{\Sigma y}{n} - \frac{m \Sigma x}{n}$$

STRESS VARIABILITY AT 10^7 CYCLES

$$S = m(x_0 - x_1) + y_1$$

$S = \log_{10}\sigma$ at 10^7 cycles

m = slope (from above)

$X = \log_{10} 10^7$ cycles = 7.00

$X_1 = \log_{10} Nf$

$Y_1 = \log_{10}\sigma$

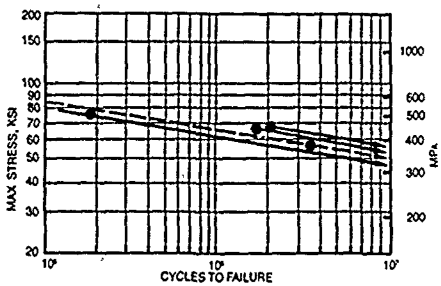
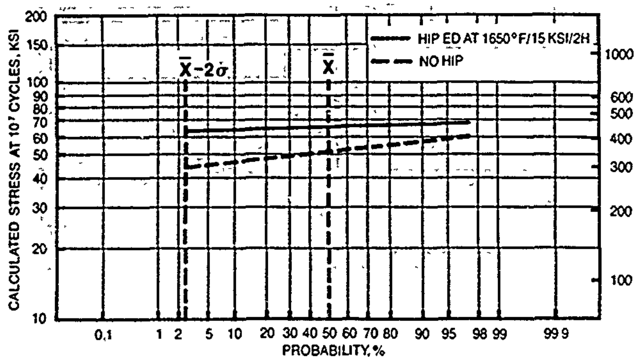


Fig 3 2 96

70°F HCF STRENGTH DISTRIBUTION OF ANNEALED CAST Ti-6Al-4V.

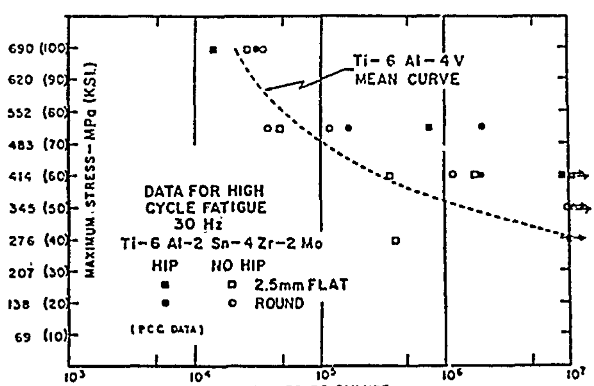
This figure shows both an improvement in endurance limit at 10^7 cycles and a significant increase in ($\bar{x} - 2\sigma$) values for HIP ed material.



MATERIAL ANNEALED AT 1550°F/2H/FC TESTED AT A = 0.99 AND F = 60 Hz

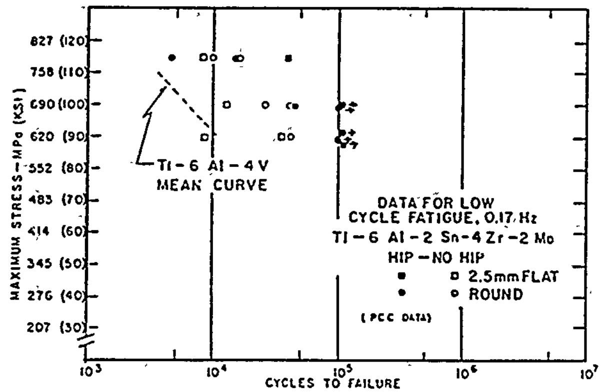
Fig 3.2.97

Fatigue Properties Report acc. to 12)



High Cycle Fatigue Properties of Titanium Alloy Before and After HIP.

Fig 3.2.98



Low Cycle Fatigue Properties of Titanium Alloy Before and After HIP.

Fig 3 2 99

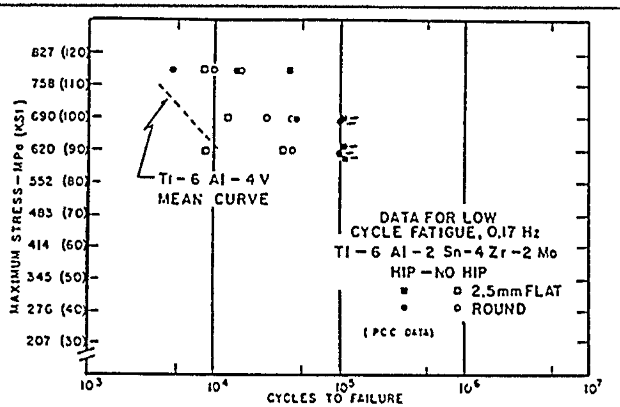


Fig 3 2.100 Low Cycle Fatigue Properties of Titanium Alloy
Before and After HIP.

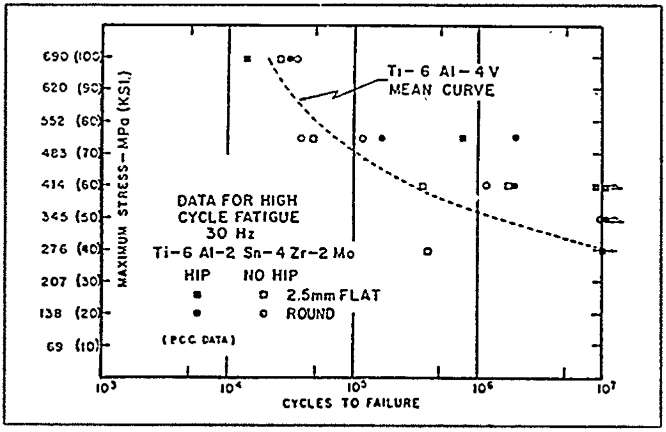


Fig 3 2 101 High Cycle Fatigue Properties of Titanium Alloy Before and After HIP.

Sources for Section 3.2.3

Report No.

1 WST-M-Programm, MBB, Germany — 1982
5. Review, AP 1215

2. Cereast Report, QETE E002484 (Q9–7) — 1984
Annex "A"

3. Alcoa Product Manual
Premium Castings Division of Aluminium Company of America, Corona, California — 1972

4. Apendix of Northrop-Letter 3872-84-124 — 1984
Diagram of Fatigue Life Cycles of A357-T6 Alloy

5. Apendix of Northrop-Letter 3872-84-124 — 1984
Diagram of Fatigue Life Cycles of A201-T7 Alloy

6. Prelimanary Properties of Alloy K0-1
L.B Hallowel, submitted by St. Kennerknecht, Cercast — 1984

7. Northrop Corporation Report 3872-92-111 — 1982

8. WST-M-Programm, MBB, Germany — 1985
7 Review, AP 122, Titangußtechnologie

Figure 3 2 70:
P.Merrien: "Compression isostatique a chand des pieces conlees en allinges de titane"
Materiaux et techniques Nov.–Dez. 1977

Figure 3 2.71:
J.C.Bittence: "HIP, the great healer of castings"
Journal Materials, Eng. Okt. 1978

Figure 3 2.72:
G.M Glenn: "Improved properties in castings by hot isost. pressing"
Sampe Quarterly, Okt. 1976

Figure 3 2 73.
The mechanical and metallurgical assessment of hot isostatically pressed Ti-6Al-4V Cast Alloy
British Aerospace, Report No MDR 0331-1980

Figuré 3 2.74.
R H Colley: Engineer's guide to Titanium Castings
Technical Report Titech Comp. — 1984

Figure 3 2.75 and Figure 3 2.76:
R M Nagen: "Compendium of cast properties of Ti-6Al-4V
Techn. Report, May 1975

Figure 3 2.77: La Fondene sons vide du Titane et de ses Allinges
Report Messier Fondery, d'Arndy, France, Okt 1977

Figure 3 2.78 and Figure 3 2.79:
W G Hansen. "Die Anwendung von Titangußteilen im MRCA-Triebwerk
RB 199 Z., Werkstofftechnik 11, 1975

Figure 3 2 80 and Figure 3 2.81:
Aerospace structural handbook
Ti-6Al-4V cast, March 1970

9. Journal of Metals, Vol. 35, No. 2, Febr. 1983 — 1983

10. Effect of processing on fatigue Life of Ti-6Al-4V Castings

F.C.Teifke, Tiline Inc., Albany, Oregon
N H.Marshall, Tiline Inc., Albany, Oregon

D Eylon, Metcut-Materials Research Group, W-PAFB, Ohio, 45433

F H Froes, Structural Metals Branch
Materials Lab. AFWAL, WPAFB, Ohio 45433

11. Howmet Corporation, Technical Bulletin, TB1660

12 R.Widner: "Densification of castings by hot isostatic pressing", Report

3.2.4 Crack Propagation and Fracture Toughness

See chapter 6.

3.3 EYE BOLT JOINTS

Since many castings have concentrated load introductions formed as "eye bolt joints", it is necessary to know how the efficiency factors (for the lug stress calculation) look with regard to advanced casting alloys.

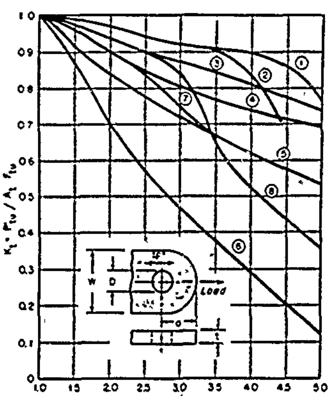
Some information is given in the report "Development in the Analyses of Lugs and Shear Pins", published by Product Engineering—June, 1983. According to this only the factor Kt (for tension) depends on the material used for the casting

All other factors:
Kbr – for shear-bearing
Ktru – for transverse load (ultimate)
Ktry – for transverse load (yield)

depend on the lug's geometry such as:
- thickness
- width
- outer radii
- bolt diameter

etc.

Because of missing data about the efficiency factor "Kt" with respect to the advanced casting alloys, this handbook can give only the value for the casting alloy A356 T6 (Fig.3 3 1) for the first lug definition A test is necessary to determine the assumption



CURVE 1:
4130 and S630 steel
14S-T6 and 75S-T6 plate ≤0 5 in. (L, T)
75S-T6 bar and extrusion (L)
14S-T6 hand forged billet ≤144 sq in. (L)
14S-T6 and 75S-T6 die forgings (L)

CURVE 2
14S-T6 and 75S-T6 plate > 0 5 in. ≤1 in
75S-T6 extrusion (T, N)
75S-T6 hand forged billet ≤36 sq in. (L)
14S-T6 hand forged billet > 144 sq in. (L)
14S-T6 hand forged billet ≤36 sq in. (T)
14S-T6 and 75S-T6 die forgings (T)

CURVE 3.
24S-T6 plate (L, T)
24S-T4 and 24S T42 extrusion (L, T, N)

CURVE 4
24S-T4 plate (L, T)
24S-T3 plate (L, T)
14S-T6 and 75S-T6 plate > 1 in (L, T)
24S-T4 bar (L, T)
75S-T6 hand forged billet > 36 sq in. (L)
75S-T6 hand forged billet ≤16 sq in. (T)

CURVE 5:
195T6, 220T4, and 356T6 aluminum casting
75S-T6 hand forged billet > 16 sq in. (T)
14S-T6 hand forged billet > 36 sq in. (T)

CURVE 6:
Aluminum alloy plate, bar, hand forged billet, and die forging (N). Note: for die forging, N direction exists only at parting plane.
75S-T6 bar (T)

CURVE 7.
18-8 stainless steel, annealed

CURVE 8
18-8 stainless steel, full hard Note. for 1/4, 1/2 and 3/4 hard, interpolate between curves 7 and 8.

LEGEND. L, T, and N indicate grain in direction F in sketch
L – longitudinal
T – long transverse
N – short transverse (normal)

Fig 3 3 1 Values of tension efficiency factors of lugs fabricated from typical steel and aluminum alloy materials produced by different manufacturing processes.

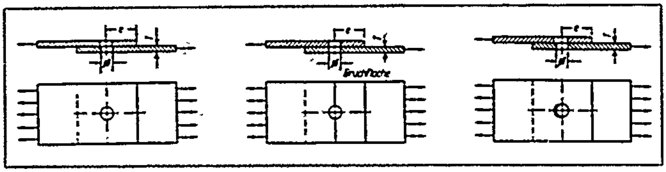


Fig 3.4.1 Failure modes of riveted joints under static loading, left: shear failure of the rivet shank; middle: tensile failure of the component material; right: hole wall failure or distortion in the component material
Bruchfläche . . . fracture surface

3.4 RIVETED JOINTS

If structural components made of aluminium casting alloys are to be used in aircraft construction, it is necessary, among other things, that they should be joined together by mechanical fasteners. A pre-requisite for this is that the static and fatigue strengths of such joints should be determined using riveted testpieces, and compared against those characteristics of riveted wrought aluminium alloys. Since up to now no information has been available concerning riveted joints in aluminium casting alloys, the static and dynamic strength of such joints were determined as part of the programme on *Low-cost Structure Technologies — Metallic Materials*[1]. An account will now be given of the results obtained.

3.4.1 Static Strength of Riveted Joints in Aluminium Casting Alloys

The strength of a riveted joint depends largely on the strength of the component material (breaking strength, hole bearing strength), the type of rivet, its make, the shape of the rivet head, and the rivet material. In static loading, rivets fail for three principal reasons (Fig.3.4.1)

- Shear failure of the rivet shank
- Tensile failure of the component material
- Failure or distortion of the hole walls.

To determine the strength of riveted testpieces in static tests, sectional overlap joints of the type shown in Fig.3.4.2 were prepared and loaded to failure according to predetermined load/time relationship. Examples of the various rivet fasteners for static and fatigue loading are given in Figure 3.4.3 and Table 3.4.4.

Fastener	Test	Total no. of testpieces
Aluminium solid rivet/countersunk head	static	20
Aluminium-solid rivet/universal head	tensile	20
Monel-solid rivet/countersunk head	tests	20
Titanium-solid rivet/countersunk head		20
Huck-blind rivet/countersunk head		16
B Cherrylock-blind rivet/countersunk head		16
Hi-Lok-special fastener/countersunk head		12
Lockbolt-special fastener/countersunk head		12

Fig 3.4.2 Testpiece and test for determining the static strength of riveted joints

The measurements of these testpieces, the loading cycle, and the evaluation of the results obtained are described in the MIL-STD-1312 specifications. In these tests the deformation characteristics of the riveted joints were determined in addition to the breaking load. According to the specifications in force, any riveted joint that had undergone permanent plastic deformation of 4% (referred to the rivet diameter) was considered as no longer functional. To determine this critical deformation, the deformation taking place during the loading must be measured and the type of distortion relevant to the dimensions in question picked out.

Results

Table 3.4.5 summarizes the results of the static tests. Testpieces prepared using aluminium alloy solid rivets failed mainly by shearing of the rivet shank. In those riveted using Monel and titanium solid rivets, the most common cause of the failure was hole wall splitting, because of the higher shear strength of the rivets. Joints formed with blind rivets and special fasteners (screw rivets) showed hole wall failure, or a combination of this with tensile failure.

To achieve a comparison of the strengths of riveted joints in the aluminium casting alloy A357-T6 against those of wrought alloys, the results obtained were compared with those of the aircraft industry design calculation for the wrought alloys 3.1364-T3 (2024-T3 aluminium-magnesium-copper alloy). The comparison revealed that the calculation values determined for almost all the testpieces were as high as, or higher than those relevant to the wrought alloys. In joints with blind rivets or special fasteners (rivet bolts), the values determined were lower than for the wrought alloys. The reason for the less favourable behaviour of joints formed with blind or special rivets may be that such fasteners, made of steel or titanium, endow the testpieces with essentially higher rigidity than in the case of joints formed using solid rivets made of softer materials.

During static tensile stressing, extremely high additional bending stresses (secondary bending) are produced in sectional riveted joints of this type. With solid-rivet joints, the softer rivet material allows a degree of plastic deformation, and this reduces the amount of secondary bending. With more rigid rivets of steel or titanium alloys this reduction cannot take place, and fracture of the

Fig.3a: Aluminium alloy solid rivet with countersunk head according to LN 9199; 1 seating head, 2 closing head, 3 shank.

Fig.3b: Aluminium alloy solid rivet with universal head according to LN 9198; 1 seating head, 2 closing head, 3 shank.

Fig.3c: Monel solid rivet with countersunk head according to LN 9179; 1 seating head, 2 closing head, 3 shank.

Fig.3d. Pure titanium solid rivet with countersunk head according to NSA 5410; 1 seating head, 2 closing head, 3 tapered shank, 4 cylindrical shank.

Fig.3e: Alloy steel blind rivet with countersunk head (1 Huck type B 100-T according to MS 90353); 1 retaining ring, 2 break point, 3 rivet sleeve, 4 shank.

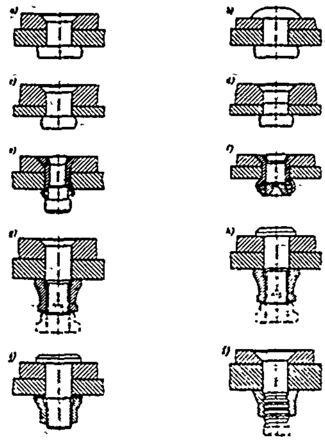
Fig.3f. Aluminium and steel alloy blind rivet with countersunk head (Bulbed-Cherrylock type CR 2248 according to NAS A39 B); 1 fixing ring, 2 break point, 3 sleeve, 4 closing collet, 5 shank.

Fig.3g: Titanium alloy screw rivet with countersunk head and aluminium alloy closing ring (Hi-Lock according to Prod. Specification M340); 1 shank, 2 closing collet, 3 hexagonal recess, 4 break point.

Fig.3h. Titanium alloy screw rivet with universal head and aluminium alloy closing collet (Hi-Lok type according to Prod. Specification M342); 1 shank, 2 closing collet, 3 hexagonal recess, 4 break point.

Fig.3i: Special alloy steel fastener with countersunk head and aluminium alloy closing collet (Lockbolt type according to NAS 1436-38); 1 shank, 2 break point, 3 closing collet.

Fig.3j: Alloy steel screw rivet with universal head and alloy steel closing collet (Taper-LOK type according to manufacturer's spec.), 1 tapered shank, 2 washer, 3 closing collet.



Figs 3a to j: various solid, blind, and special rivet fasteners for static and fatigue testing.

Fig 3.4.3

Table 3 4 4
Materials for fasteners and closing collets

Fig. no.	Rivet type	Rivet material German designation	Rivet material US designation	Strength in N/mm² R_m	Strength in N/mm² R_p	Closing collet designat.	Closing collet material German designat.	Closing collet material US designat.	R_m in N/mm²	Nominal diameter for static and fatigue tests*) 4.0	4.8	6.4
3a	Solid rivet LN 9199	3.1324.4	2024	≈ 300	≥260	–	–	–	–	+	O +	+
3b	Solid rivet LN 9198	3.1324.4	2024	≈ 300	≥260	–	–	–	–	+	O +	+
3c	Solid rivet LN 9197	2.4360.1	Monel	≈ 630	≥360	–	–	–	–	+	+	
3d	Solid rivet NSA 5410	3.7024	Pure Titanium T40	≈ 400	≥380	–	–	–	–	+	+	
3e	Blind rivet Huck B 100 T	Collet 1.7704 Rivet shank 1.7704	AISI 4037**) AISI 8740**)	≥1100 ≥1100	≥670 ≥670	–	–	–	–	+	+ O	+
3f	Blind rivet Cherry Bulbed	Collet 3.3354 Rivet shank 1.7704	5056 AISI 8740**)	≈ 300 ≥1100	≥170 ≥670	–	–	–	–		+	
3g	Screw rivet Hi-Lok Countersunk head	3.7164	Ti-6Al-4V	≥1100	≥670	HL 70	3.1364	2024	≈ 400		+	+
3h	Screw rivet Hi-Lok Universal head	3.7164	Ti-6Al-4V	≥1100	≥670	HL 70	3.1364	2024	≈ 400			O
3i	Special fastener Lockbolt	1.7704	AISI 8740**)	≥1100	≥670	4LC-C	3.1364	2024	≈ 400		+	+
3j	Screw rivet Taper Lok	1.7704	AISI 8740**)	≥1100	≥670	TLM 1001	1.7704	AISI 8740**)	≥1100			O

*) + static tests O fatigue tests. **) Material only approximately coded.

Table 3.4.5

Results of the main static tests, testpiece material A357-T6, testpiece geometry MIL-STD-1312 computation value = fracture strength or 1.5 deformation value

Testpiece designation	Fastener type	Material	Standard	Deformation value in N	Fracture value in N	Computation value in N	Computation value in N	Wrought alloy standard	Type of failure
AS 1/1	Solid rivet	3.1324.4	LN 9199	5 820	7 320	7 320	6 480	LN 29731	1
AS 1/3	Ø 4.0 countersunk			5 960	7 200	7 200	6 480	resp	1
AS 1/4				6 120	7 480	7 480	6 480	HSB 21121-01	1
AS 1/5				5 600	7 220	7 220	6 480		1
AS 2/1	Solid rivet	3.1324.4	LN 9199	*)	9 820	9 820	8 500	LN 29731	1
AS 2/2	Ø 4.8 countersunk			*)	10 800	10 800	8 500	resp	1
AS 2/3				*)	10 880	10 880	8 500	HSB 21121-01	1
AS 2/4				7 680	10 320	10 320	8 500		1
AS 2/5				7 000	9 880	9 880	8 500		1
AS 3/1	Solid rivet	3.1324.4	LN 9199	8 080	10 880	10 880	9 800	LN 29731	1
AS 3/2	Ø 4.8 countersunk			8 080	10 880	10 880	9 800	resp	1
AS 3/3				8 120	10 640	10 640	9 800	HSB 21121-01	1
AS 3/4				*)	10 720	10 720	9 800		1
AS 3/5				*)	10 640	6 180	9 800		1
AS 4/1	Solid rivet	3.1324.4	LN 9199	16 000	17 000	17 000	17 000	LN 29731	1
AS 4/2	Ø 6.4 countersunk			15 800	18 800	16 800**)	17 000	HSB 21121-01	1
AS 4/3				*)	15 200	15 200**)	17 000		1
AS 4/4				15 980	18 320	18 320	17 000		1
AS 4/5				15 800	16 400	15 400**)	17 000		1
AU 1/1	Solid rivet	3.1324.4	LN 9198	7 200	9 180	8 160	6 700	LN 29730	1
AU 1/2	Ø 4.0 universal			7 080	7 840	7 840	6 700	HSB 21111-01	1
AU 1/3				7 040	7 880	7 880	6 700		1
AU 1/4				7 140	7 820	7 820	6 700		1
AU 1/5				7 080	7 880	7 880	6 700		1
AU 2/1	Solid rivet	3.1324.4	LN 9198	*)	10 800	10 800	9 600	LN 29730	1
AU 2/2	Ø 4.8 universal			*)	10 320	10 320	9 600	HSB 21111-01	1
AU 2/3				*)	10 640	10 640	9 600		1
AU 2/4				*)	10 230	10 230	9 600		1
AU 2/5				*)	10 640	10 640	9 600		1
AU 3/1	Solid rivet	3.1324.4	LN 9198	9 920	10 400	10 400	9 600	LN 29730	1
AU 3/2	Ø 4.8 universal			8 640	10 200	10 200	9 600	HSB 21111-01	1
AU 3/3				8 160	10 200	10 200	9 600		1
AU 3/4				8 400	10 280	10 280	9 600		1
AU 3/5				8 480	10 400	10 400	9 600		1
AU 4/1	Solid rivet	3.1324.4	LN 9198	16 240	17 880	17 880	17 000	LN 29730	1
AU 4/2	Ø 6.4 universal			16 640	17 280	17 280	17 000	HSB 21111-01	1
AU 4/3				16 640	16 780	16 780**)	17 000		1
AU 4/4				16 240	16 400	16 400**)	17 000		1
AU 4/5				16 320	16 480	16 480**)	17 000		1
MS 1/1	Solid rivet	Monel	LN 9179	7 120	10 000	10 000	8 480	LN 29731	2
MS 1/2	Ø 4.0 countersunk	2.4360.1		6 800	9 400	9 400	8 480	HSB 21221-01	2
MS 1/3				7 540	9 200	9 200	8 480		2 and 3
MS 1/4				7 280	10 160	10 160	8 480		2
MS 1/5				7 300	8 680	8 680	8 480		2 and 3
MS 2/1	Solid rivet	Monel	LN 9179	*)	12 480	12 480	10 000	LN 29731	2
MS 2/2	Ø 4.8 countersunk	2.4360.1		*)	12 240	12 240	10 000	HSB 21111-01	2
MS 2/3				7 600	11 800	11 800	10 000		2 and 3
MS 2/4				8 080	12 400	12 120	10 000		2 and 3
MS 2/5				6 880	10 840	10 320	10 000		2 and 3
MS 3/1	Solid rivet	Monel	LN 9179	8 660	10 260	10 260	8 640	LN 29731	2 and 3
MS 3/2	Ø 4.0 countersunk	2.4360.1		8 840	11 360	11 380	8 640	HSB 21111-01	2 and 3
MS 3/3				8 760	11 700	11 700	8 640		2 and 3
MS 3/4				8 120	10 600	10 600	8 640		2 and 3
MS 3/5				8 560	10 800	10 800	8 640		2 and 3
MS 4/1	Solid rivet	Monel	LN 9179	13 840	16 800	16 800	12 400	LN 29731	1
MS 4/2	Ø 4.8 countersunk	2.4360.1		12 640	16 360	16 360	12 400	HSB 21111-01	1
MS 4/3				12 980	16 480	16 480	12 400		1
MS 4/4				12 920	16 360	16 360	12 400		1
MS 4/5				13 000	16 480	16 480	12 400		1
HSB 3/1	Huck blind rivet	Alloy steel	MS 90353	7 040	12 820	10 560**)	16 800	HSB 21440-01	3
HSB 3/2	Ø 4.8 countersunk	AISI 4037		8 200	14 720	12 300**)	16 800		3
HSB 3/3				7 400	14 000	11 100**)	16 800		2 and 3
HSB 3/4				7 280	14 800	10 920**)	16 800		3
HBS 4/1	Huck blind rivet	Alloy steel	MS 90353	20 200	37 100	30 300**)	38 800	HSB 21440-01	2 and 3
HBS 4/2	Ø 6.4 countersunk	AISI 4037		20 200	33 800	30 300**)	38 800		2 and 3
HBS 4/3				20 000	36 600	30 000**)	38 800		2 and 3
HBS 4/4				17 600	34 300	26 400**)	38 800		2 and 3
CBS 1/1	B Cherry blind rivet	Al/steel	PAN 3021	3 700	6 800	5 550**)	6 520	HSB 21460-01	2
CBS 1/2	Ø 4.0 countersunk		CR 2248	3 920	6 780	5 880**)	6 520		2
CBS 1/3				4 140	6 720	6 110**)	6 520		1 and 2
CBS 1/4			PAN 3021	3 840	6 860	5 760**)	6 520		2
CBS 2/1	B Cherry blind rivet	Al/steel	CR 2248	3 780	8 270	5 640**)	7 380	HSB 21460-01	2
CBS 2/2	Ø 4.8 countersunk	Al/steel		4 040	9 480	6 060**)	7 380		2
CBS 2/3				*)	7 400	–	7 380		2
CBS 2/4				3 840	6 800	5 760**)	7 380		2
CBS 3/1	B Cherry blind rivet		PAN 3021	4 560	10 640	6 840**)	9 540	HSB 21460-01	2
CBS 3/2	Ø 4.8 countersunk		CR 2248	5 160	10 780	7 740**)	9 540		2
CBS 3/3				5 200	10 700	7 800**)	9 540		2
CBS 3/4				5 280	10 920	7 920**)	9 540		2

Table 3.4 5 continued

Testpiece designation	Fastener type	Material	Standard	Deformation value in N	Fracture value in N	Computation value in N	Comparison value in N	Wrought alloy standard	Type of failure
HPS 1/1	Hi-Lok fastener	Titanium	DAN 6	7 440	11 380	11 360**)	16 720	HSB 21310-01	2 and 3
HPS 1/2	Ø 4 8 countersunk			7 540	11 840	11 840**)	15 720		2
HPS 1/3				7 640	12 400	11 480**)	15 720		2
HPS 1/4				7 480	13 200	11 190**)	16 720		2
HPS 2/1	Hi-Lok fastener	Titanium	DAN 6	8 520	14 920	13 360**)	19 700	HSB 21310-01	2 and 3
HPS 2/2	Ø 4.8 countersunk			8 560	14 920	12 640**)	19 700		2 and 3
HPS 2/3				8 840	15 400	13 280**)	19 700		2 and 3
HPS 2/4				9 120	15 520	13 680**)	19 700		2 and 3
HPS 3/1	Hi-Lok fastener	Titanium	DAN 6	24 400	38 200	36 800**)	37 400	HSB 21310-0*	2 and 3
HPS 3/2	Ø 6.4 countersunk			24 400	40 000	36 800**)	37 400		2 and 3
HPS 3/3				23 600	38 800	36 400**)	37 400		2 and 3
HPS 3/4				21 800	38 800	32 700**)	37 400		2 and 3
TS 1/1	Solid rivet	Titanium	NSA 5410	7 080	10 720	10 820	8 320	HSB 21141-01	2
TS 1/2	Ø 4.0 countersunk			7 160	10 000	10 000	8 320		2
TS 1/3				6 820	9 840	9 840	8 320		2
TS 1/4				6 820	9 440	9 440	8 320		2
TS 1/5				6 780	9 440	9 440	8 320		2
TS 2/1	Solid rivet	Titanium	NSA 5410	*)	10 800	10 800	10 100	HSB 21141-01	2
TS 2/2	Ø 4 8 countersunk			*)	10 880	10 880	10 100		2
TS 2/3				*)	11 440	11 440	10 100		2
TS 2/4				7 880	12 440	12 440	10 100		2
TS 2/5				*)	11 280	11 280	10 100		2
TS 3/1	Solid rivet	Titanium	NSA 5410	9 400	10 820	10 820	9 040	HSB 21141-01	2 and 3
TS 3/2	Ø 4 0 countersunk			9 300	11 700	11 700	9 040		2
TS 3/3				8 840	11 040	11 040	9 040		2
TS 3/4				9 520	11 520	11 520	9 040		2 and 3
TS 3/5				9 040	12 320	12 320	9 040		1
TS 4/1	Solid rivet	Titanium	NSA 5410	13 120	16 880	16 880	11 600	HSB 21141-01	1
TS 4/2	Ø 4.8 countersunk			11 360	14 160	14 160	11 600		1
TS 4/3				11 200	14 000	14 000	11 600		1
TS 4/4				12 520	15 200	15 200	11 600		1
TS 4/5				11 360	14 000	14 000	11 600		1
HBS 1/1	Huck blind rivet	Alloy steel	MS 90353	3 800	9 640	5 700**)	11 800	HSB 21440-01	2
HBS 1/2	B 100T Ø 4 0	AISI 4037		4 080	9 600	6 120**)	11 800		2
HBS 1/3				4 260	9 880	6 420**)	11 800		2
HBS 1/4				3 680	9 360	5 520**)	11 800		2
HBS 2/1	Huck blind rivet	Alloy steel	MS 90353	3 800	11 280	5 700**)	13 200	HSB 21440-01	2
HBS 2/2	B 100T Ø 4 8	AISI 4037		5 000	11 080	7 500**)	13 200		2
HBS 2/3				4 880	11 280	7 320**)	13 200		2
HBS 2/4				4 120	12 160	6 180**)	13 130		2
LPS 1/1	Lockbolt fastener	Alloy steel	NAS 1436	6 280	12 000	9 380**)	16 400	HSB 21321-01	2 and 3
LPS 1/2	Ø 4 8 countersunk	AISI 4037		7 080	11 880	10 620**)	16 400		2 and 3
LPS 1/3				6 780	11 760	10 170**)	16 400		2 and 3
LPS 1/4				6 780	11 440	10 170**)	16 400		2 and 3
LPS 2/1	Lockbolt fastener	Alloy steel	NAS 1436	7 680	14 120	11 520**)	19 800	HSB 21321-01	2 and 3
LPS 2/2	Ø 4 8 countersunk	AISI 4037		7 840	13 880	11 760**)	19 800		2 and 3
LPS 2/3				9 840	17 600	14 760**)	19 800		2
LPS 2/4				9 980	17 840	14 970**)	19 800		2 and 3
LPS 3/1	Lockbolt fastener	Alloy steel	NAS 1438	22 800	38 000	34 200**)	37 000	HSB 21321-01	2
LPS 3/2	Ø 6 4 countersunk	AISI 4037		21 200	35 200	31 800**)	37 000		2 and 3
LPS 3/3				18 700	35 000	28 050**)	37 000		2
LPS 3/4				21 400	35 700	32 100**)	37 000		2

*) Defective test, **) The computation value for the casting is lower than for the wrought alloy, 1 = shear failure 2 = hole wall failure 3 = tensile failure

testpiece ensues. How great the influence of the plastic behaviour of the rivet can be, is shown by comparing the Huck type of blind rivet (rivet sleeve and rivet shank both of alloy steel) with the Bulbed Cherrylock type (aluminium alloy rivet sleeve, steel shank). Because of the aluminium sleeve, the latter behaves as a softer rivet than the steel Huck rivet, and the test results are more favourable with Bulbed-Cherrylock than with Huck rivets.

A further reason for this unfavourable behaviour in hole wall and tensile failure ranges is that the casting alloy A357-T6 used in this case has a tensile and hole wall bearing strength about 15% lower than that of the aluminium wrought alloy chosen for the comparison.

3.4.2 Fatigue Behaviour of Riveted Joints in Aluminium Casting Alloys

Since the fatigue behaviour of riveted joints depends on many factors, all these influences have to be determined both by theoretical calculation and by comparative fatigue test investigations. To test the influence of the rivet type and the rivet head shape on the fatigue behaviour, the riveted testpieces detailed in Table 3.4 6 were prepared using the casting alloy A357-T6, and tested to failure by pulsed tensile stressing in the fatigue range at a stress ratio of $R = +0.1$

The number of cycles to failure determined in the tests, and the Wöhler diagrams prepared from these data are shown in Figs.3 4.9–3.4.14. In Fig.3.4.15 are shown the positions of fracture. Fig.3.4.8 shows the specimens used for test described here. Examination of the results reveals that with solid rivets the head shape has no significant effect on the fatigue behaviour, and this is true of both types of testpiece, the one with lower load transfer and lower secondary bending, and the one in which both these factors are higher As in the case of wrought alloys, the fatigue resistance of blind rivet joints was slightly less good than that of solid rivet joints.

Table 3 4 6
Comparative fatigue tests on riveted joints
(Nominal diameter 4 8 mm, one stage tests)

Fastener	Testpiece material	R	Hole quality*)	Total no of test pieces	Testpiece type
Solid rivet universal head	Al casting alloy A.367-T6	+0.1	13	12	low load transfer, low secondary bending
solid rivet countersunk		−0.1	13	12	
Huck blind rivet countersunk		−0 1	13	12	
Solid rivet universal head		+0 1	13	12	High load transfer, high secondary bending
Solid rivet countersunk		−0.1	13	12	
Huck blind rivet countersunk		+0.1	11	8	

*) Hole quality 11: wide tolerance range, drilled with two-phase drill, hole quality 13 wide tolerance range, drilled with pointed twist drill

Table 3.4 7
Comparative fatigue tests on riveted joints
(Nominal diameter 6 4 mm, one stage tests)

Fastener	Testpiece material	R	Hole quality*)	Total no. of test pieces	Testpiece type
Hi-lok screw rivet universal head	Al casting alloy A367-T6	+0 1	11	10	low load transfer, low secondary bending
Hi-lok screw rivet, universal head		−0.1	7	10	
Taper-lok universal head		+0.1	7	10	

*) Hole quality 7: narrow tolerance range, reamed, hole quality 11: wide tolerance range, drilled with two-phase drill.

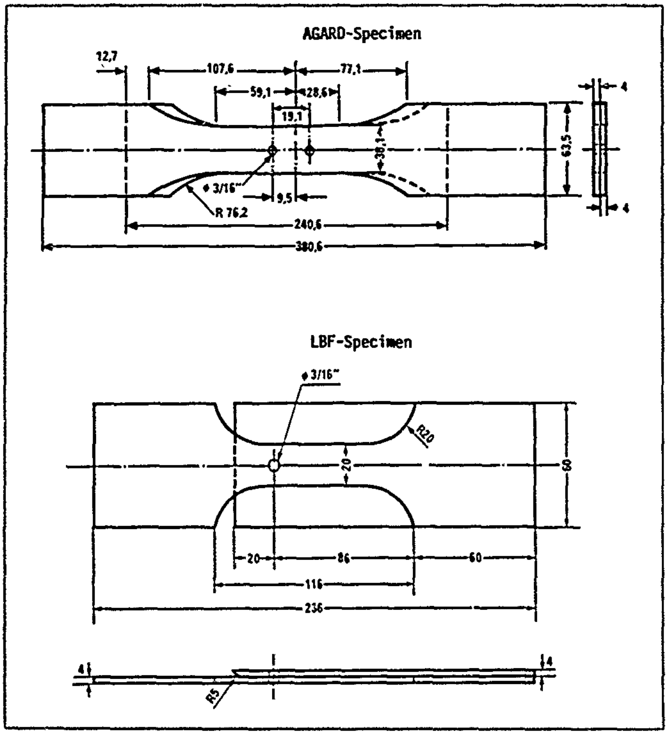
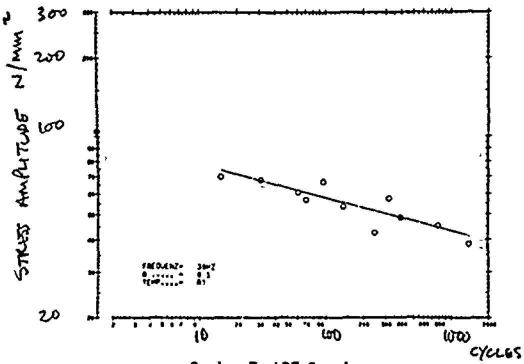
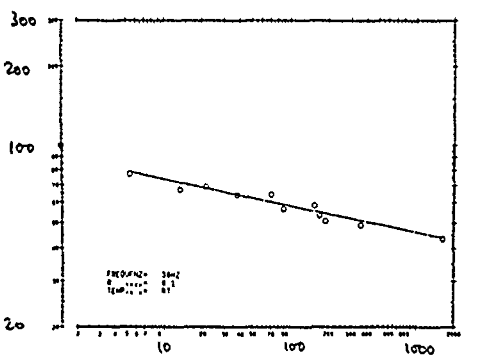


Fig 3.4 8 Types of Specimen



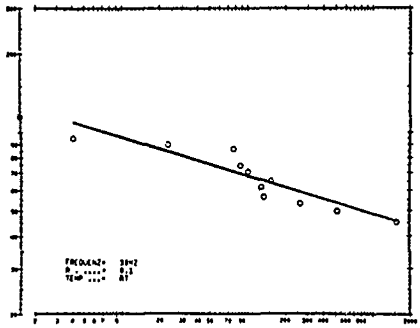
Series T: LBF-Specimen
Casting Alloy A357-T6
Al-Solid Rivet with Universal Head, 4,8 Ø

Fig 3.4.9



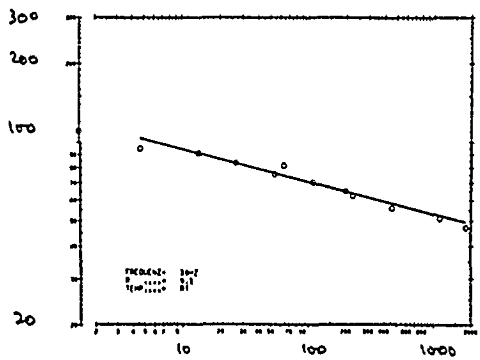
Series U: LBF-Specimen
Casting Alloy A357-T6
Al-Solid Rivet with CSK-Head, 4,8 Ø

Fig 3.4.10



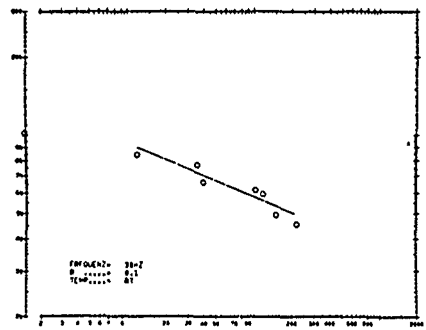
Series W: AGARD-Specimen
Casting Alloy A357-T6
Al-Solid Rivet with Universal Head, 4,8 Ø

Fig 3 4 11



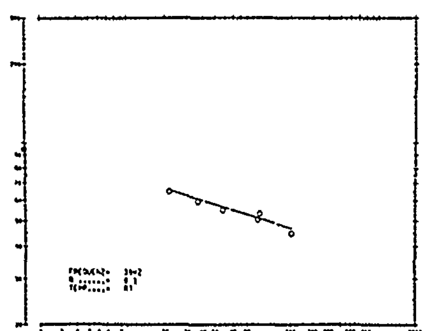
Series X: AGARD-Specimen
Casting Alloy A357-T6
Al-Solid Rivet with CSK-Head, 4,8 Ø

Fig 3.4 12



Series Y: AGARD-Specimen
Casting Alloy A357-T6
Huck-Blind Rivet with CSK-Head, 4,8 Ø

Fig 3.4.13



Series V: LBF-Specimen
Casting Alloy A357-T6
Huck-Blind Rivet with CSK-Head, 4,8 Ø

Fig 3.4.14

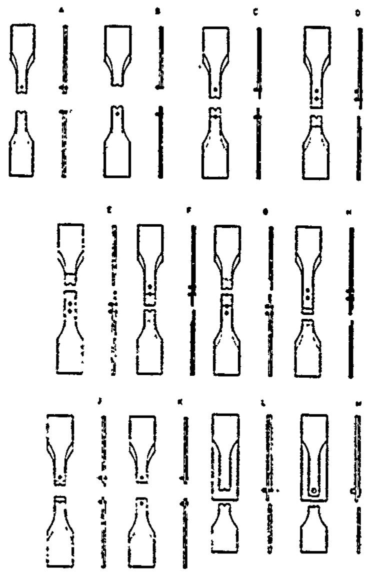


Fig 3 4 15

A comparison of the two forms of testpieces (those with lower, and those with higher load transfer and secondary bending) showed a very small difference in the fatigue strength as compared with similar testpieces made using wrought alloys.

Thus, no direct comparison against wrought aluminium alloys was possible, because no data were available for the latter concerning the rivet diameters and testpiece dimensions used in the present case. To achieve a comparison between wrought and casting alloys as regards the fatigue resistance of riveted joints, the tests carried out earlier with wrought aluminium alloys were repeated using the casting alloy A357-T6 (Table 3.4.7).

To assemble the casting alloy testpieces, the same fasteners were used as in the case of the wrought alloys. The manner of drilling the holes was also chosen to allow a comparison of the fatigue resistance of the two materials. After carrying out fatigue tests with one-stage loading, the following fastener types and stress ratios were compared:

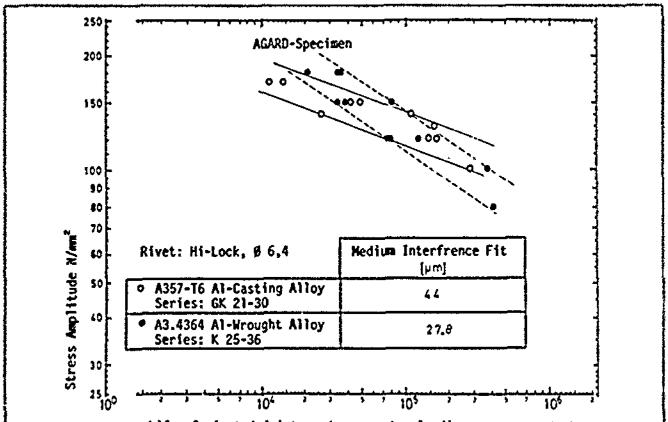
Hi-Lok	Rivet bolt R = +0.1
Hi-Lok	Rivet bolt R = −0.1
Taper-Lok	Rivet bolt R = +0 1

These comparisons are portrayed in Figs.3.4 16—3 4 18. The fatigue resistance of the riveted joints made with the casting alloy at high loads is, as expected, less good than with the wrought alloys. At a number of load cycles between about $4 \cdot 10^4$ to 10^5, the fatigue strength of both materials in the riveted condition is comparable, and at higher load cycle numbers the casting alloy A357-T6 behaved more favourably

CONCLUSIONS

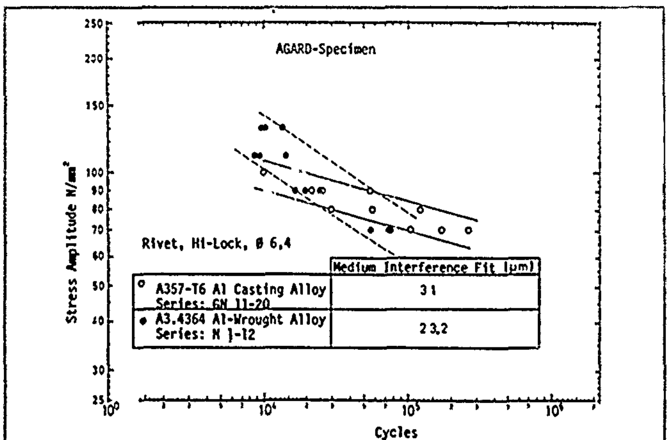
1. All the manufacturing processes and commercially available mechanical permanent fasteners developed for use with wrought aluminium alloys and tested to date, are also suitable for forming joints with aluminium casting alloys. Compared with joints in wrought alloys, the tested static strengths of joints in casting alloys are comparable in the case of solid rivets, but lower with joints formed using blind rivets or special fasteners.

2. The static and fatigue tests carried out in the present programme clearly confirmed that components made of aluminium casting alloys can indeed be joined by means of permanent fasteners. The fatigue data also



Life of riveted joints under one-step loading of testpieces with low transfer and secondary bending

Fig 3 4 16



Life of riveted joints under one-step loading of testpieces with low transfer and secondary bending

Fig 3.4 17

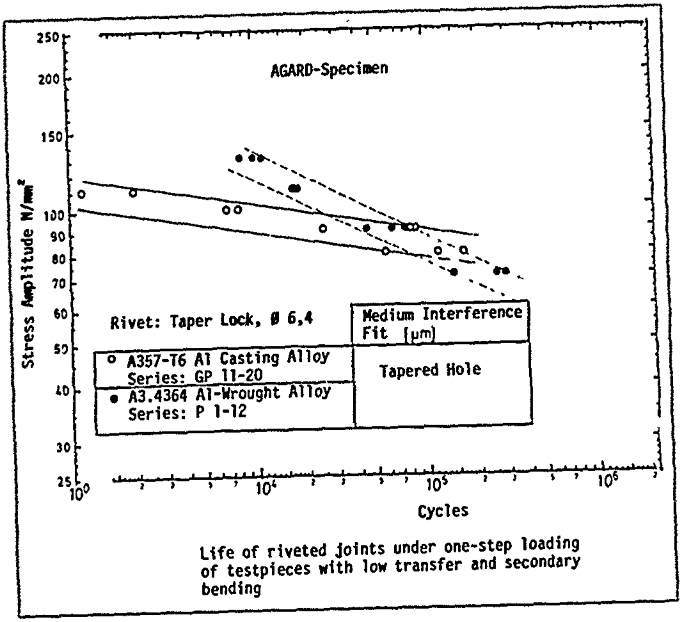


Fig 3 4 18

showed a satisfactory comparison between the wrought and the casting alloys.

3. Aluminium casting alloys are used not only in aircraft construction, but also in many other branches of industry, particularly when aiming to reduce weight. Nowadays, the use of aluminium castings in shipbuilding, and in the construction of rail and road vehicles is on the increase.

4. It is self-evident that in each individual case as accurate an optimization study as possible should be carried out as regards strength, costs service life, reliability and weight. At present such information is not generally available, since in investigations of this type it has hitherto been customary to examine only those parameters that have a bearing on the strength.

5. The results of as yet uncompleted value-analytical investigations indicate that modern casting technology offers the possibility of using castings in aircraft construction, which would require very little finish-machining, thus achieving considerable savings in cost.

REFERENCES

1. Mietrach D
Basis solution for the economical lightweight production of aircraft structures Aluminium + SUPPLEMENT IN ENGLISH 57 (1981) 6, pp. E 134/E 139 and 7, pp. E 168/E 170

2. Hoffer K
Life of rivet joints in aircraft construction ALUMINIUM + SUPPLEMENT IN ENGLISH 57 (1981) 2, pp. E 12/E 15

Author:
Dipl.-Ing. Kalman Hoffer (1920), head of the Abteilung Betriebsfestigkeit (Production Research Department), MBB-UT, Bremen, Germany.

3.4.3 Woehler-Diagrams of Riveted Ti 6Al4V

Introduction

For fatigue dimensioning of parts special data are required which have been determined by fatigue tests. Woehler tests have been carried out on double shear specimens (Fig.3 4.19), with results given in this report.

Specimens

The specimens Ek43-5139, Ek43-5140 and Ek-5271 are shown in Figure 3.4 20 to 3.4.22. They are double shear specimens including three Hi-Locks in a row. The specimens are 32 mm in width and 308 mm in length. The two outer butt straps have a thickness of 2.5 mm and are made from Ti 6Al4V wrought material. The part in the middle has a thickness of 4 mm and is made from Ti 6Al4V investment casting material. The Hi-Locks have a diameter of 6.4 mm The specimens have been wet assembled; the Hi-Locks have been wet inserted. The specimens have been manufactured with the following features:

Ek43-5139: no shim, normal hole, clearance fit
Ek43-5140: 0.5 mm shin, normal hole, clearance fit
Ek43-5271: 0.5 mm shim, expanded hole, clearance fit

A liquid shim EA934NA cured at R.T. has been used For hole expanding the "split-sleeve-method" (SSCE) has been used. The degree of expanding was approximately 3%.

Test Procedure

The static and dynamic tests have been carried out on the load controlled Instron 1251 test equipment. The specimens have been loaded up to fracture. The specimens were clamped rigidly. The direction of load was longitudinal to the specimens.

Test Results

All values obtained are tabled and shown as Woehler diagrams in Figure 3 4 23 to 3 4 25. The evaluation was done by non-linear regression calculation The basis of the statistical evaluation was a logarithmic normal distribution in stress direction. The position of fracture is shown in Figure 3 4 26.

Hole Diameter

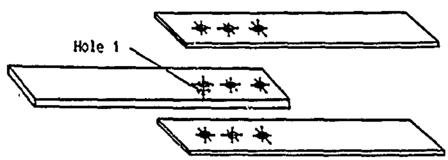
The hole diameter and the respective Hi-Lock fastener diameter have been measured at the first hole location. The results shown below are the medium values of two measurements displaced by 90°

Influence of the Shim

Figure 3 4 27 compares the results of assembled specimens *with and without* shims. The difference is noticeable, except for a larger scatter.

Influence of Expanding

Figure 3 4 28 compares the results of the expanded and non expanded holes. It can be said that the fatigue life is substantially improved by expanding the holes for Ti-investment casting.



Specimen No.	Drilled and Reamed D (mm)	Rivet-Diameter d (mm)	Fit d-D (mm)
5139-1	6.354	6.326	-0.028
-2	6.357	6.325	-0.032
-3	6.354	6.330	-0.024
-4	6.358	6.328	-0.030
-5	6.357	6.330	-0.027
5140-1	6.355	6.332	-0.023
-2	6.353	6.332	-0.021
-3	6.353	6.332	-0.021
-4	6.353	6.330	-0.023
-5	6.356	6.330	-0.026
-6	6.354	6.325	-0.029
-7	6.351	6.325	-0.026
-8	6.352	6.335	-0.017
-9	6.352	6.329	-0.023
-10	6.353	6.334	-0.019

Specimen No.	Drilled and Reamed (mm)	Expanded (mm)	Reamed D (mm)	Rivet-Dia. d (mm)	Fit d-D (mm)
5271-1	5.740	5.930	6.356	6.327	-0.029
-2	5.741	5.928	6.351	6.336	-0.015
-3	5.742	5.928	6.354	6.333	-0.021

Fig 3 4.19

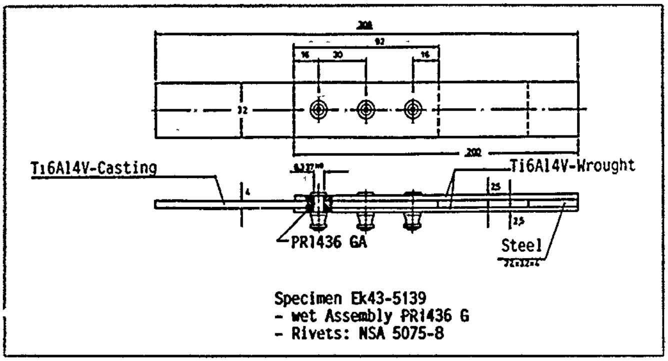


Fig 3 4 20

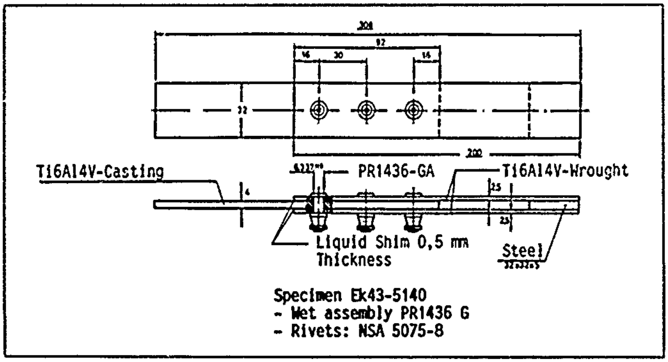


Fig 3.4 21

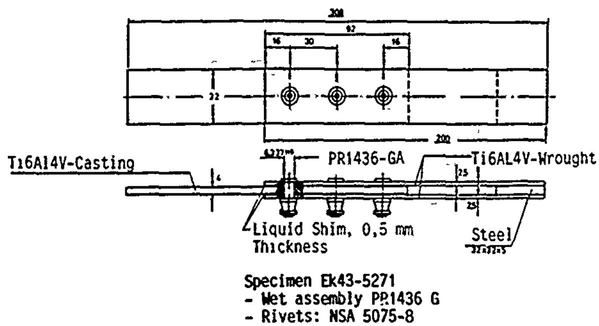


Fig 3.4.22

Specimen No.	Thickn. T (mm)	Width B (mm)	Hole D (mm)	Area T x B (mm²)	Max. Load Po (N)	Min. Load Pu (N)	Stress Ampl. Sa (N/mm²)	Cycles N -	Text
5140 – 1	3.97	31.60		125.5	102000	10200	365.9	1	Statical
5139 – 1	3.98	31.60		125.8	50000	5000	178.9	8308	Position of Fracture
5139 – 2	4.05	31.60		128.0	40000	4000	140.6	19855	Position of Fracture
5139 – 3	4.03	31.50		126.9	30000	3000	106.3	49965	Position of Fracture
5139 – 4	4.07	31.50		128.2	26000	2600	91.3	92057	Position of Fracture
5139 – 5	4.01	31.70		127.1	23500	2350	83.2	155888	Position of Fracture

$$S_a (P_U = 50\%) = 66.9 + 298.9 / e^{(\log N / 3.741)^{3.953}}$$

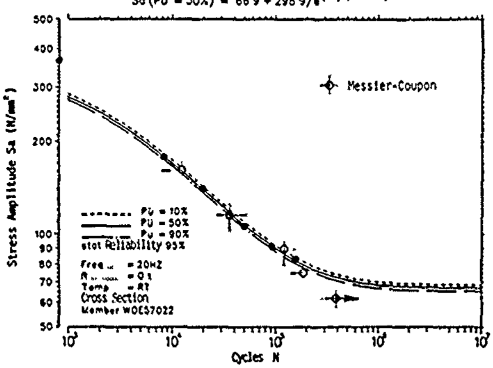


Fig. 3.4.25 : Specimen Ek43-5139
Investment Casting Ti6Al4V
Rivet: Hi-Lock, Ø 6,4 mm

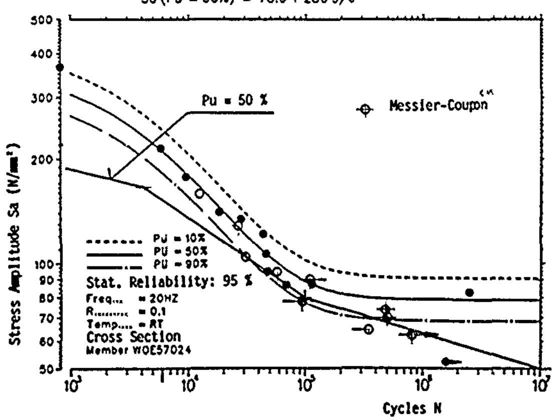
Fig 3.4.23

Specim. No.	Thickn. T	Width B	Hole D	Area TxB	Max. Load Po	Min. Load Pu	Stress Ampl. Sa	Cycles N	Text
	(mm)	(mm)	(mm)	(mm²)	(N)	(N)	(N/mm²)	-	
5140 - 1	3 97	31 60		125 5	102000	10200	365 9	1	Statical
5140 - 2	3 99	31.50		125 7	60000	6000	214 8	5804	Bruchl. B
5140 - 3	4 05	31.50		127 6	40000	4000	141 1	18357	Bruchl. B
5140 - 4	4 08	31.70		129 3	25000	2500	87 0	114592	Bruchl. B
5140 - 5	4 03	31 40		126 5	30000	3000	106 7	45702	"
5140 - 6	4 10	31 60		129 6	15000	1500	52 1	1593425	D A
5140 - 7	4 01	31.50		126 3	50000	5000	178 1	9500	Bruchl. B
5140 - 8	4 07	31 50		128 2	27000	2700	94 8	47480	"
5140 - 9	3 99	31 50		125 7	23000	2300	82 3	2507322	A
5140 -10	3 97	31 40		124 7	24000	2400	86 6	68575	Bruchl. B
5140 - 6	4 10	31 60		129 6	35000	3500	121 6	43695	Bruchl. B
5140 - 9	3 99	31.50		125 7	37500	3750	134.3	28211	"

A = Not broken, raised up to Po = 35000 N respectively 37500 N
D = Not considered for the evaluation

Bruchl. = Position of Fractun

$$S_a (P_U = 50\%) = 78.6 + 286.9 / e^{(\log N / 3.965)^{5.227}}$$



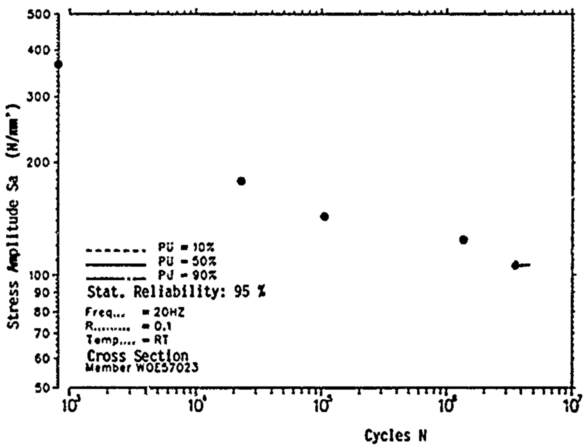
Specimen Ek43-5140
Investment Casting Ti6Al4V
Rivet; Hi-Lock, Ø 6,4 mm
Liquid Shim; 0,5 mm Thickness

Fig 3.4 24

Specim. No.	Thickn. T (mm)	Width B (mm)	Hole D (mm)	Area T x B (mm²)	Max. Load Po (N)	Min. Load Pu (N)	Stress Ampl. Sa (N/mm²)	Cycles N –	Text
5140 – 1	3.97	31.60		125 5	102000	10200	365 9	1	Statical
5271 – 1	3.98	31 60		125 8	40000	4000	143.1	105478	Bruchl. B
5271 – 2	4 01	31 50		126 3	50000	5000	178.1	22912	"
5271 – 3	4 00	31 70		126 8	30000	3000	106.5	3516503	D A
5271 – 3	4 00	31 70		126 8	35000	3500	124 2	1349709	Bruchl. B

A – Not broken, raised up to Po = 35000N

Bruchl. = Position of Fracture



Specimen Ek43-5271
Investment Casting TI6AL4V
Pearced Hole
Rivet: Hi-Lock, Ø 6,4 mm
Liquid Shim, 0,5 mm Thickness

Fig 34 25

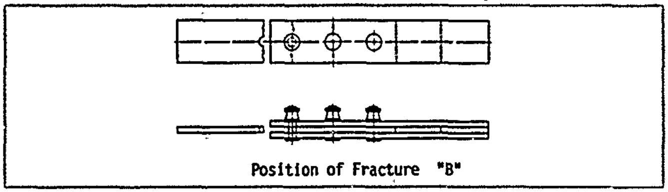


Fig 3 4 26

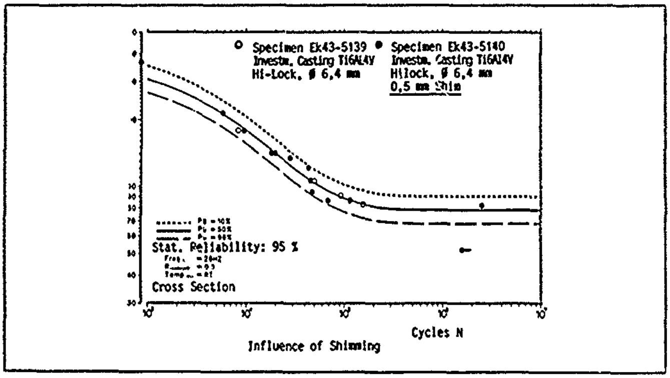


Fig 3 4 27

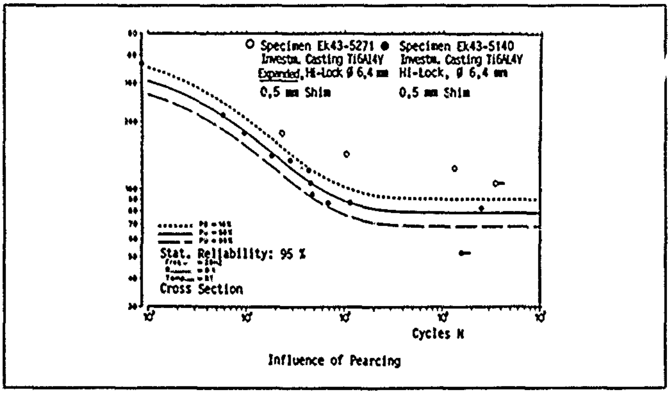


Fig 3.4 28

3.5 WELD REPAIR

In general a casting may not be welded without the permission of the user. That means also, that the maximum size, number and place of possible defects, which could be repaired by welding, should be defined in a specification. Areas should be specified, where welding is not allowed and the "free of defect" status has to be fulfilled by the foundry for this zone.

Defects in non-critical areas of the casting may be removed and the casting repaired by welding in accordance with *AMS 2694* using base material as filler material. Repair welding shall be performed prior to any heat treatment and final non destructive testing.

Mechanical Properties of Welded A357-Alloy:
Values of welded specimen equivalent with the base material (*with* heat treatment "T6" after welding).

Values in per cent from the base material (*without* heat treatment

Welding Proc.	Mechan. Prop.	
	Rp 0.2/Rm	A5
EB	95%	30%
TIG	55%	60%

EB – Electro Beam welding
TIG – Tungsten-Inert-Gas welding

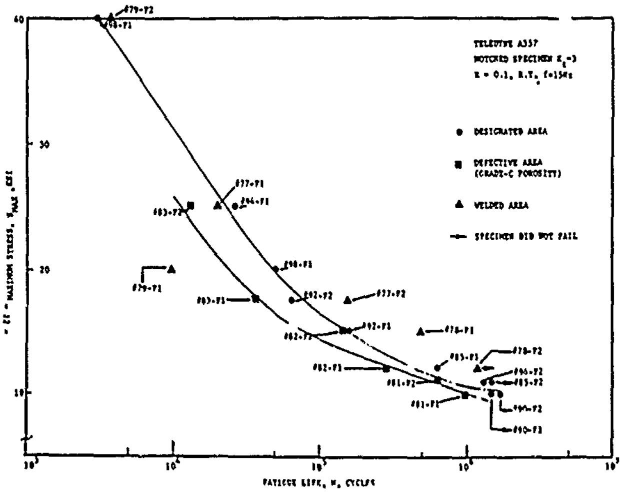
Mechanical Properties of Welded A201-Alloy
Values of welded specimen equivalent with the base material (*with* heat treatment "T7" after welding).

Values in per cent from the base material (*without* heat treatment:

Welding Proc.	Mechan. Prop.	
	Rp 0.2/Rm	A5
EB	75%	
TIG	60%	

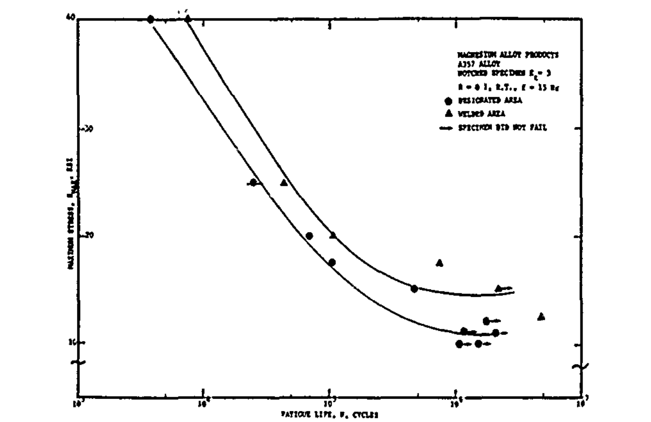
Fatigue Behaviour
A very important fact is that a welded area will have some influence on the fatigue life of the area. Consequently tests from welded areas with respect to fatigue life should be conducted.

The following examples (Figs.3.5.1–3.5.3) will give a rough idea of the different behaviour of welded and unwelded specimens.



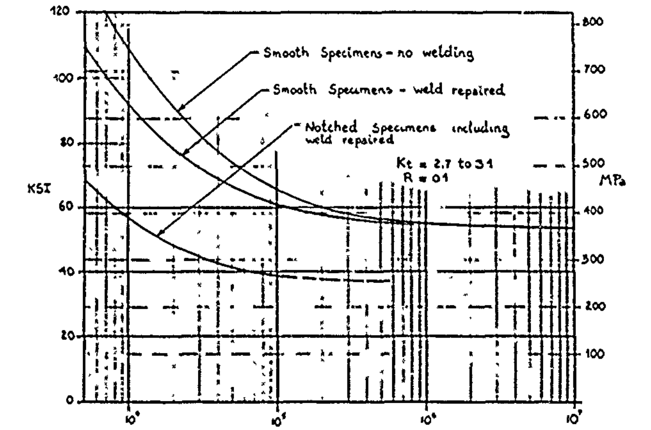
S-N Fatigue, Teledyne Casting A357 Alloy

Fig 3.5.1



S-N Fatigue, Magnesium Alloy Products, A357 Alloy

Fig 3 5 2



Fatigue Test, Titech Corp., Ti6Al4V Alloy

Fig 3 5 3

4. APPLICATIONS

4.1 INTRODUCTION

One of the major advantages of using castings in aerospace structure is their high degree of versatility They can be cast in thicknesses from a few millimetres in thickness to complete aircraft subsections including tail assemblies, bulkheads and canopy frames. Figure 4 1 11 shows an experimental tail section for the F-16. It is one of the largest aerospace castings produced Although this particular casting was produced under a research and development programme and never reached production, it shows the potential of castings for wide spread low cost application in future systems

For years, the application of castings in load carrying structure in aircraft has been limited by the required use of a casting factor. Figure 4 2 1 shows the first known application of a casting in a load critical aircraft application without a casting factor Such an application must be carefully controlled involving the use of statistically derived design allowables, metallographic quality control, and increased inspection techniques, nevertheless, it is possible.

The remaining figures in this section were chosen to show a wide range of aerospace applications demonstrating high levels of complexity, variance in size, thickness or casting method. For example, while most of the A357 items are sand castings, Figure 4 1 6 shows a low pressure permanent mould casting and Figure 4 1 10 an investment mould casting. Each figure is accompanied by a short description illustrating what is unique about that particular casting and some of its vital statistics

The company name accompanying each figure indicates the supplier of the information for that item and not necessarily the sole manufacturer. Many castings where the production run is expected to be large may have several foundry sources. For example, castings for the Air Launched Cruise Missile section shown in Figure 4 1 9, have been produced by Hitchcock Industries, ALCOA, and Weldman Dynamics.

4.1.1 Pylon Casting

Over 15,000 pylon castings have been flown in the past 25 years on Northrop aircraft without failure. These were first produced in the early 1960s when specifications, such as MIL-A 21180, were only being developed for aircraft applications. Tensile properties throughout the casting of 50 ksi (345 MPa) UTS, 40 ksi (276 MPa) YS and 5% elongation are required with the provision that a specified quantity may be slightly lower without requiring a retest as long as they are not located in attachment areas One casting is destroyed in each 25 consecutively produced to determine tensile properties One attached tensile coupon is tested from each casting to control the heat treatment to a specified yield strength range Each casting is required to meet grade B radiographic quality Welding is generally permitted but limited to size and location.

Alloy: A357-T6
Specification Northrop (NAI 1310)
Weight 65 lb (29 kg)
Wall thickness tolerance, ± 0.030 in (19 mm)
Outer surface tolerance: ± 0 030 in (19 mm) to basic mould line
Mechanical properties: UTS 50 ksi, YS 40 ksi, E – 5% (345 MPa), (276 MPa)
Courtesy: Northrop

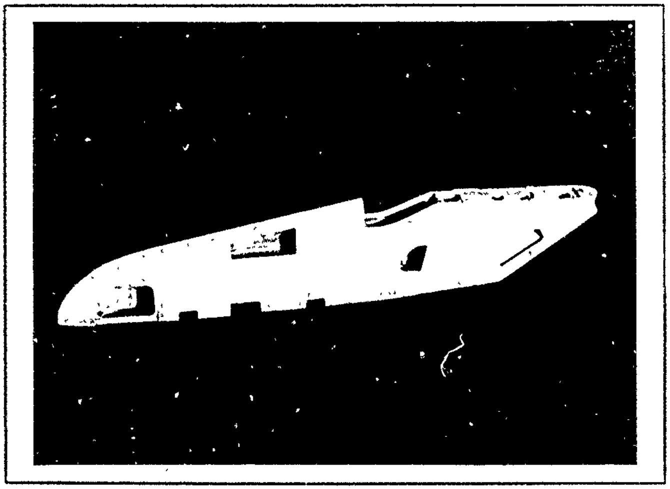


Fig 4 1 1

4.1.2 Airbus A320 Cargo Bay Door

Purchaser: MBB
Specification: DIN 29531 — Class 1 — 10
Alloy: A357T6
Wall thickness tolerances: 075" ± 016"
1.9 mm ± 0 4 mm
Dimensions. 47 3" × 39.4" × 4.7"
1200 mm × 1000 mm × 120 mm

Mechanical Properties:

Specification	*UTS ksi (MPa)*		*YS ksi (MPa)*		*E (%)*
Critical areas	48	330	40	280	5
Others	41	280	35	240	3
Typical in castings					
Critical areas	52	357	45	307	7.5
Others	51	355	44	304	6.5

Courtesy: Founderies Montupet

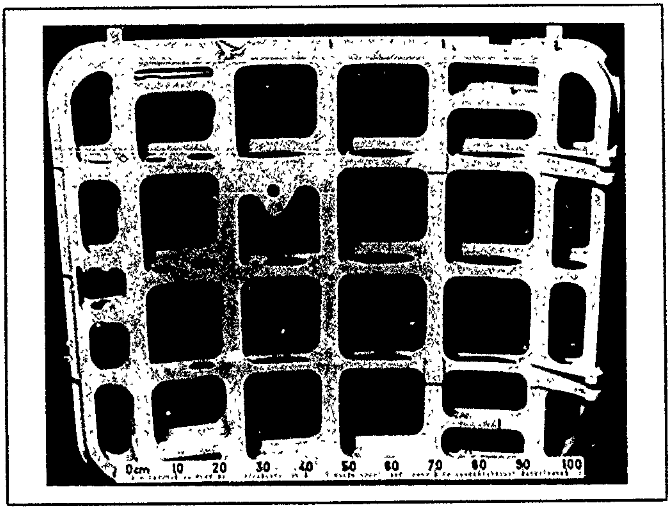


Fig 4 1 2

4.1.3 Pilot Box Structure

Purchaser: Dassault
Specification. Air 3380C Class 1-0
Alloy: A357T6
Weight: 22 lb (10 kg)
Wall thickness tolerances: .098" ± .019"
2.5 mm ± 0.5 mm

Mechanical Properties:

Specification			Typical in Castings		
UTS	YS	E (%)	UTS	YS	E (%)
40 ksi	29 ksi	2.5	49 ksi	40 ksi	10
280 MPa	200 MPa	2.5	340 MPa	275 MPa	10

Courtesy: Fonderies Montupet

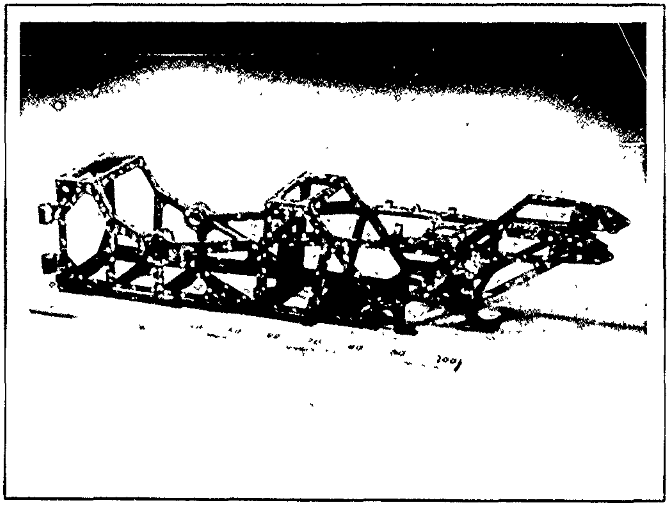


Fig 4.1.3

4 1.4 Landing Flap Holder

Purchaser: MBB
Specification: DIN 29531 — Class 2
Alloy: A357T6
Weight: 4.5 lb (2 kg)
Wall thickness tolerances: 236" to 079" ± 012"
6 mm to 2 mm ± 0 3 mm

Mechanical Properties:

Specifications	*UTS ksi (MPa)*		*YS ksi (MPa)*		*E (%)*
Critical areas	49	340	40	280	5
Others	45	310	35	240	3
Typical in castings					
Critical areas	51	350	44	300	6 5
Others	49	340	41	285	4

Courtesy: Fonderies Montupet

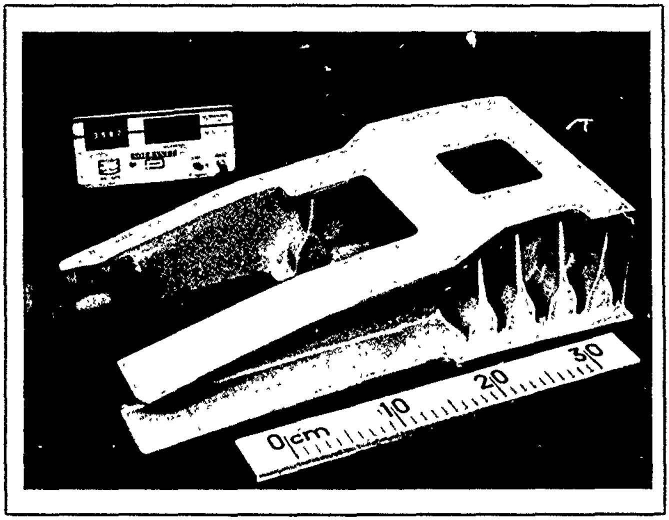


Fig 4 1.4

4.1.5 Missile Cheek

Purchaser: Manufacture d'armes de tulle
Specification: Air 3380C — Class 2-0
Alloy: A357T6
Weight: 4.0 lb (1,8 kg)
Wall thickness tolerances: .066" ± .012"
1,7 mm ± 0.3 mm
Courtesy: Fonderies Montupet

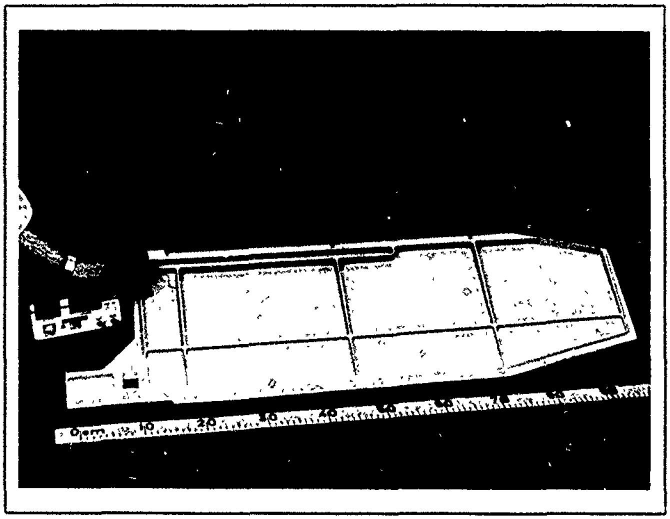


Fig 4.1.5

4.1 6 Antenna Bases for Military and Commercial Aircraft

Aircraft antenna castings require the culmination of all aspects of the casting process including metallurgical integrity as well as dimensional and surface finish precision.

Process. Low Pressure Premenent mould
Alloy: A357
Specification. MIL-A-21180, Class 1

Critical Requirements
A. *Short Base* 100% radiographic to grade B with a minimum wall thickness of the mast section of .061 ± 010" (1.6 ± .25 mm). Radii cast to .020" (51 mm) and a cast recess of .050 ± .010" (1 27 ± .25 mm) Weight: .66 lb (29 kg)
B. *Med. Base.* 100% Radiographic to grade B with the mast section having a wall thickness of .100 ± .010" (2.54 ± .254 mm) and a cast step of .010" (254 mm). All dimensions ± .010" (254 mm). Weight: .875 lb (.389 kg)
C. *Long Base:* 100% Radiographic to grade B. Mast section wall thickness .187 ± 0.10" (4.75 ± 2.5 mm) with straightness held to 0.15" (3 8 mm) radii cast to 0.30" (.76 mm). Weight: 1 88 lb (.836 kg).
Courtesy: Progress Casting Group

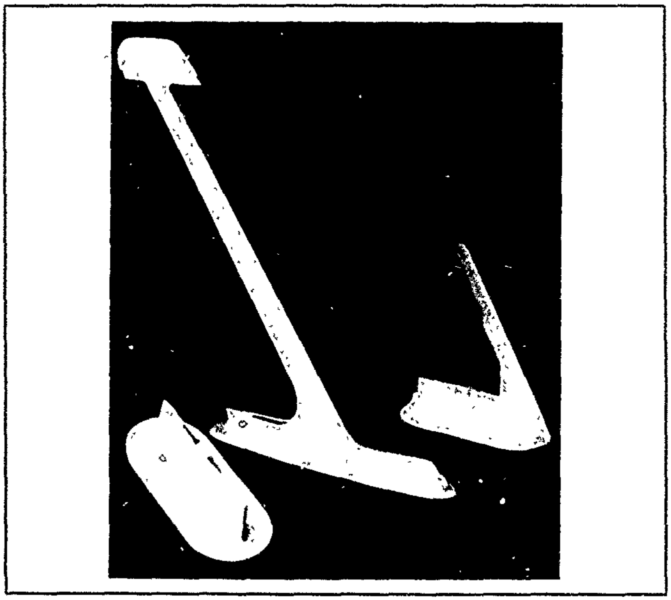


Fig 4.1 6

4 1.7 Forward Support Housing

A complex casting with concentric walls 0 080" to .120" (2.0 mm to 3 0 mm) thick with a good surface finish with high and consistant mechanical properties. In the construction of the mould a total of 11 internal cores are used. This casting used in the F-16 weighs 34 lb (15 kg).

Alloy: A357 0 T6
Specification: AMS 4219B
Method of Production Bottom poured by L.P. sand process

Typical Mechanical Properties:

Cut-up tests from casting		Yield strength		Tensile strength		EL%
Location	*Average of*	*ksi*	*(MPa)*	*ksi*	*(MPa)*	
Drive entrance	2	42.06	290 0	50 26	346.5	3.2
Mounting pads	2	40 03	276 0	47.145	325.1	5.5
Splitter flange	3	40 09	276 4	44.30	305.4	3 2
Bottom flange	4	40.54	279.5	45.84	316 1	4.5
Thin walls		42.63	293.9	45.86	316 2	4 5
Spec min. (cut from castings)		30 00	206 9	38 00	262 0	2 0

The tensile results show a good degree of consistency of properties throughout the thick and thin walled areas of the casting.

Courtesy: Haley Industries Limited

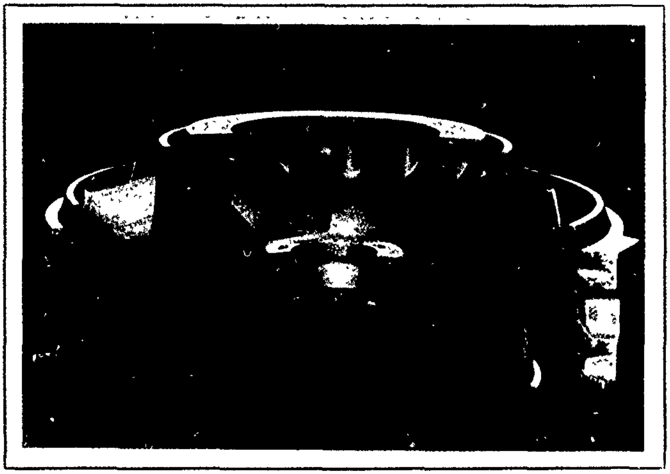


Fig 4.1.7

4.1 8 Bifurcation

Material: Aluminium A357 T61
Specification MIL-A-21180

Mechanical Property Requirements:
Critical: UTS 45 ksi (310 MPa), YS 31 ksi (214 MPa), Elong. 5%

Non-critical: UTS 38 ksi (262 MPa), YS 28 ksi (193 MPa), Elong 4%

Weight: 40 lb (18 kg)
Size: 52" × 12" × 10" (1320 mm × 305 mm × 254 mm)
No or cores: 15
Section thickness .160" to .870" (4 06 mm to 22 1 mm)
Dimensional tolerance ± .030" (± .762 mm)
Application: High stress pivot hinge for commercial aircraft

Courtesy: Hitchcock Industries

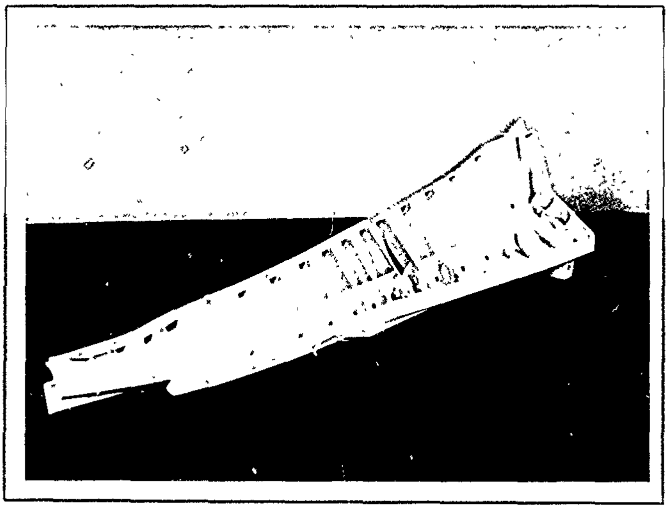


Fig 4.1 8

4.1.9 Cruise Missile Fuselage Section

This is one of the four tank sections which make up the ten casting fuselage of the Air Launched Cruise Missile (ALCM). These four sand castings range in thickness from ⅛" to 1½" (3.2 mm to 38 mm) and are machined only on the mating surface. When impregnated to insure against fuel leakage and bolted together they form a 13 ft (4 0 m) long tank assembly weighing approximately 400 lb (180 kg). The entire fuselage structure is approximately 21 ft (6 4 m) long.

Courtesy The Boeing Company

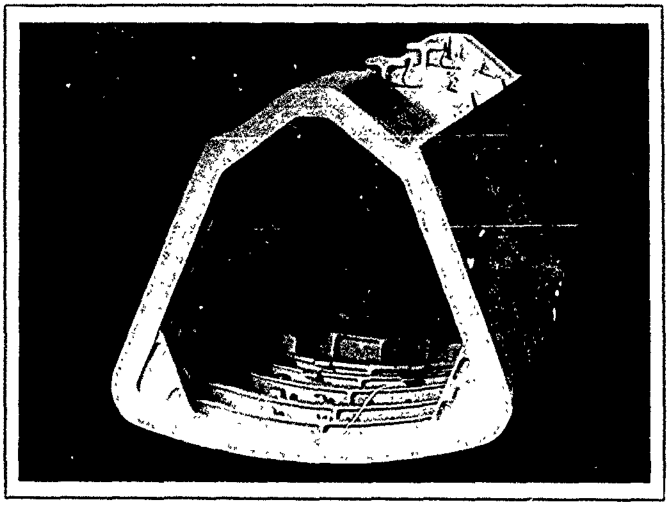


Fig 4.19

4.1.10 Bell Helicopter 406 Combat Scout's Outer Swashplate

Process: Investment cast in A357 aluminum

This swashplate is the dynamic component providing forces necessary to apply pitch to the rotary wing, thus providing the helicopter with maneuverability. This is a single load path design with no redundant system, thus becoming a critical part in the flight regime

The part is a 20" × 20" (508 mm × 508 mm) vacuum melt/vacuum pour investment casting with cored passages for weight reduction. This radiographic class "B" casting consistantly provides class "A" radiographic quality which results in superior fatigue properties.

Courtesy: Howmet Turbine Components Corporation

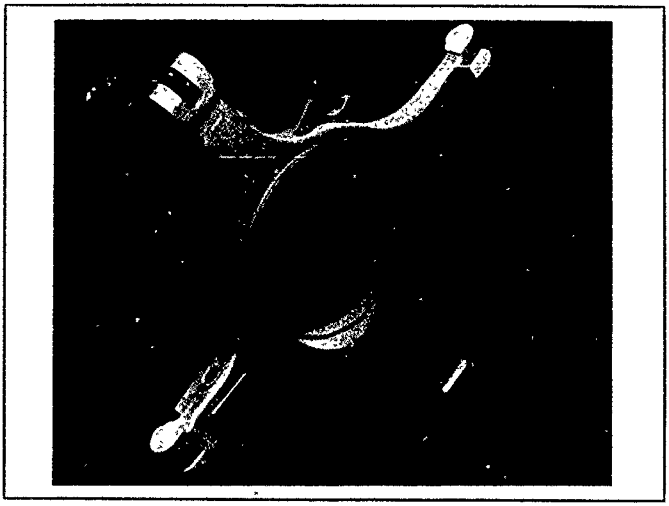


Fig 4.1.10

4.1.11 Vertical Stabilizer Substructure

An experimental vertical stabilizer built for potential application on the General Dynamics F-16. This large thin wall cast structure met or exceeded all the design criteria. In addition to meeting mechanical properties the actual weight was 49 lb (22 kg), versus a maximum of 52 lb (23 kg) and the part achieved two life cycles in the full-scale fatigue test with no failure.

Alloy: A357.0-T6
Weight: 52 lb (23 kg) maximum
Size: 11.5' × 3.5' × 4" (3500 mm × 1070 mm × 100 mm)
Typical wall: 0.80" (20 mm) — 30 to 40% thinner than typical for castings of this size and complexity
Specifications: MIL-A-21180
Mechanical properties: 45-36-4 high stress areas, 35-29-4 other areas
Casting process: Dry Sand Assembly
Number of cores: 37

Courtesy: Alcoa/General Dynamics

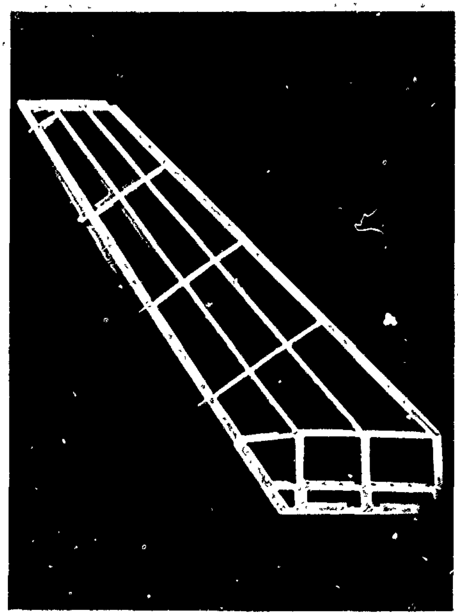


Fig 4.1.11

4.1.12 Canopy Frame

Large frame cast structure for the Grumman F-14 canopy. Requires high mechanical properties and unique heat treat and straightening practices to achieve close dimensional requirements for fit to the aircraft structure. A total of 774 castings were shipped from 1972 to 1987

Alloy: A357.0-T6
Weight: 98 lb (44 kg) maximum
Size: 41" × 24" × 134" (1041 mm × 609 mm × 3403 mm)
Typical thickness: .125" (3.17 mm)
Specifications. MIL-A-21180
Mechanical Properties:
UTS 50 ksi (345 MPa), YS 40 ksi (276 MPa), 5%el
high stress areas
UTS 41 ksi (283 MPa), YS 31 ksi (214 MPa), 3%el
other areas
Casting process: Dry sand assembly
Number of cores: 97

Courtesy: Alcoa

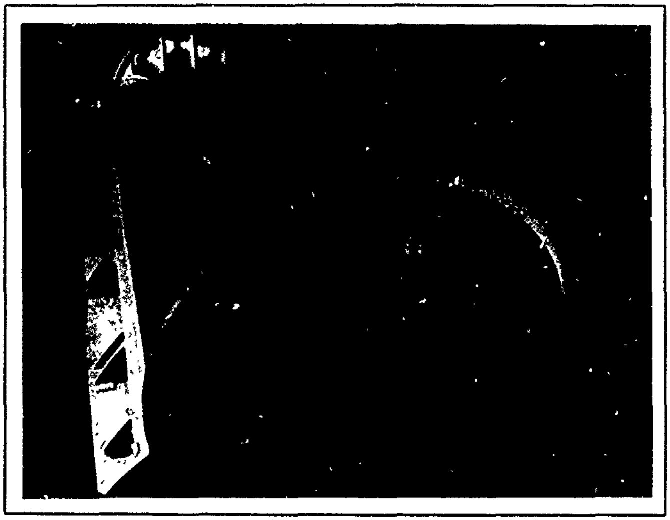


Fig 4.1.12

4.1.13 MRCA Tornado, Intake Floor

Purchaser:	MBB (Messerschmitt-Bölkow-Blohm)			
Foundry:	Messier and Merlin Gerin			
Specification:	DIN 29 531 — Class 1-0			
Alloy:	A 356 T6			
Wall thickness tolerances:	1.8 mm + 0.4 mm/—0.2 mm .070" + .016"/—.008"			
Dimensions:	700 mm × 430 mm × 330 mm (27.6"×16.9"×13")			

Mechanical Properties:	*UTS (MPA)*	*YS (MPA)*	*E (%)*
Critical areas	340	270	5
Others	310	250	3

This component belongs to the primary structure and is located in the forward engine air intake. The old version consisted of 13 machined parts/9 sheet metal parts and c.400 fasteners. The cast version consists of one part only. By comparison with the old version cost reductions of more than 60% at the same weight were achieved by using the casting.

Courtesy: MBB (Messerschmitt-Bölkow-Blohm)

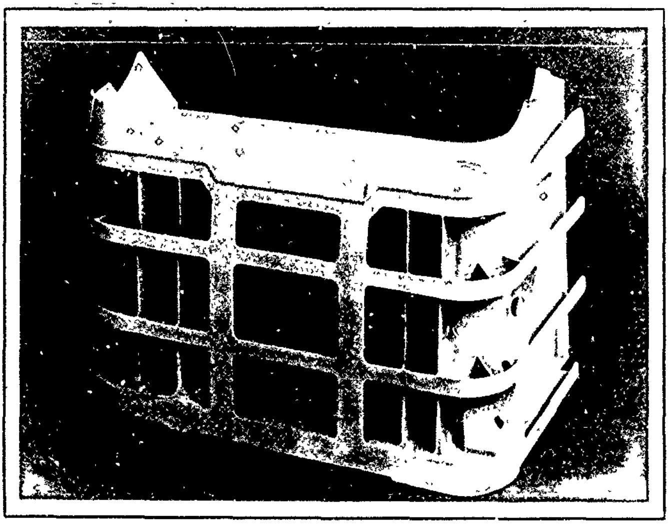


Fig 4.1.13

4 1 14 MRCA Tornado: NIB Centre Structure

Purchaser:	MBB (Messerschmitt-Bölkow-Blohm)
Foundry:	Merlin Gerin and Tital
Specification:	DIN 29 531 — Class 1-0
Alloy:	A 357 T6
Wall thickness tolerances:	1 6 mm ± 0 15 mm .063" ± 006"
Dimensions:	510 mm × 260 mm × 80 mm (20 1"×10 2"×3.2")

Mechanical Properties	*UTS (MPA)*	*YS (MPA)*	*E (%)*
Critical areas	340	280	5
Others	310	240	3

The NIB is located in the fixed wing area of the MRCA Tornado and is a primary component. The series version consists of 15 machined and sheet metal parts. The casting consists of only one part. Value analyses have shown 20% weight savings and 25% cost savings for the casting.

Courtesy: MBB (Messerschmitt Bölkow-Blohm)

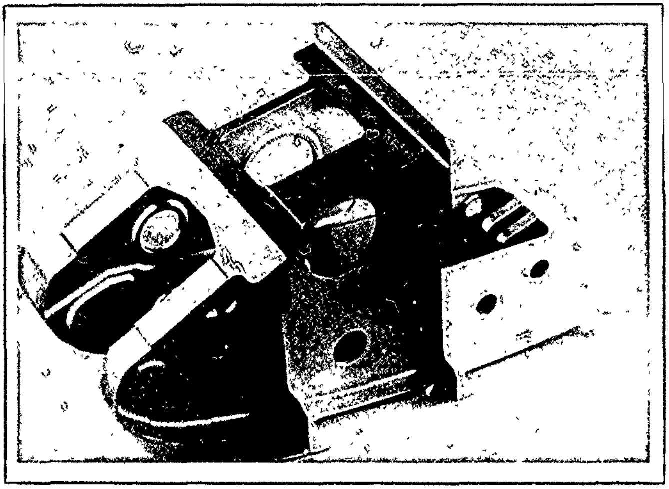


Fig.4.1 14

4 2 D357

4 2.1 General Dynamics F-16 Modular Common Inlet Duct Casting

This is the first attempt to produce a cast structural component utilizing no casting factor (1.33). Over 80% of this casting requires 50 ksi (345 MPa) UTS, 40 ksi (276 MPa) YS and 5% elongation. One casting is destroyed in each 20 consecutively produced to determine tensile properties. About 80 tensile coupons are obtained and dendrite arm spacing evaluated. Each casting shall meet grades A&B radiographic quality Welding is permitted but limited.

Alloy: D357-T61
Wall thickness tolerance: ± .030" (76 mm)
Dimensions: Length — 25" (635 mm)
Width — 60" (1524 mm)
Mechanical properties: UTS — 50 ksi (345 MPa)
YS — 40 ksi (276 MPa)
E — 5%
Weight: approx. 478 lb (21 kg)

Courtesy General Dynamics

Fig 4 2 1

4.3 A201

4.3.1 Turbocharger Compressor Impeller

This compressor wheel is cast for a West German diesel engine manufacturer, for use in a twin turbo boost application. KO1 alloy was selected for its resistance to moderate elevated temperatures during use and the high strength required while functioning at 20,000 RPM

Alloy: KO1-T7 (A201)
Casting size: 3.75" × 6 9" dia (95 mm × 175 mm dia)
Section thickness: 0 045" to 3.75" (1 1 mm to 95 mm)
Grain size range: 130 to 300 um
Mechanical properties: Tensile 69 ksi (478 MPa)
Yield 64 ksi (443 MPa)
Elongation 8%

Courtesy: Cercast Industries

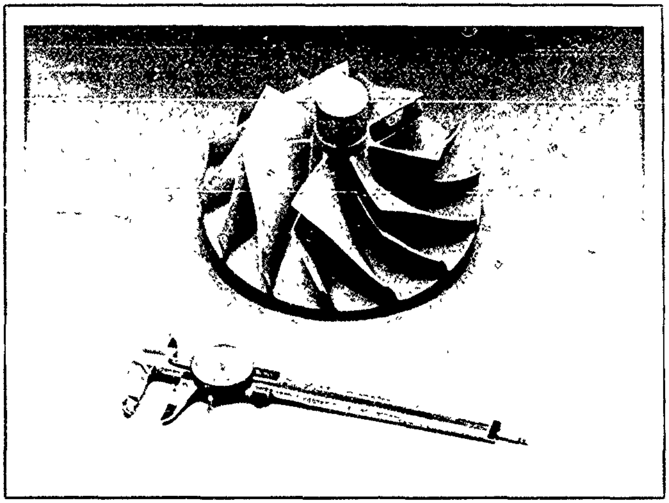


Fig 4.3 1

4.3.2 Rollover Beam for Helicopter

This strength casting forms an integral part of the canopy structure of a U.S. military helicopter. Originally, the part was fabricated by riveting a central machined beam with two KO1 investment castings at the extremities. Significant cost savings were realized by the customer by having the component cast in one piece. Today, over 500 parts have been delivered for this successful programme.

Alloy: KO1-T7 (A201)
Casting size: 21.8" × 11.7" × 4.2"
(554 mm × 297 mm × 107 mm)
Section thickness: 0.085" to 0.4" (2.1 mm to 10.1 mm)
Grain size range: 140 to 210 um.
Mechanical properties: Tensile 64.3 ksi (443 MPa)
Yield 58.5 ksi (403 MPa)
Elongation 6%

Courtesy: Cercast Industries

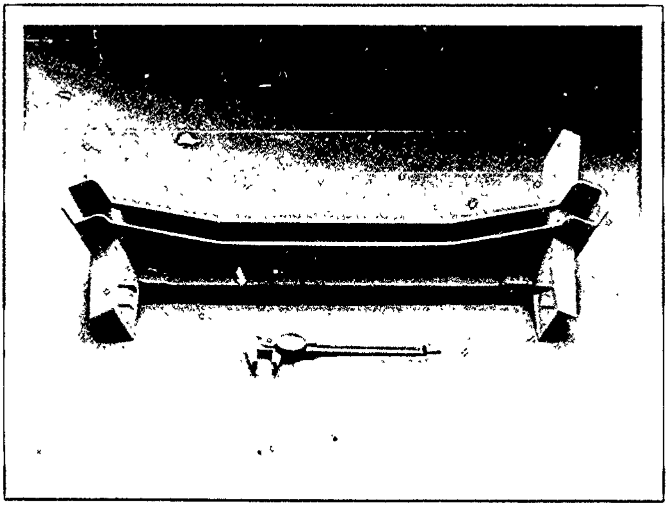


Fig 4.3.2

4.3.3 Engine Control Support

This structural casting is used as an engine control support for a U.S. missile. Developed several years ago, the part was designed in KO1 in order to take advantage of the high strength to weight ratio needed. This casting features heavy mounting lugs adjacent to thin wall stiffening ribs, with uniformly high mechanical properties throughout.

Alloy: KO1-T7
Casting size: 18" × 16" × 5.7"
(457 mm × 406 mm × 145 mm)
Section thickness. 0 12" to 0 55" (3 mm to 14 mm)
Grain size range: 160 to 220 um.
Mechanical properties: Tensile 65 0 ksi (448 MPa)
Yield 56.0 ksi (386 MPa)
Elongation 6.5%

Courtesy Cercast Industries

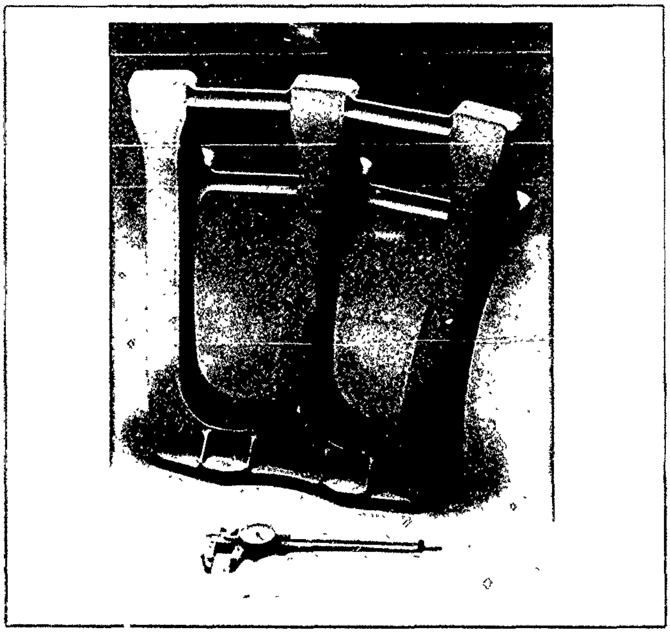


Fig 4 3 3

4.4 TI 6AL-4V

4.4.1 Optical Pointing System

The application for the two investment cast mating parts is an optical pointing system. Titanium was selected because the combination of its lightweight and high rigidity resulted in the ability to achieve extremely stable pointing. The complexity of design precluded manufacture by any technique other than casting.

The hollow square tubular sections with several bulkheads on the yoke were created with a soluble wax core which is chilled to reduce shrinkage variations. Wall thickness in some sections of the arm are a nominal 0.10" (2.5 mm). The three round sections on the bottom of the yoke were produced with mechanical cores and loose tool pieces to create the undercut details.

To ensure complete freedom from residual stresses after creep hot sizing, the part is re-vacuum annealed without fixturing.

Typical mechanical properties:

UTS ksi 137	YS ksi 120	%E
MPa 945	MPa 828	12%

Customer: Ball Aerospace
Specification: MIL-T-81915 Type III Comp A
Alloy: TI6AL-4V

Courtesy: Titech International

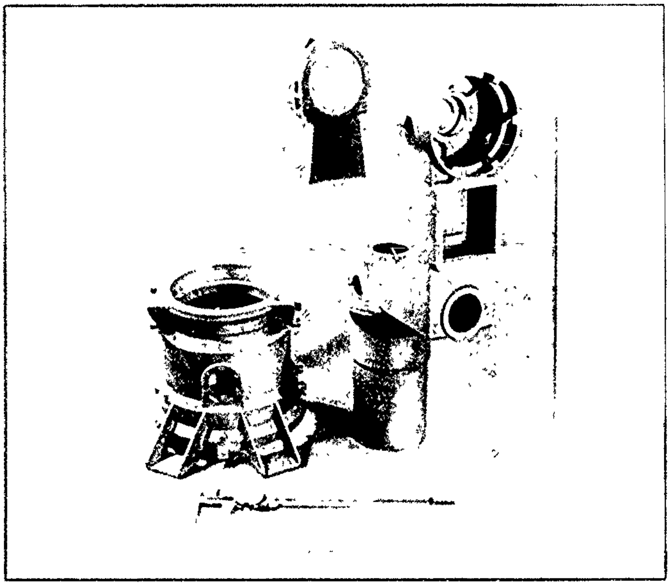


Fig 4.4.1

4.4.2 Exhaust Nozzle Actuation Ring

TI 6AL-4V Alloy Exhaust Nozzle Actuation Ring for military aircraft gas turbine engine. This intricate investment casting includes three (3) separate annular cores with limited access, as shown in the cross-section close-up. Tight dimensional tolerances require special post-cast sizing operations. Extensive areas of thin walls add to the complexity of this 30 lb (13 kg) casting. Overall diameter is 41" (1040 mm).

Specification: General Electric

Courtesy: Precision Castparts Corp.

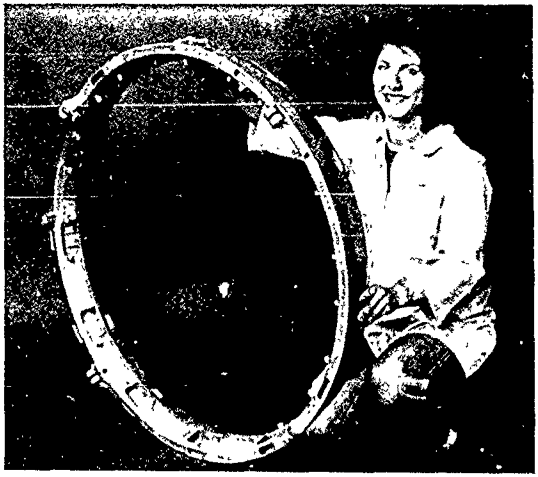


Fig 4.4.2

4 4 3 Fan Frame

This complex gas turbine engine component is the largest one-piece titanium production class casting of its kind

There are three major concentric elements combined in this state-of-the-art casting: heavy walled flanges which support twelve hollow, thin wall airfoil struts, along with heavy engine mount bosses and an internal housing which supports the main turbine axle. Several through-core and blind end cores are contained throughout this intricate casting.

The development of this casting design resulted in the elimination of a ninety-plus separate piece fabrication, a significant weight reduction, and a superior airflow path, all of which increase total engine performance.

Technical data: TI-6AL-4V Alloy
Hip and heat treated
51" (1295 mm) diameter
300 lb (133 kg) net casting weight
Specification: General Electric

Courtesy: Precision Castparts Corp.

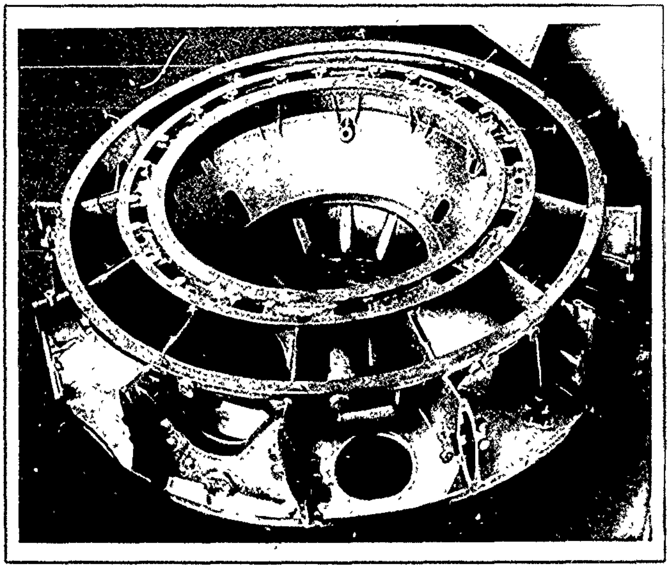


Fig 4 4 3

4 4 4 TFE1042 Front Frame

Garrett Turbine Engine Company
Titanium 6AL-4V
21" (533 mm) dia, 40 lbs (18 kg)
Specification: Garrett Turbine Engine Company

The front frame is a critical structural component of the GTEC TFE1042 gas turbine engine. It not only supports the fan and the accessory gearbox, but also holds the engine into the airframe.

The casting pictured is a complex mid-size titanium part which utilized state-of-the-art coring technology. Eight fragile ceramic strut cores along with 28 water soluble cores help to form this challenging 20 strut casting.

Courtesy: Howmet

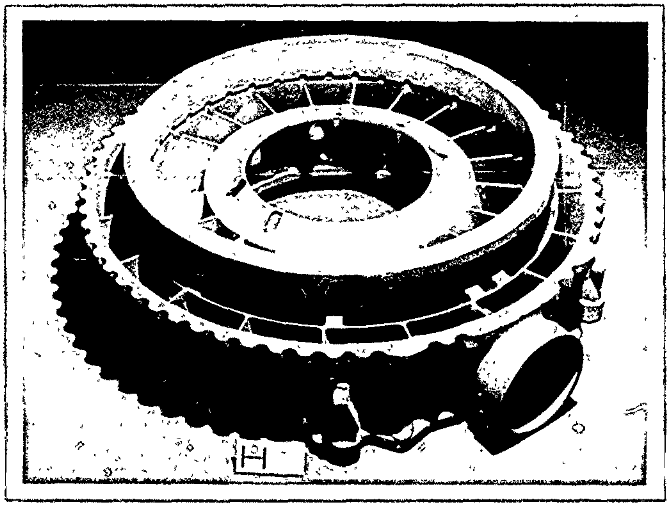


Fig 4 4 4

5. QUALITY ASSURANCE METHODS/CORROSION BEHAVIOUR

5.1 QUALITY ASSURANCE METHODS

5.1.1 General

Buyers and casters must agree on the meaning of quality. Each factor affecting quality must be decided by a set of rules for inspecting castings and criteria for accepting or rejecting castings.

Specifications must be set up for alloy composition and mechanical properties, hardness, surface condition and interior soundness. Inspection may include chemical anlyses, tensile, impact, bend and hardness tests, visual, microstructure examination, fluorescent or dye penetrant inspections X-ray inspections, gamma-ray, ultrasonic and special tests must be described and carried out to ensure good agreement among the producer's inspectors and the customer's inspectors.

The word "quality" does not imply any particular degree of desirability It designates a combination of characteristics to a specific casting.

Quality is relative and not absolute What may be good quality in a particular product when used for one purpose, may be quite inadequate if the same product is used for a different purpose.

In engineering and industrial work this situation is governed by specifications or test codes, which define standards of quality required under different conditions and state their limits. Such guidance simplifies deciding which quality standard to maintain, stating the variations allowable and methods of measuring them. These standards are based on experience with the kind of product concerned.

Rigid controls generally imply a combination of high quality, low quantity and high cost. On the other hand, more flexible controls are apt to result in lower quality standards, greater quantities and lower costs. The designer must balance the degree of quality control against the casting application, to achieve a cost effective solution according to his needs.

The term "Premium quality" is becoming a more frequent descriptive requirement. Premium quality castings having better internal soundness and inherent high mechanical properties are more costly than ordinary commercial castings. They should be used in highly stressed components for service under severe conditions or substituted for parts fabricated from wrought alloys, where highest strength-to-weight ratio is essential.

Conclusively, it can be said that the scope of testing constitutes an important cost factor so that its scope should be adjusted to the task of the component. Expressed in simpler terms, the scope of series tests should be "as extensive as necessary but as small as possible".

5.1.2 Specifications

The specification is developed by either the maker or the user, who specifies the intended condition of a casting throughout its manufacture or upon its completion. A specification must consider not only what is possible, desirable and necessary, but also what is practical, either now or in the future.

Specifications concerning castings are listed in Table 5.1. The abbreviations for most common specifications are given below

MIL.	Military Specifications or Handbooks, available from the US Naval Forms and Publication Center
AMS.	Aerospace Materials Specifications, available from the US Society of Automotive Engineers
ASTM.	Specifications of the American Society for Testing and Materials, available from ASTM in the US
SAE	Society of Automotive Engineers Handbook. This has limited use as the handbook covers wrought ferrous materials only. SAE handbook available in the US
QQ.	Federal specifications (US), available from US Naval Forms and Publications Center
DIN	German materials specifications, available from Deutsches Institut fur Normung
LN.	Luftnorm — German aircraft specifications
BSI:	British Standards Institution testing specifications available BSI London, England
AIR:	French Aircraft norm standards, available from Ministère de la Défense Nationale.

5.1.3 Quality Assurance at the Foundry

Quality assurance of castings can be divided into quality assurance measures at the manufacturer's (foundry) and at the buyer's.

Quality control at the foundry commences upon arrival of the material such as the raw material, wax, moulding materials and binders

Dimensional checks with adjustments and test facilities as well as electronic measuring equipment relate to the tools, patterns and castings so that production is monitored right from the early stages of the process through to series-production. Analytical equipment is used to record the composition of the molten masses and castings, and the smallest of additives which are determined for the achievement of certain properties.

In addition to an assessment of the texture and the determination of mechanical properties (tensile tests on separately cast, integrally cast specimens and/or specimens taken from the part) X-ray and dye penetrant tests are carried out. Moreover, qualification tests can be carried out on the component.

To summarize, the following quality assurance methods are applicable to castings.

- qualified material
- qualified personnel
- documentation of process
- visual inspection
- dimensional checks
- penetrant test
- X-ray test
- metallographic investigations
- tensile tests on specimens
- component tests.

The testing facility shall be surveyed and approved by the casting purchaser. The test facility shall be responsible for

Table 5.1
Specification

MIL - A - 8860	Airplane Strength and Rigidity, General Specification for
MIL - A - 21180	High Strength Aluminum Castings
MIL - C - 6021	Castings, Classification and Inspection of
MIL - H - 6088 E	I.C. Testing Procedur as related to Heat Treatment of Aluminum Alloys
MIL - I - 6866 B	Penetrant Inspection
MIL - STD - 276	Impregnation of Aluminum Castings
MIL - STD - 453	Radiographic Inspection
AMS 2635 C	Radiographic Inspection
AMS 2645 H	Fluorescent Penetrant Inspection
AMS 4228	K01 - T6 Material Spec.
AMS 4229	K01 - T7 Material Spec.
AMS 4241	Aluminum Alloy Castings, Sand Composite 7,0 Si-0,58 Mg-0,15 Ti -0,06 Be (D. 357.0-T6) Solution and Precipitation Heat Treated Aircraft Structural Quality
AMS 4242	Aluminum Alloy Castings, Sand Composite 4,7 Cu-0,60 Ag-0,35 Mn-0,25 Mg-0,25 Ti (B 201.0-T7) Solution Heat Treated and Overaged Aircraft Structural Quality
ASTM B-117	Salt Spray and SCC Testing
ASTM B-557	Tensile Testing
ASTM E8-82	Tensile Testing - U.S.
ASTM E-34	Chemical Analysis of Aluminum and Aluminum Base Alloys
ASTM E-155	Radiographic Standards
ASTM E-165-60T	Methods for Liquid Penetrant Inspection
ASTM G-44	K01 Corrosion Behavior
DIN 50 125	Tensile Testing - Germany
LN 29 512	Tensile Testing - Germany
BSI 4A.4	Test Methods - U.K.

the performance of all inspection requirements as specified in the data sheet.

5.1.3.1 *Preproduction Tests*
In advance of production, unless otherwise specified in the contract or order, two castings, heat treated and straightened to drawing requirements, shall be submitted for examination and written approval

One casting shall be identified as the "dimensional sample" and shall be for dimension approval. The other casting shall be identified as the "foundry control sample" and shall be for X-ray and strength inspection as necessary for approval according to the procurement documents.

The submitted castings shall be fully representative of the foundry practice that will be used in production. If chills are required, their size and location shall be permanently identified and recorded. Pouring temperature of the submitted casting shall be recorded.

5.1.3.2 *Chemical Analysis*
Chemical composition is usually controlled by a certified master heat as supplied to the foundry by the alloy producer

It is necessary that each melt prepared for casting be analyzed by spectrographic methods in the foundry regardless of whether a master heat or returned gates and risers are used.

The foundry shall certify this chemical composition for a particular batch of castings according to a pre-determined specification chosen by the user.

Suggested specifications:

ASTM E34	Chemical Analysis of Aluminium and Aluminium Base Alloys.
MIL A 21180	High Strength Aluminium Castings.
AMS 4241	Aluminium Alloy Castings, Sand Composite 7.0 Si-0.58 Mg-0.15 Ti – 0.06 Be (D.357.0-T6) Solution and Precipitation Heat Treated Aircraft Structural Quality
AMS 4242	Aluminium Alloy Castings, Sand Composite 4.7 Cu – 0.60 Ag – 0.35 Mn – 0.25 Mg – 0.25 Ti (B 201.0-T7) Solution Heat Treated and Overaged Aircraft Structural Quality.

5.1.3.3 *Gas Content of the Liquid Metal*
In the liquid state, aluminium alloys always dissolve gases and mainly hydrogen. This occluded gas is rejected when the solidification occurs, and can create porosities in castings. Then, to decrease the gas content, the liquid bath must be cleaned with nitrogen, chlorine or argon, and the level of the gas content must be checked before the pouring operations. Several kinds of apparatus are available on the market to perform this inspection.

5.1.3.4 *Heat Treatment*
The heat treatments of castings are one of the main steps of the fabrication. All operations of heat treatment must be very precise and checked. First of all, the furnaces and facilities will be certified by the quality assurance department with a complete inspection twice a year. Secondly, each phase of heat treatment must be identified and checked (temperatures, measurements and mechanical properties on attached coupons).

5.1.3.5 *Visual Inspection*
Each casting shall be examined visually.

Certain types of defect are obvious upon visual examination of the casting: cracks, cold shuts, ceramic inclusions, positive metal and missing features. These defects may or may not be discovered by other NDT methods, and should be covered on the user's drawings.

5.1.3.6 *Hardness Measurement*
The resistance of metals to plastic deformation by indentation may be measured by hardness tests such as Brinell, Rockwell and Vickers.

Hardness is a good indication of consistency and when correlated with chemical composition and heat treatment, is a cost effective control of casting acceptability.

Hardness certification by the foundry is generally expressed as a range (for a specific heat treat lot) as a result of testing.

5.1.3.7 *Dimensional Control*
The dimensions of the castings shall be within the dimensions and tolerances specified on the applicable drawings

Chapter 2 of this Handbook outlines the tolerances recommended for castings. More rigorous tolerances are possible and will depend on the specific part, the casting producer and the justification for increased cost. Users with specific problems requiring closer tolerances than accepted standards should contact the supplier with specific details

Casting acceptance will generally be based on the foundry's ability to supply parts which meet the customer's drawing specifications

Complex castings employing cast tooling points or "targeted" spot faces requiring supplemental machining operations at an outside facility are often "source inspected" at the foundry before shipment. In this way, the user is able to inspect and approve the casting dimensionally before costly machining operations are performed

5.1.3.8 *Penetrant Inspection*
Due to the high sensitivity desired for the inspection of aluminium castings, fluorescent penetrant is preferred to dye penetrant inspection. Penetrant inspection is a sensitive non-destructive method for detecting cracks, gas and shrinkage porosity and ceramic inclusions. The technique employs a highly penetrating fluorescent liquid which is visible under "Black Light".

Basically two systems of fluorescent penetrant inspection are recommended for aluminium castings:

A) "Water Wash — This system employing a water washable penetrant with excess removed by water spray is most widely used and recommended. A higher detection sensitivity is possible if the processed casting is dusted with a powdered developer.

B) "Post Emulsified" — The post emulsified penetrant is not water washable immediately. An emulsifier is applied to the surface after penetration and then washed away. Emulsifying time is critical and yields improved sensitivity of detection. Again, the processed casting may be dusted with a powdered developer for easier defect detection. The post-emulsified treatment is more labour intensive and results in higher costs to the user.

Ultimate defect detection is possible by chemically etching the casting surface prior to penetrant examination. The etching procedure employing a mix of acids and oxidising agents, removes smeared and contaminated material to

GENERAL INSPECTION GRADES FOR CASTINGS	
GRADE	DESCRIPTION
A	Very difficult to attain, requiring castings to be free from all defects detectable by X-ray examination.
B	This is a high standard which cannot easily be attained. Multiple gates are often required to reduce internal shrinkage to an acceptable level. It is also difficult to attain consistently, since small gas inclusions are cause for rejection.
C	This is a moderately high standard which can be attained consistently with adequate gating and good foundry practices. Sampling plan is allowed with this class of casting.
D	This is a liberal standard which can be attained easily with most configurations.

expose the underlying structure. Again, this labour intensive and hence expensive process is recommended for only the most critical castings.

The following specifications are recommended for penetrant inspection:

ASTM E-165-60T "Methods for Liquid Penetrant Inspection"
AMS 2645 H "Fluorescent Penetrant Inspection"
MIL-I-6866B "Penetrant Inspection"

5.1.3.9 *Radiographic Inspection*
Radiographic inspection is one of the most useful tools in casting quality assurance, and is commonplace in all casting foundries. For aluminium investment castings, the preferred radiation source is X-ray with a camera power generally not exceeding 160 Kw

The radiographic inspection shall be performed in accordance with MIL-STD-453. ASTM E-155 shall be used to define radiographic acceptance standards.

According to the classes defined in MIL-C-6021 there are four X-ray grades (A,B,C,D) which describe the quality of the casting.

Grades A&B are extremely difficult to meet and — as in the case of all X-ray specifications — one should designate selected areas (highly stressed areas) of the casting which must meet this specification.

Grade C is the preferred X-ray class for high quality parts (low stressed areas). Grade D is preferred for general X-ray examination and allows a relatively large degree of imperfection or discontinuity.

According to the classes there is a definition in MIL-C-6021 for each discontinuity like gas holes, shrinkage, foreign material, sponge, shrink cavity, dendritic and filamentary. The contractor shall establish the class and the grade

It is important to know that the cost of castings depends very strongly on the defined class and grade. The following table shows some price implications of radiographic inspection (intended as guideline only):

Casting costs reflect labour and material costs as well as increased scrap rejection due to non conformance to specifications, as a result of shrinkage porosity, gas porosity, cracks, inclusions, oxides, and segregation of alloying elements, etc.

The following specifications are recommended for radiographic inspection.

MIL-STD-453 Radiographic Inspection
MIL-C-6021 H NDT Classifications & Inspection
AMS 2635 C Radiographic Inspection
ASTM E-155 Radiographic Standards

GRADE / CLASS		CASTING COST	REMARKS
Grade:	A	+ (30-50 %)	Casting Quality Level
	B	+ (8-12 %)	
	C	+ (4- 6 %)	
	D	+ (1- 3 %)	
Class:	1	+ (20-30 %)	Casting Inspection Frequency
	2	+ (15-25 %)	
	3	+ (10-15 %)	
	4	+ (0 %)	

Notice:
The ASTME 155 standards represent samples with thicknesses of ¼ inch and ¾ inch They are not adapted for inspection of castings having thicknesses lower than 4 mm. The structure parts currently show thicknesses of 2 mm It must be known that the severity of the X-ray inspections is increased a lot when the thickness becomes thinner, because the sensitivity of the method is improved. That means that it will be necessary for the future to create new standards with adapted reference samples. But, before having these ones, it can be very helpful to use reference radiograms chosen among representative films obtained on the same casting family.

5.1.3.10 *Mechanical Properties*
Castings and test bars must be tested to ascertain that mechanical property specifications are met. The strength requirement of the casting tested in full size shall be as specified on the drawing or in other purchase information.

Mechanical testing is often the final verification for casting integrity and qualifications, as a result of correct chemistry, microstructural, NDT and heat treating control parameters.

As standard procedure, the foundry should cast separate test bar clusters from each melt used to produce castings, and make available the mechanical properties of the heat treated bars. This is at least a basic check for foundry and user and reflects any changes in processing. This method is the least costly of mechanical verifications, however, cast test bars indicate only the quality of the metal from which the casting is made. They do not give actual properties of the casting, neither are they a quantitative measure of casting quality. They are not truly representative of the final casting. The chief value in tensile testing lies in assuring consistency of metal properties from heat to heat or from one casting lot to the next.

Semi-critical castings may employ integrally cast coupons or test bars attached to the casting gating system The bars are later heat treated with the casting, and mechanical properties will more closely resemble properties of the finished part. Important factors often overlooked are the solidification conditions in both test bar/coupon and in the casting itself. Generally the complexity and wall thickness of the casting result in slower alloy solidification than in the attached bar. As a result, mechanical properties in the integral bar will often be superior to that of the casting, and display grossly optimistic mechanical properties.

The discrepancy between integral bars and casting may be minimized by engineering test coupons which solidify comparably and have similar microstructural conditions (grain size, DAS, etc). The foundry should be consulted in these circumstances to properly develop meaningful correlation studies. Although more relevant than separate cast test bar values, to qualify castings will result in additional effort and premium costs.

Critical application castings are best qualified by test coupons cut from designated (critical) and non-designated areas. It is suggested that one casting be tested per heat treat lot for small parts, and a testing schedule be established by foundry and user for larger castings.

Due to the high cost of destroying a casting for mechanical testing (including machining and testing costs), and the need to qualify every single casting in critical applications, efforts have been made to estimate casting properties using grain size or DAS controls (Chapter 5.1.3.11) together with integral cast coupons

Specification AMS 4241 exists whereby the mechanical properties of attached cast coupons are related to the DAS ratio of coupons from a specific casting area, to estimate properties of a specific D357 casting area. In this manner, individual castings and parts of castings may be mechanically qualified by measuring local surface DAS and knowing the properties and DAS of attached coupons

It is important that test specimen designs be uniform throughout the industry. Applicable specifications covering mechanical testing of static properties are as follows

ASTM B557	Tensile Testing
BSI 4A 4	Test Methods — U.K.
BS 18	Tensile Testing — U.K.
ASTM E8-82	Tensile Testing — U.S
LN 29512	Tensile Testing — Germany
DIN 50125	Tensile Testing — Germany

Notice
Due to the generally thin sections of aluminium investment castings, test bars are substandard in size.

When comparing mechanical properties determined from substandard bars, gauge length, testing speed, and test bar geometry should be stated.

Test parameters will vary (and hence results) from one country to another

5.1.3.11 *Metallographic Investigations/DAS*
On the basis of the micrograph, it is possible to make a statement on the mechanical values using the DAS method (*Dendrite Arm Spacing*). An additional non-destructive quality assessment can thus be made at any part of the casting.

The surface microstructure shall be evaluated as an added means of quality assurance only. Castings which exhibit an unacceptable microstructure shall be held for disposition by the cognizant engineering procurement personnel.

The microstructure of the casting surface in the designated areas of the casting shall not exceed the maximum size coarseness determined in accordance with specification AMS-4241. This specification, along with AMS/ARP 1947, establishes a non-destructive test procedure to evaluate the Dendrite Arm Spacing (DAS) of A357 aluminium castings.

AMS/ARP 1947 "Determination and Acceptance of Dendrite Arm Spacing in Aluminium Castings."

a) Microstructure acceptance criteria determination
Two integrally attached coupons shall be evaluated which represent a significant difference in DAS The DAS and ultimate tensile strength (UTS) of each coupon shall be determined. The maximum DAS acceptable shall be determined in the following manner:

$$DAS_{max} = \frac{DAS_2 - DAS_1}{UTS_1 - UTS_2}(UTS_1 - UTS_1) + DAS_1$$

Where

DAS_{max} = maximum size DAS acceptable to meet minimum tensile properties (1×10^{-4} inches)

UTS_1 = Ultimate tensile strength of coupon with smallest DAS (Ksi)

UTS_2 – Ultimate tensile strength of coupon with largest DAS (Ksi)

UTS_1 – Ultimate tensile strength minimum required (Ksi)

DAS_1 – Size of DAS of coupon with smallest structure (1×10^{-4} inches)

DAS_2 – Size of DAS of coupon with largest structure (1×10^{-4} inches)

b) Casting examination for acceptance
The DAS shall be determined on the casting surface at each test location shown on the casting drawing. When test locations are not shown on the casting drawing, areas selected for the excision of tensile coupons shall be used. The DAS in all test locations shall be equal or less than the maximum acceptable size determined in a).

c) DAS test procedure
Test locations shall be prepolished. Prepolishing shall be sufficient to produce an outline of the secondary arm structure after etching. Material removal during polishing shall not exceed 0.005 inch thickness. Prepolished test locations shall be electro-polished and electro-etched.

The microstructures of electro-etched locations shall be transferred to a replica plate provided in the Transcopy kit, following the procedure described in the supplier's literature. Any other method of microstructure replication, such as replicating tape, shall be approved by the contractor.

The replica plates shall be individually identified by test location and placed within an envelope which identifies the test casting represented by the replicas. Microstructure shall clearly distinguish the secondary arm spacing from the casting surface. Improper polishing, underetching, or overetching can produce a misleading microstructure.

If the microstructure is improperly polished, underetched, or overetched, the test location shall be repolished very lightly using 400 to 600 grit paper, re-electro-polished and re-electro-etched. The current density and etching time shall be established. Under-etched locations shall not be re-electro-etched without repolishing. The test casting shall be rinsed in running water to remove the etching solution after the examination has been completed.

A photographic reproduction shall be made at a magnification of 100X in the area which most clearly defines the general microstructure. Areas selected for evaluation shall be identified either directly on the photograph or on a copy of the photograph.

Either of two methods of microstructure evaluation are acceptable; however, the measurement of clearly defined secondary dendrite arm spacing (DAS) is preferred. When this is not possible, the alternate procedure of measuring the distance between silicon particles located in a random manner along a single line shall be used. The measurement of DAS is possible if the microstructure of Table 5.2 is obtained; however, if the microstructure of Table 5.3 is obtained, then the alternate procedure is necessary. All measurements used in the evaluation of a casting for acceptability shall be made by the same method.

Preferred Measurement Method: Extend a straight line across an area of well defined structure such as is illustrated in Table 5.2. The line is drawn perpendicular to the growth direction of the secondary arms. The average distance between intercepts of silicon particles along the line shall be used to define the DAS of the structure. By measuring the total length of drawn line and counting the number of interceptions, the average DAS value can be determined in the following manner:

$$\text{DAS, inches} = \frac{\text{Length of Intercept Line (inches)}}{\text{Number of Interceptions}} \times \frac{1}{\text{Magnification}}$$

At least two areas of the microstructure shall be evaluated. The average value of the two areas shall be referred to as the DAS of that test site.

Alternative Measurement Method – This alternate procedure consists of drawing a straight line of known length across the microstructure and counting the number of times the line is intercepted by silicon particles (see Table 5.3). The average distance between silicon particles is then used to quantify the structure. Particle Intercept Distance (PID) is determined by the following.

$$\text{PID, inches} = \frac{\text{Length of Intercept Line (inches)}}{\text{Number of Interceptions}} \times \frac{1}{\text{Magnification}}$$

At least two lines shall be drawn which vary in their orientation to each other as much as practical. The average PID of the two lines shall be reported.

d) Test reports
The test results shall be itemized as average values from each site on the casting or integrally attached test coupon. A photograph or copy of the photograph of the microstructure at each test site shall be reported which clearly delineates the lines drawn for microstructure measurements.

The test laboratory shall maintain on file for a minimum period of 90 days the replica plate or tape used in the evaluation.

5.1.3.12 *Component Tests*
Specific tests (such as component tests, leak tests) will be necessary on account of the operational spectrum. These tests have to be required by the customer. They can be done by the foundry or the buyer. Normally static tests are required but sometimes also dynamic component tests with defined loads are applied.

Heat treated castings used in vacuum, compressed air or liquid fuel applications are often pressure tested to determine soundness and integrity of critical sections. Fixtures usually constructed by the foundry, enable the casting to be pressurized with various fluids to determine leak rate or local defects. Impregnation of aluminium alloys is commonplace, particularly microporous K01 castings, either to repair particular defects or in general to add a measure of security in critical applications.

Common leak detection methods include:

A) Pressurization with helium gas (having smaller molecules than air) and electronic leak detection.

B) Pressurization with air while castings are immersed under water. Leaks are thus detected visually and this comprises the most popular and cost effective method of pressure testing.

C) Pressurization with water or oil media using a hydraulic pump. This method is usually employed as an integrity test for castings employing high pressures.

Normally, the pressure test shall be carried out after completion of finish-machining of the relevant component. In addition, the components must have been cleaned and degreased internally and externally.

Table 5.2
DAS Microstructure

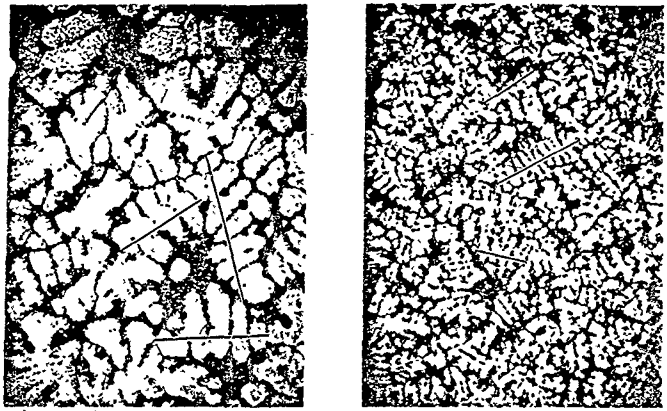
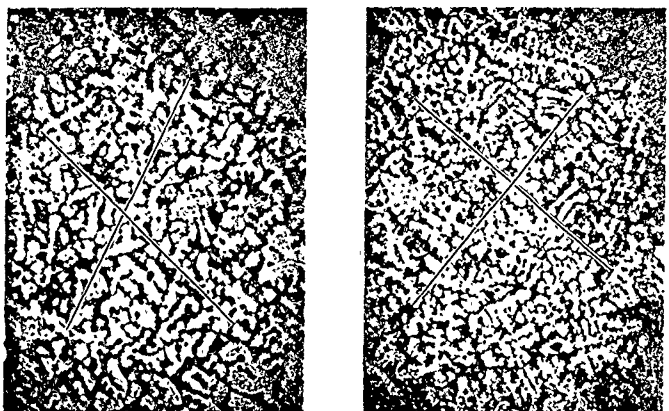


Table 5 3
DAS Microstructure



For specific testing details, specifications written by the user should be established with consultation from the foundry.

Sample Specifications:

MTU WA900 Pressure testing of Castings (MTU Munich, Germany)

MIL-STD-276 Impregnation of Aluminium Castings

5.1.4 Quality Assurance at the Buyer's

The buyer performs not only qualification tests but also series tests (e.g. visual inspections, dimensional checks, dye penetrant and X-ray tests, metallographic photos and component tests). The type and scope of such tests depends on the task of the component and the mechanical requirements to be fulfilled by the casting. Normally the tests are done by the foundry by approved personnel and the buyer makes spot checks only. But this depends on the quality of the foundry, the type of the casting and the confidence between ...ndry and customer.

5.1.5 Classification of Castings/Casting-Factor

The following specifications from a part of this handbook.

MIL-C-6021 Castings, Classification and Inspection of

MIL-A-8860 Airplane Strength and Rigidity, General Specification for

MIL-A-21180 Aluminium Alloy Castings, High Strength

5.1.5.1 *Classification of Castings*

Castings shall be classified by classes and inspected in accordance with MIL-C-6021. Aluminium castings in structural applications shall conform to specified requirements. Allowable properties based on static and fatigue test data other than data from MIL-Specifications may be used subject to acceptance by the procuring a... ...ity.

According to MIL-C-6021 there are four classes. These classes should not be confused with the four casting strength classifications (class 1, 2, 11, 12) listed in MIL-S-21180

Class 1:
A casting, the single failure of which would cause significant danger to operating personnel or would result in a significant operational penalty. In the case of missiles, aircraft and other vehicles; this includes loss of major components, loss of control, unintentional release or inability to release armament stores, or failure of weapon installation components.

Class 2:
A casting not included in Class 1.

Class 3:
Castings having a margin of safety of 200.

Class 4:
Castings having a margin of safety greater than 200 percent, or for which no stress analysis is required. All target drone castings and aerospace ground support equipment fall in to this category, except for such critical parts, the failure of which would make the equipment unsatisfactory and cause the vehicles which they are intended to support, to be inoperable.

From the point of view of economy, it is extremely important also to divide the casting into critical and non-critical zones. This applies to mechanical and geometrical areas. Mechanically critical areas are zones subjected to very high static loads (areas with maximum bending moments or concentrated load introduction), other areas are classified as non-critical. This means that by special measures such as the provision of cooling elements or gating systems, the foundry can produce the critical areas with a particularly fine texture and thus achieve high strength values in these areas.

Geometrically critical areas are zones in which the foundry has to observe certain closer tolerances and dimensions.

The contractor's design activity shall establish the class by critical areas and stress levels for each casting design. The classification(s) and critical area(s) shall be indicated on the applicable drawing.

5.1.5.2 *Casting-Factor*

At present, many certification authorities still require the use of a casting factor in computations prior to introduction of a casting in the aircraft structure. The following requirements relate to civilian aircraft.

Critical Castings:
According to FAR Part 25, for each casting whose failure would preclude continued safe flight and landing of the airplane or result in serious injury to occupants, the following apply:

1. Each critical casting must
   a) Have a casting factor of not less than 1.25; and
   b) Receive 100 percent inspection by visual, radiographic, and magnetic particle or penetrant inspection methods or approved equivalent nondestructive inspection methods.
2. For each critical casting with a casting factor less than 1.50, three sample castings must be static tested and shown to meet
   a) Defined strength requirements corresponding to a casting factor of 1.25; and
   b) Deformation requirements at a load of 1.15 times the limit load.
3. Examples of these castings are structural attachment fittings, parts of flight control systems, control surface hinges and balance weight attachments, seat, berth, safety belt, and fuel and oil tank supports and attachments, and cabin pressure valves.

Noncritical Castings:
For each casting other than those specified above the following apply:

1. Except as provided in subparagraphs 2 and 3 of this paragraph, the casting factors and corresponding inspections must meet the following table:

Casting factor	Inspection
2.0 or more	100 percent visual.
Less than 2.0 but more than 1.5	100 percent visual, and magnetic particle or penetrant or equivalent nondestructive inspection methods.
1.25 through 1.50	100 percent visual, magnetic particle or penetrant, and radiographic, or approved equivalent nondestructive inspection methods.

2. The percentage of castings inspected by nonvisual methods may be reduced below that

specified in sub-paragraph 1. of this paragraph when an approved quality control procedure is established

3 For castings procured to a specification that guarantees the mechanical properties of the material in the casting and provides for demonstration of these properties by test of coupons cut from the castings on a sampling basis

a) A casting factor of 1 0 may be used, and
b) The castings must be inspected as provided in subparagraph 1 of this paragraph for casting factors of "1 25 through 1.50" and tested according to critical castings of this section

Recent developments on the aluminium castings sector (in response to the requirements of the aerospace industry) and the consistent application of specific quality assurance measures have made it possible to manufacture reproducible aluminium castings. An essential prerequisite for reducing or eliminating the casting factor in the near future has therefore been established (see also chapter 6).

5.2 CORROSION BEHAVIOUR

The following sections were principally extracted from the AGARD CORROSION HANDBOOK, VOLUME 1, AIRCRAFT CORROSION, CAUSES AND CASE HISTORIES (AGARDOGRAPH NO 278)

5.2.1 General

Some aircraft structures experience severe environmental conditions in service. The loads developed in flight and during ground manoeuvres are generally high, and in the interest of achieving low overall weight, structural materials are selected that have high strength, high stiffness, and low specific gravity. High strength materials, including castings, allow excess weight to be kept to a minimum. However, other properties, such as the ability of the materials to resist corrosive attack are also important. Unfortunately low weight and high strength in aircraft structures and materials may not always be compatible with high resistance to corrosion, and therefore trade-offs may need to be made. By proper attention to corrosion at the design stage and in assembly, and by careful inspection and early repair of corrosion damage and protective systems, it is generally agreed that corrosion effects on aircraft can be minimized. It should be pointed out that castings experience corrosion in the same manner as wrought metals. The only differences could be microstructural with castings exhibiting more porosity and microsegregation as compared with wrought structures.

Corrosion is the destructive attack of a metal, elemental or alloy, by chemical or electrochemical reaction(s) with its environment. No two metals react identically in a given environment. Several factors are basic in determining the amount and type of corrosion. Micro-constituent composition, location, quantity, continuity and electrical potential relative to the base metal are all important. The AGARD Corrosion Handbook, Volume 1, (AGARDograph No.278) provides an excellent description of the operating environment, corrosion theory, common aircraft alloys and their corrosion behaviour, inspection for corrosion, corrosion prevention and control procedures, and a detailed description of the various types of corrosion. It is recommended that the above document be used as a reference for detailed information on aircraft corrosion The following is a brief description of the types of corrosion.

There are eight major types of corrosion processes which will be briefly discussed. They are

1. General Corrosion
2. Galvanic Corrosion
3. Pitting Corrosion
4. Intergranular Corrosion
5. Fretting Corrosion
6. Hydrogen Embrittlement
7. Stress Corrosion Cracking
8. Corrosion Fatigue

5 2 1 1 *General or Uniform Corrosion*

Corrosion of metals by uniform chemical attack is the simplest and most common form of corrosion. Corrosion of aircraft structures can occur under normal service conditions and particularly in areas where water is apt to collect This type of deterioration is characterized by uniform corrosion over the entire surface of the metal and is caused by numerous and closely packed anodes and cathodes of the electrolytic cell on the surface of a single piece of metal. Therefore, uniform corrosion can be considered as localized electrolytic attack occurring consistently and evenly over the entire surface.

Uniform corrosion generally affects large surface areas and, provided the corrosion prone area is accessible for visual inspection, it can usually be detected fairly early and remedial action taken. Uniform corrosion occurring in sealed interior areas or other visually non-inspectable areas can lead to serious damage unless special non-destructive inspection methods such as x-radiography and ultrasonic inspection are used for early detection followed by corrective maintenance. However, in some cases, a small amount of uniform corrosion will passivate and protect the metal from further attack. This is true with aluminium and it is primarily a property of the specific metal.

5.2.1.2 *Galvanic Corrosion*

Galvanic corrosion occurs when metals of different electrochemical potential are in contact in a corrosive medium. The less noble metal will form the anode of the electrolytic cell and will be corroded while the more noble metal will act as the cathode and will remain largely unaffected. The resulting damage to the anodic metal will be more severe than if the same metal were exposed to the corrosive environment without the presence of, and contact with the cathodic metal. Galvanic corrosion can often be discerned from other forms of corrosion because the corrosive attack is usually more severe at the interface between two dissimilar metals.

Based on experiences in corrosion testing and a knowledge of the galvanic behaviour of metals and alloys, the tendency of metals and alloys to form galvanic cells and the prediction of the probable direction of the galvanic effect can be determined. The galvanic series takes into consideration all of the specific aspects of the reaction such as the condition of the materials and the specific environment. This can be determined by measuring the electric potential difference between the two materials in the environment of interest. Some care must be taken when using the galvanic series to assess the galvanic corrosion potential of dissimilar metals, since some metals may occupy different positions in the series depending on their state and surface condition. This is most commonly observed with metals such as stainless steels which can exist in either a passive state or active state. In the passive state, most stainless steels will occupy positions toward the noble end of the galvanic series, while in the active state they will behave more anodically. This behaviour is believed to be due to the state of the protective oxide films which tend to form on stainless steels due to the uniform corrosion process. This film is believed to passivate the surface and resist further corrosive attack. When the oxide film is intact and effective as a protective covering, the metal behaves cathodically, whereas a damaged film leaves the metal unprotected and it therefore tends to behave anodically.

5.2.1.3 *Pitting Corrosion*

Pitting corrosion is a localized type of attack which leads to the formation of deep and narrow cavities. All engineering metals and alloys are susceptible, and the conditions leading to pitting vary from metal to metal, depending in part on whether the metal is normally active or passive. Excessive porosity of a poor casting could serve as preferential sites for pitting.

For active metals, uniform exposure of a large surface to a corrosive medium would tend to cause uniform corrosion. Pitting of an active metal will occur as a result of local wetting, or defects in a protective coating which allow very localized exposure. In passive metals such as stainless steels and aluminium alloys, which form naturally protective oxide films, pitting occurs as a result of localized damage to the protective film. However, whether the metal is active or passive, pitting involves the formation of small areas which are anodic with respect to the rest of the surface, and which therefore suffer severe corrosive attack in the presence of an electrolyte.

In aircraft structures, pitting may occur in many areas, but areas subject to local contamination by highly corrosive media, such as battery compartments, toilet, and galley areas, are prime sites. Pitting corrosion is particularly common in aircraft structures operating in marine environments since the chloride ions promote the local dissolution of protective oxide films. Pitting in passive metals is uncommon in solutions which do not contain halide ions, since the oxide films would tend to be stable and remain protective.

Pitting corrosion is one of the most insidious forms of corrosion because the pits are often very small and difficult to see with the naked eye, particularly if they are hidden by general corrosion products or coatings. The electrochemical conditions at the base of a pit can be such that other forms of corrosion, such as intergranular attack will occur, leading to widespread subsurface damage. In highly loaded structures the stress concentration at the base of a pit can be sufficient to cause fatigue or stress corrosion cracking to occur.

5.2.1.4 *Intergranular Corrosion*

Intergranular corrosion is a highly localized form of dissolution which affects the grain boundary regions in a polycrystalline metal. The corrosive attack can produce a network of corrosion or cracking on the metal surface around these boundary areas, occasionally dislodging whole grains, or it may penetrate deeply into the metal leaving behind very little visible evidence of the damage. This form of corrosion is particularly troublesome to cast metallic structures.

In intergranular corrosion the materials in the grain boundary areas behave anodically with respect to the bulk of the metal in the grain interiors. In corrosive environments, dissolution of the anodic grain boundaries usually occurs at a very rapid rate. The small area of the anode with respect to the cathode area is an important factor influencing the corrosion rate. The anodic nature of the grain boundary may be due to the local segregation of impurities, or either the enrichment or depletion of the grain boundary in alloying elements. These effects may be associated with the precipitation of grain boundary phases, which may themselves behave anodically with respect to the adjacent alloy. Castings that have not undergone equilibrium cooling during solidification can have a cored microstructure with microsegregation of alloying elements at or near the grain boundaries thereby causing susceptibility to intergrannular corrosion.

5.2.1.5 *Fretting Corrosion*

Fretting is a form of wear which occurs between contacting surfaces which are undergoing vibratory motion involving relative displacements, or slip of small amplitude. The degradation of the rubbing surfaces usually involves a combination of wear and a corrosion reaction, and therefore the terms of fretting corrosion or wear oxidation are frequently used. It usually gives rise to the formation of pits or grooves in the metal surrounded by corrosion products.

In the classic case, fretting occurs between parts which are intended to be fixed by some form of mechanical fastener, but where vibratory stresses cause loosening of the fastener system to allow small cyclic displacements to occur between the two contacting faces. However, exceptions occur, for example between ball bearings and their races, or between mating surfaces in oscillating bearings and flexible couplings. The basic requirements for fretting corrosion are that there is repeated relative motion between the surfaces, that the surfaces are under load and that the load is sufficient to cause slip or plastic deformation on the surfaces. The fretting action will be more severe, the more aggressive the corrosion environment.

The mechanisms of fretting corrosion are not completely understood, however they are generally thought to include either mechanical wear followed by oxidation of metallic wear debris, or mechanical rupture and loss of naturally occurring oxide films followed by re-oxidation of the exposed bare metal. In either case, the damage occurs locally at high points on the contacting surfaces. If the fretting couple consists of dissimilar metals, the softer metal will deform the greatest amount, so that the oxide film on the softer metal will be disrupted, but that on the harder metal will remain intact. The softer metal will therefore tend to suffer the greatest damage due to fretting corrosion. This concentration of damage will also tend to increase if the softer metal is the more electromechanically active metal in the couple.

Fretting damage is particularly serious since it can lead to unexpected fatigue failures. Under fretting conditions fatigue regions depend mainly on the state of stress in the surface and particularly on the stresses superimposed on the cyclic stresses. The direction of growth of the fatigue cracks is associated with the direction of contact stresses and takes place in a direction perpendicular to the maximum principal stress in the fretting area.

5.2.1.6 *Hydrogen Embrittlement*

A great deal of information has been collected in recent years to demonstrate that environmentally induced failure processes may often be the result of hydrogen damage. Atomic hydrogen is a cathodic product of many electrochemical reactions, forming during many naturally occurring corrosion reactions as well as during many plating or pickling processes. Whether hydrogen is liberated as a gas, or atomic hydrogen is absorbed by the metal depends on the surface chemistry of the metal.

Due to its small size and mass, atomic hydrogen has very high diffusivity in most metals. It will therefore penetrate most clean metal surfaces quite easily and will migrate rapidly from favourable sites where it may remain in solution, precipitate as molecular hydrogen to form small pressurized cavities, cracks, or large blisters, or it may react with the base metal or with alloying elements to form hydrides.

The accumulation of hydrogen in high strength alloys often leads to cracking, and this often occurs in statically loaded components several hours or even days after the initial application of the load or exposure to the source of hydrogen. Cracking of this type is often referred to as hydrogen-stress cracking, hydrogen delayed cracking, or hydrogen induced cracking. Similar fracture processes can occur in new and unused parts when heat treatments or machining treatments have left residual stresses in the parts, and have been exposed to a source of hydrogen. For this reason, all processes such as pickling or electroplating must be carried out under well-controlled conditions to minimize the amount of hydrogen generated.

5.2.1.7 *Stress Corrosion Cracking*

Alloys are often selected because they are known to be resistant to corrosion in a particular operating environment. However, experience has shown that components may still fail by a process involving the corrosion induced initiation and growth of cracks when a tensile stress exists above some critical level in the surface of the part. When the mechanisms of crack growth involve the synergistic action of the corrosive environment and the sustained stress acting at an exposed surface, the failure mode is known as Stress Corrosion Cracking (SCC). This mode of failure has been called sustained load environmental cracking and is dependent on the simultaneous occurrence of three distinct conditions:

1. The existence of a surface tensile stress of a sufficient magnitude in the part concerned.

2. The presence of an aggressive environment with access to the surface of the part.

3. A material which is susceptible to localized corrosion along specific paths which may or may not link up.

If any one of these factors is absent, the stress corrosion phenomenon will not develop.

Stress corrosion is a localized form of corrosion which is particularly insidious since it will often occur with little or no visual evidence of surface corrosion, such as discolouration or the build up of noticeable corrosion products. Stress corrosion cracks can travel over long distances with time, and as they propagate, they lower the residual strength of the affected part. The cracks may propagate deeply into thick section parts, while the visible surface crack length may often be quite small.

Once the stress corrosion crack has formed, it will continue to grow, stopping only when the tensile stress has fallen below the critical value, or when the corrosive environment is excluded. The crack may permanently arrest if tensile residual stresses are relaxed by the initial crack advance. If the stresses are due to assembly forces, such as from interference fit bushings or fasteners, or are a result of service operations, the cracks may continue to grow until the component can no longer sustain them, causing catastrophic failure.

5.2.1.8 *Corrosion Fatigue*

Fatigue involves the initiation and growth of cracks in solids which are subjected to repeated cyclic stresses. The mechanical loads involved are generally quite small, and the stresses resulting from these loads are usually less than the yield strength of the material. Fatigue cracks usually initiate at free surfaces and at stress concentration sites such as abrupt changes in section, key-ways, fillet radii, fastener holes, or internal discontinuities such as inclusions or cavities. The total fatigue life of a component may be considered in terms of the number of cycles of stress required to cause crack initiation, and the number of cycles required to cause the crack to grow to a size where the remaining load bearing cross sectional area can no longer sustain the applied loads. Sudden catastrophic rupture of the remaining ligament then occurs.

When fatigue occurs in the presence of a corrosive environment, failure usually occurs in a shorter time and in fewer cycles than would be the case in a dry or benign environment. This synergistic effect between fatigue and corrosion is known as corrosion fatigue, and it may involve either a decrease in the number of cycles to crack initiation or an acceleration of fatigue crack growth rates, or both. An important feature of corrosion fatigue is that mechanical damage and corrosion damage occur simultaneously and synergistically. In many cases the two modes of degradation will occur successively or alternately, in which case the damage would not be attributed to corrosion fatigue. This might be the case, for example, when pitting corrosion occurred first in a metal component, and then fatigue crack propagation occurred from the base of a corrosion pit. The fatigue contribution to the failure process could occur even in the absence of a corrosive environment. The correct description of the failure process in this case would be pitting followed by fatigue, rather than corrosion fatigue. However, while hypothetical failure processes can be classified quite easily, and even failures produced under laboratory conditions, it is not always easy to correctly classify failures under service conditions.

5.2.1.9. *Standards*

The following standards are applicable

ASTM B117	Salt Spray & SCC testing
ASTM G44	K01 Corrosion Behaviour
AMS 4229	K01-T7 Material Spec.
AMS 4228	K01-T6 Material Spec.
MIL-A-21180	K01 Material Spec.
MIL-H-6088E	I.C. Testing Procedure as related to "heat treatment of aluminium alloys"

5.2.2 **Aluminium-alloy A357**

Aluminium-silicon alloys are generally corrosion resistant. Although magnesium in solid solution tends to make the potential more anodic and silicon more cathodic, when both are in solid solution in the ratio of Mg_2Si, the electrode potential is essentially the same as the potential of aluminium. In this manner, the strengthening precipitates of A357 do not promote intergranular corrosion of the cast structure.

Copper is present in Al-Si-Mg alloys to increase strength and fatigue resistance of the alloy, without loss of castability.

The solid solubility of copper in aluminium (disregarding the effects of Mg, Mn, Si, Zn, Fe and Ti) at room temperature is approximately 0.05%. Therefore theoretically as long as the copper is ≤ 0.05% in A357 alloys, the alloy should exhibit excellent resistance to intergranular corrosion. Therefore keep Cu ≤ 0.05% to get good corrosion resistance.

To sum up, from available published data and reports, it may be concluded that A357 has an excellent corrosion resistance for a wide range of solidification conditions. See also Table 5.4.

5.2.3 Aluminium-alloy A201

The aluminium casting alloy A201 was developed to achieve superior strength at room and elevated temperatures. It has been used extensively in sand, permanent mould and investment cast parts for a variety of applications. However in a few instances, there have been reports of failures due to stress corrosion cracking. Although these have been rare, great concern has been expressed regarding the stress corrosion cracking (SCC) susceptibility of alloy A201.

Alloy A201 has a nominal composition of 4.7% Cu, 0.3% Mg, 0.28 Mn, 0.25 Ti, 0.01% Si, 0.01% Fe, 0.6% Ag, and balance aluminium. The high copper level suggests that under certain conditions of heat treatment, stress corrosion could be a problem. There has been much history of stress corrosion cracking in high strength wrought aluminium alloys such as 2024.

However, according to the patent for A201 alloy, the silver addition is essential to impart good stress corrosion resistance. Studies done by the foundry Cercast have shown this to be untrue and that under certain specific conditions, the alloy can be sensitized to stress corrosion cracking. Overaging reduces the susceptibility to SCC. However, overaging has a deleterious effect on ductility.

Based on the results of the stress corrosion cracking studies conducted by laboratories the following conclusions can be drawn:

a) Alloy A201 castings properly heat treated to the T7 temper are substantially immune to stress corrosion cracking; the T4 temper gives intermediate susceptibility to stress corrosion cracking, and the T6 temper is highly susceptible to stress corrosion cracking.

b) Variations in the chill or solidification rate of a casting do not influence the stress corrosion cracking resistance of alloy A201.

c) Quenching rate from the solutionizing temperature exercise considerable influence over the stress corrosion cracking resistance of A201 alloy castings in the T7 temper. Slow cooling from the solutionizing temperature to room temperature produces severe susceptibility to stress corrosion cracking. This is due to formation of a grain boundary network of anodic $CuAl_2$ particles. Coarse $CuAl_2$ particles in the matrix do not appear to influence stress corrosion resistance.

The recommended practice for heat treating alloy A201 to ensure maximum resistance to stress corrosion cracking is as follows:

1. Solutionize at 505°C to 528°C (940 to 980°F) for 2 hours, increase to 528°C to 532°C (980 to 990°F) and hold for 17 hours.
2. Quench in water at 66°C (150°F) to 88°C (190°F) and hold for 5 minutes, then air cool to room temperature.
3. Age at room temperature for 12 to 24 hours
4. Artificially age to the T7 temper, 185°C (365°F) to 191°C (375°F) for 5 hours and then air cool to room temperature.

The solution heat treatment step is critical in making good A201 alloy castings. Careful temperature control must be maintained in order to obtain adequate dissolution of second phase in the cast structure and prevent incipient melting (i.e. burning). This is necessary to achieve good mechanical properties as well as resistance to stress corrosion cracking.

Coatings recommended for alloy A201 include those produced by sulphuric anodizing with a dichromate seal, or as an alternate, chemical conversion coatings such as those produced by the Alodine 1200, treatment

Specimens in the -T4 and -T6 conditions, with anodized coatings and with chromate conversion coatings, have passed the 30-day, 3½% NaCl alternate-immersion test. Reportedly, the stress-corrosion cracking resistance of A201 in the -T6 condition is not as good as A357 alloys but is better than the high strength forging alloys such as 7075-T6, 7079-T6 and 2014-T6 forgings.

In the T7 condition requirements include 30 days in alternate immersions of 3½% sodium chloride with 10 minute immersion and 50 minutes air under stress of 75% of the yield strength. The stress corrosion cracking resistance of A201 alloy is considered to be adequate in the T7 condition.

Table 5.4 shows the results of intergranular corrosion testing

5.2.4 Summary: Al-Alloys A357 and A201

Basically, alloy A357 is relatively corrosion resistant for a wide variety of chemical and heat treatment variations.

Alloy A201 can be sensitive to corrosion particularly SCC, and a correct combination of selected alloying elements and particular heat treatment are necessary to yield a satisfactory corrosion resistance performance. Most A201 castings are also protected with electrochemical conversion coatings with special primers or paint before being used in service.

5.2.5 Titanium-alloy TiAl6V4

5.2.5.1 *General*

For the most corrosive environments such as chemical plant and seawater equipment, commercially-pure titanium (known as CP) is ideal. Its corrosion resistance, especially in oxidizing acids, is far better than any stainless steel or the traditional nickel-copper alloys, and its moderate strength is good up to over 750°F (400°C).

Where higher strength or erosion resistance is needed, Ti-6Al-4V (usually called 6-4 alloy) is the standard material. While still retaining good corrosion resistance, its mechanical properties are better than most steels, especially when its low weight is taken into account. The 6-4 alloy has a useful temperature range that is similar to that of CP and the cost of the castings is about the same in either material.

5.2.5.2 *Surface Treatments*

Anti-corrosive plating is not required on titanium

Table 5 4

Alloy & Temper	DAS or Grain size (µm.)	Corrosion Depth (µm.) (MIL-H-6088E) *
A201 - T7	120	195
A201 - T7	190	197
A357 - T6	40	8
A357 - T6	110	10

* Maximum allowable penetration of 250 µm. recommended by CERCAST INC. for respective testing.

Intergranular Corrosion
Testing of Investment Cast A357 and A201
(Foundry: Cercast INC.)

components, as the basic material is as good in this respect as the platings (nickel, copper and chrome) which are conventionally applied to ferrous materials to resist corrosion.

5.2.5.3 *Corrosion Resistance*
Titanium is extremely corrosion resistant, its alloys being almost as good in this respect. Because of these excellent properties titanium and its alloys are being increasingly used for commercial and military engine, chemical processing and airframe applications.

Its corrosion resistance is due to the rapid formation, in air or water, of a stable oxide film which protects the base metal.

The data in this section are gathered from a variety of sources

a) *Galvanic Effects*
Titanium comes high in the galvanic series as shown in Table 5.5 and will not suffer electrolytic corrosion when used in contact with other metals. However, when designing an assembly involving titanium being in contact with other metals, for use in a hostile environment, consideration must be given to the other metals involved.

Stainless steel parts should be used in the passivated condition, and steel bolts, nuts and washers should preferably be silver-plated. Nickel plating is acceptable for use in normal atmosphere conditions. Never use zinc-plated parts in contact with titanium.

b) *Seawater Environment*
In one test programme, 73 samples of titanium (22 pure, the rest various alloys) were immersed in seawater at depths to 6,780 feet (2067 m) and periods to 3 years.

There was no measurable corrosion on any sample, this being defined as below 0.1 mils per year (2.5 microns per year)

5.2.5.4 *Summary*
Titanium casting applications are wide spread in commercial and military engine, chemical processing and airframe applications.

Chemical processing applications take advantage of the corrosion resistance of titanium. For example radial impellers are used for pumping salt water in a desalinization plant. Another similar application is a large inducer used in the torpedo ejection system of a submarine. The resistance to salt water corrosion is of prime importance in this application.

Titanium's high resistance to erosion and corrosion will often extend the life of a component compared to cheaper metals, so that its initial cost is more than recovered in lower overhaul and replacement parts costs and less downtime for the plant in which it is fitted

Table 5 5
GalvaNAIC Series in Flowing Seawater 13 ft/sec (4 m/sec)
at 75°F (24°C)

METAL	POTENTIAL VOLT*
T 304 Stainless Steel (passive)	0.08
Monel	0.08
Hastelloy C	0.08
TITANIUM (unalloyed)	0.10
Silver	0.13
T 410 Stainless Steel (passive)	0.15
Nickel	0.20
T 430 Stainless Steel (passive)	0.22
70-30 Cupro-Nickel	0.25
90-10 Cupro-Nickel	0.28
Admiralty Brass	0.29
G Bronze	0.31
Aluminum Brass	0.32
Copper	0.36
Naval Brass	0.40
T 410 Stainless Steel (active)	0.52
T 304 Stainless Steel (active)	0.53
T 430 Stainless Steel (active)	0.57
Carbon Steel	0.61
Cast Iron	0.61
Aluminum	0.79
Zinc	1.03

*Steady-state potential, negative to saturated calomel half-cell

6. DAMAGE TOLERANT DESIGN WITH CASTINGS

6.1 BACKGROUND

During the late 1960s there were a number of aircraft structural failures which were attributed to cracking problems in relatively high strength structural materials. These failures resulted in unacceptable maintenance and repair costs, excessive aircraft downtime and in some cases loss of life and aircraft.

Fortunately, the state-of-the-art of fracture mechanics had reached the stage of development where it could be employed for the first time as a quantitative tool in aircraft failure analysis. Based on the success of this fracture mechanics approach the United States Air Force required the implementation of a damage tolerant analysis in the design of all critical components in new aircraft. This was accomplished through MIL-A-83444 "Airplane Damage Tolerance Requirements". Similar documents have been or are being developed for other agencies, both military and civilian.

Concurrent, but independent of the development and implementation of damage tolerant design requirements, the state-of-the-art in premium quality aluminium and titanium castings has progressed to the point where their use in critical aircraft structure now appears possible. If produced in sufficient quantity, cost savings of over 30 percent have been demonstrated in programmes to develop an experimental aluminium bulkhead for the YC-14 and a vertical tail structure for the F-16. This reduction in cost with no increase in weight over the wrought product has been made possible largely through the elimination of lap joints and mechanical fasteners. Despite these cost advantages and the fact that several thousand castings are used in secondary structure of many modern aircraft, cast aluminium has had very limited use in primary load carrying aircraft applications.

Many factors have served to limit this extended use. Included are the lack of design allowables, the imposition of casting factors, and unknown damage tolerance behaviour. While the lack of allowables and the use of a casting factor may be issues which are near resolution, the impact of damage tolerant design requirements on critical casting applications is largely unknown and will be a major factor in their extended application. The remainder of this chapter will deal with these concerns and requirements. Hopefully, damage tolerant requirements, when properly applied, will encourage the reliable use of castings rather than serve as an additional barrier.

6.2 DAMAGE TOLERANT DESIGN

The application of damage tolerance to design is not just a method of calculating the stress on a part containing a flaw. Damage tolerant design involves three essential factors: (1) the assumption of a pre-existing flaw in every critical part, (2) an analysis of the rate at which this flaw will grow during the service life of a product and, (3) the critical size at which this crack will cause component failure. The materials producer and the designer are equally responsible in the success of a damage tolerant approach. To manufacture a casting which can be used in a damage tolerant design the foundry must understand and apply the use of non-destructive inspection techniques beyond the capability of conventional x-ray techniques. In addition, for the first time metallography will be required as a quality acceptance procedure. Fracture mechanics testing may be required to verify and guarantee fracture toughness values similar to the way in which tensile and yield strength values are currently assured. These additional requirements will introduce additional cost and require greater expertise in the quality control and acceptance process. Some foundries and users may not be willing to undertake these changes.

None of the current damage tolerant requirements refer to castings or make any distinction between product forms. It is the stated intent of the previously referenced MIL-A-83444 to ensure that the maximum initial flaw size in any material will not grow to a size such as to endanger flight safety at any time during the design life of the aircraft. To assist in the application of MIL-A-83444, the United States Air Force has prepared AFWAL-TR-82-3073, "USAF Damage Tolerant Design Handbook. Guidelines for Analysis and Design of Damage Tolerant Aircraft Structure". This document contains the data to support the rationale and assumptions in the damage tolerance requirements and recommended practices.[1] A companion document (4 volumes) MCIC-HB-01R "Damage Tolerant Handbook. A Compilation of Fracture and Crack Growth Data for High Strength Alloys" has also been published.[2] This document provides a single comprehensive reference source on available fracture mechanics data. At the present time (1987) no data on castings are included in this compilation although sufficient data should be available on A357 and A201 aluminium, for inclusion in the next revision.

Figure 6.1 is a somewhat simplified illustration of how the three damage tolerant factors will influence predicted life and critical crack size. In this case, the baseline data are for 2024-T851 tested to an F-16 flight load spectrum. If similar initial flaw sizes and crack growth rates are assumed for a casting, changing the fracture toughness level from 22 KSI $\sqrt{in}$ (24.2 MPa $\sqrt{m}$) to 13 KSI $\sqrt{in}$ (14.3 MPa $\sqrt{m}$) would reduce the predicted aircraft life by almost 50 percent.

While the remainder of this section will refer primarily to aluminium castings which represent the majority of experience and available data, the application and requirements for the use of titanium castings in loaded structure will be similar.

6.2.1 Durability Design

In addition to a damage tolerant analysis the United States Air Force has recently initiated durability design requirements. Durability is a measure of the structure's resistance to fatigue cracking during service and a statistical assessment of the repair costs. As long as such cracks can be economically repaired, the analysis is concerned with small crack sizes which affect life-cycle-costs rather than safety of flight. Durability requirements are specified in MIL-A-87221, the "USAF Durability Design Handbook. Guidelines for the Analysis and Design of Durable Aircraft Structures". Where castings are employed as load carrying members in military aircraft, whether primary structure or not, they will be subject to such an analysis. From a foundry standpoint, the quality control practices described in this document to ensure adequate damage tolerance will also relate to durability. For the designer, although the analysis is different, the mechanical property data requirements are essentially the same.

6.3 INITIAL FLAW SIZE

In a damage tolerant analysis the initial flaw size is the largest flaw that can be assumed to be in a structure at the time of manufacture. From a practical standpoint, this represents the largest defect that may not be found during quality control inspection. In wrought products these flaws can be in the form of inclusions, forging laps, forming cracks, scratches, etc. For the most part these defects are of an external nature and are identified through visual, X-ray, ultrasonic, eddy-current, and liquid penetrant inspection. On the other hand castings are particularly vulnerable to defects such as gas porosity, internal shrinkage, and dross inclusions. User acceptance techniques for castings are, for the most part limited to X-ray radiography (for internal flaws) and liquid penetrate (for surface flaws). From a practical standpoint, internal defects are currently detectable when their size is greater than one percent of the thickness of the material being examined, assuming inspection is not masked by excessive porosity.

Specific initial flaw sizes are recommended in MIL-A-83444. These values are essentially 0 05" (1 27 mm) on one side of holes and cutouts and 0 125" (3.17 mm) for surface crack lengths at locations other than holes. Where the contractor can demonstrate a capability for identifying smaller flaw sizes, these smaller flaw sizes can be negotiated with his procurement agency. In the case of castings, the user should be able to justify the use of the flaw sizes specified in MIL-A-83444.

A durability analysis requires an initial flaw size of 0 01 inch (0 254 mm). However, this is only a specified starting point for durability analysis and should not be confused with an inspection capability requirement as referenced above for damage tolerance.

6 4 CRACK GROWTH RATE

The rate at which a flaw will grow until it reaches a critical crack size in a structure can be a rather elusive value. Crack growth rates for wrought products depend on the magnitude (max stress) of the applied stress, the ratio of minimum to maximum stress (stress ratio), and the environment (humidity and temperature). The ordering of loads or spectrum effects are also important in relating the life of a crack growth specimen to the actual life of a component. The generic standard for crack growth testing of metals at constant amplitude is contained in ASTM E647. Although castings are not affected by specimen orientation, the establishment of valid data is difficult due to their intermittent growth characteristics as will be discussed later.

While the above effects are very complex, overall it appears that the crack growth rates for castings compare favourably with the crack growth rates for wrought products. In fact, some data such as those shown in Figure 6.2 indicate that the potential for superior crack growth characteristics for castings may exist.[3] In this study several samples of a cast aluminium component exhibited longer spectrum fatigue lives than either the mechanically fastened or adhesively bonded components. Unfortunately, the scatter in the casting data was such that other samples also exhibited the shortest lives. Consequently, the designer can not presently rely on the high values. Very little is quantitatively known about the effect of casting discontinuities on crack growth rate. It is not known whether the growth rate will increase as it goes through an area of high porosity as the small voids link up (as in a roll of perforated paper) or whether each void will tend to act as a crack stopper, temporarily slowing the progress of the crack. Using typical crack growth specimens developed for wrought products as shown in Figure 6.3, investigators have had problems with intermittent growth rates, branching, and uneven crack fronts with castings. This difficulty has also been encountered in pre-cracking fracture toughness specimens as shown in Figure 6 4.

The use of metallographic controls on dendritic arm spacing or cell size in procurement specifications to reduce scatter in tensile properties of the A357 aluminium alloy has recently been initiated. The long term impact of these controls with their inherent finer microstructure, on crack growth has not yet been established for production castings. Other considerations such as the effects of weld repair on crack growth rate are also under investigation, but it may be years before these relationships are firmly established. In the meantime, it appears that the crack growth resistance of castings will not be a disqualifying factor for their application in critical load carrying structure.

6.4.1 Fatigue Crack Growth Rate Data

6 4 1 1 *A201-T7*

Figure 6 5 shows fatigue crack growth rate data obtained from five specimens from two producers, of step block castings of A201-T7 alloy. These specimens were tested at the AFWAL Materials Laboratory.[4] The specimens were standard compact-tension (CT) specimens, 0.368 inches (9.35 mm) thick (B) and 2 000 inches (50 8 mm) wide (W).

All chemistry was within the following limits:

Copper	4.5—5 0 percent
Silver	0.5—1.0 percent
Manganese	0 20—0.50 percent
Magnesium	0 25—0.35 percent
Titanium	0 15—0.30 percent
Iron	0 05 percent max
Silicon	0 10 percent max
Aluminium	Balance

Ultimate strength, yield strength and fracture toughness values were reported by the supplier to be 60 KSI, 55 KSI, and 30—33 KSI $\sqrt{\text{inch}}$ (413 7 MPa, 379 2 MPa, and 33 0—36.3 MPa $\sqrt{\text{m}}$) respectively. Crack growth tests were conducted in accordance with ASTM standard E 647, "Standard Method for Constant-Load-Amplitude Fatigue Crack Growth Rates Above 10—8 m/cycle". Specimens were pre-cracked and tested on a 25 kip (111 2 KN) electrohydraulic fatigue machine. Crack length was measured optically using a travelling microscope. An R ratio of 0.1 was applied sinusoidally at 25 Hz. All tests were conducted at room temperature in lab air.

The seven point polynomial method was used to convert the "a" versus "K" data to values of "da/dn" versus ΔK". A comparison of data in Figure 5, with similar data from MIL-HDBK-5D on 2124-T851 wrought plate 2 inch (50 8 mm) — 5 inch (127 mm) thick, indicates that, within the 10^{-6} to 10^{-5} inch/cycle (25 4 × 10^{-6} to 254 × 10^{-6} mm/cycle) range, both materials have similar crack growth rates. During testing it was noted that the fatigue crack followed a tortuous route and branched regularly. While this branching apparently contributes to the good fatigue crack growth resistance of A201-T7 it makes the stress intensity measurements less exact.

6.4.1.2 *A357-T6*

Specimens from similar step block castings of A357-T6 from two different producers were also tested.[4] Specimen configurations, test equipment and loading procedures were the same as for the A201-T7 alloy. Alloy chemistry was within the following limits except for low silicon in specimen 97CG1

Silicon	6.5–7.5 percent
Magnesium	0.55–0.65 percent
Iron	0.20 percent max
Titanium	0.10–0.20 percent
Beryllium	0.04–0.07 percent
Zinc	0.10 percent max
Copper	0.20 percent max
Manganese	0.10 percent max
Aluminium	Balance

The results from three specimens from producer B castings are shown in Figure 6.6. Specimen 36CG1 results deviated from the others at low K's. At a stress intensity of approximately 11 KSI $\sqrt{in}$ (13.3 MPa $\sqrt{m}$) and above, all of the producer B results assume the same form.

The crack arrest data based on producer A castings revealed somewhat greater scatter as shown in Figure 6.7. At low ΔK values specimen 89CG1 had the least crack growth resistance while specimen 97CG1 had the most crack growth resistance. The low silicon specimen 97CG1 was in line with the other producer A plots.

The Boeing company has done appreciable crack growth testing of A-357 specimens from several large experimental cast bulkheads for the YC-14 aircraft. These bulkheads were produced by two different foundries.[5] These tests were conducted under similar conditions as the previously shown AFWAL tests except that the stress ratio, R, was 0.06 rather than 0.10. The test data is summarized in Figure 6.8, which also shows upper and lower bounds of similar data from separately cast test bars. Of all the specimens cut from the bulkheads, four of these specimens contributed to the majority of the scatter shown in Figure 6.8. Figure 6.9 shows these same crack growth data with these four specimens excluded. Boeing's examination of these four specimens indicated a slight increase in microshrinkage compared to the others.

Additional tests on Boeing bulkhead castings were conducted at AFWAL at a stress ratio of R = 0.20 and very carefully controlled conditions of 5 percent dry air.[6] These data are shown in Figure 6.10. Relatively little scatter is noted in these data and that present is on the right or slower crack growth side of the curve.

Following the success of the Boeing CAST programme, an effort was initiated to design, build and test an experimental vertical tail for the F-16 aircraft.[7] The preliminary design was based largely on the CAST programme data. Verification of the design included the crack growth evaluation specimens subsequently extracted from the cast tail structure. These data are shown in Figures 6.11 and 6.12. The data included three different "R" ratios and two humidity conditions. Differences in crack growth rate due to stress ratio and humidity, while evident, do not appear to be any less or more severe than observed for wrought aluminium products.

Cast A357-T6 was included in an overall investigation of the fracture properties of a number of wrought alloys including 2024-T351, 7475-T7351, 7050-T736, 7475-T76, 7075-T6, 7075-T7351, 7178-T651 and 6061-T651.[8] This programme, conducted by MBB UT Bremen, reported data on A-357 which compared well with the Boeing and AFWAL data previously discussed. In the MBB report the A-357 had nearly the same crack growth characteristics as 2024-T351 plate which, in turn, had better crack growth behaviour than any of the 7000 series alloys which they tested. The basis for these findings are shown in Figure 6.13. Unfortunately, from a casting standpoint, MBB also concluded that the residual strength of the A357, using a centre cracked plate, was lower than any or the wrought products. This conclusion based on the data in Figure 6.14 is somewhat reflected in the fracture toughness data reported in Section 6.5.1 of this report.

6.4.1.3 *Ti 6Al-4v*

Ti 6Al-4V is the most widely produced titanium alloy in both the wrought and cast form. As with wrought aluminium, wrought titanium benefits from subsequent mechanical working which allows microstructural configurations not possible with the cast part. Without additional processing, the differences between castings and the wrought product show up primarily in reduced high cycle fatigue (or crack initiation resistance) for the castings. However, titanium castings appear to be more amenable than aluminium to variations in thermal processing and the benefits of hot isostatic pressing (HIP), to the point where titanium alloy castings can be produced with properties which can be compared to the wrought product.

Metallurgically this comaparability is due to a phase transformation in titanium from alpha to alpha+beta at temperatures well below the solidification temperature (beta transus temperature). The cast beta structure is tansformed into an alpha colony plate structure which is much the same as the beta annealed structure in wrought titanium products. This results in improved creep and fracture resistance without a loss in fatigue crack growth.

The major benefit of the HIP process is to improve the high cycle fatigue strength of castings through pore closure. These high cycle fatigue benefits are shown in Chapter 3 in this handbook. The overall crack growth characteristics which are relatively unaffected by either variations in microstructure or the HIP process, are shown in Figure 6.15.

While the benefits of such improvement practices are well documented in the literature and are standard practice at several foundries, they are not yet covered by recognized industry or government processing standards.

6.5 CRITICAL FLAW SIZE

Critical flaw size is the size at which growing cracks will propagate in an unstable manner and cause the specimen or component to fail. The critical flaw size is a function of the fracture toughness (K_{Ic}) as well as applied stress. Fracture toughness is particularly important to foundries producing castings because, for damage critical applications, the foundries will have to guarantee castings to meet toughness requirements in the same way that tensile values are now guaranteed. The guaranteed values may not necessarily be included in industry specifications, but they must be agreed-upon values negotiated with the customer. These are the values the designer will use in his design and obviously the application will not reach its desired lifetime if these guaranteed values are not met. A typical fracture toughness specimen was shown in Figure 6.4 and the appropriate test methods are fully described in ASTM E-399. Unfortunately, in order to obtain valid test data on castings the thickness of this specimen may have to exceed the section thickness available from typical aerospace castings. Consequently, appropriate test areas or prolongations may have to be designed into a part. In some cases other tests such a R-curve and J-integral evaluations, (which are also described in ASTM test methods) may have to be negotiated as a substitute.

The aluminium industry has identified specific wrought alloys as the only ones on which fracture toughness guarantees will be given. These alloys are, for the most part, similar to non-guaranteed alloys; but with tighter chemistry, particularly on elements which have been shown to be fracture toughness critical. For example, Fe and Si are lowered in modifying 7075 and 2024 to produce 7175 and 2124 respectively. Fracture toughness guaranteed alloys such as 7175 and 2124 will generally sell at a premium to cover these tighter chemistry controls and the expense of qualifying fracture toughness tests. This approach of wrought alloys appears to be logical for casting alloys. The new AMS specifications (AMS 4241 and AMS 4242) include both metallographic controls and tighter chemistry than that specified for A357 and A201. The designation for these new alloys is D357 and B201.

The state-of-the-art in the development of industry wide specifications and metallographic controls for high performance titanium castings is not as well developed as it is for the aluminium product. However, the basis for such quality control does exist and the potential payoff for such standardization and the application of such standards is quite high. In the meantime, any fracture toughness guarantees have been the result of individual negotiations between the customer and foundry.

6.5.1 Fracture Toughness Data

Plane strain fracture toughness data (K_{Ic}) on advanced aluminium castings which meet ASTM E-24 requirements are exceedingly difficult to obtain. This is largely due to unequal growth along various portions of the crack front and the need for a thicker specimen than is usually available from castings to ensure a plane-strain condition at the crack tip. To ensure this plane-strain condition, ASTM defines fracture toughness values as "K_Q" which become valid "K_{Ic}" numbers only after meeting certain criteria specified in ASTM E-399. Very few specimens tested in any of the referenced programmes met the ASTM validity requirements. The valid K_{Ic} values for A357-T6 ranged from 16.0 to 19.4 KSI $\sqrt{in}$ (17.5 to 21.3 MPa $\sqrt{m}$). In contrast typical values for wrought 2124-T851 plate ran from a low of 17 KSI $\sqrt{in}$ (18.7 MPa $\sqrt{m}$) in the short transverse direction to values of 21 to 37 KSI $\sqrt{in}$ (23.1 to 40.6 MPa $\sqrt{m}$) in the longitudinal direction as shown in Table 6.16. Obviously, the fracture toughness of aluminium castings will need improvement to be fully competitive with wrought products in the longitudinal and transverse directions.

The small amount of data that do exist on the fracture toughness of titanium castings indicate K_{Ic} tests on castings may be no more difficult to make than on the wrought product. However, due to the wide variations in thermal processing that are available for both the wrought and cast materials, realistic comparisons between the two forms should be made with caution.

6.5.1.1 *A201-T7*

The Northrop data on step block A201-T7 castings are shown in Table 6.17. All the values were valid K_{Ic} values. As these values ranged from 23.2 to 33.2 KSI $\sqrt{in}$ (25.5 to 36.5 MPa $\sqrt{m}$), it appears that the A201-T7 alloy will have superior fracture toughness compared to the A357-T6 alloy.

Swiss Aluminium Ltd has done appreciable evaluation of the A201 alloy in both the T6 and T7 conditions. Most of these data are in company reports.[10] "R" curve data, welding and thickness effects are addressed. For a specimen thickness of .571 in (14.5 mm) they reported an average K_{Ic} value of 34.4 ± 2 KSI $\sqrt{in}$ (37.9 ± 2.2 MPa $\sqrt{m}$).

6.5.1.2 *A357-T6 (Boeing)*

None of the specimens extracted from the experimental bulkhead produced during the CAST programme at Boeing exhibited valid K_{Ic} numbers.[5] They did obtain K_Q values on A-357 ranging from 13.9 KSI $\sqrt{in}$ (15.3 MPa $\sqrt{m}$) to 24.4 KSI $\sqrt{in}$ (26.8 MPa $\sqrt{m}$) which are shown in Table 6.18. Pre-design test data from Boeing on separately cast test plates are shown in Table 6.19. In this case, four tests did result in valid K_{Ic} numbers.[11]

6.5.1.3 *A357-T6 (General Dynamics)*

Fracture toughness data from the General Dynamics programme to fabricate and test an experimental F-16 vertical tail also reflect this difficulty.[7] Table 6.20 shows K_Q values from A-357 specimens cut from this tail structure. While invalid by ASTM criteria, these numbers are all well above the value of 13 KSI $\sqrt{in}$ (14.3 MPa $\sqrt{m}$) which was taken from the CAST programme and used in the damage tolerant analysis of the F-16 component.

6.5.1.4 *A357-T6 (Northrop)*

Another source of fracture toughness data on A357 was the Northrop programme to study processing effects on A357 and A201 casting alloys.[9] The A357 data are shown in Table 6.21. None of these values passed the ASTM criteria.

6.5.1.5 *A357-T6 (Other Data)*

Data were obtained from the Premium Casting Division of ALCOA, a producer of A357.[12] Two of their four tests developed valid K_{Ic} numbers. Their data are shown in Table 6.22.

Martin Marietta Aerospace evaluated A357-T6 for large diameter elbow castings in a space system. They used a semi-elliptical surface flaw specimen and obtained K_Q values of 23 and 27 KSI $\sqrt{in}$ (25.3 and 29.7 MPa $\sqrt{m}$) on parent material and 24 and 26 KSI $\sqrt{in}$ (26.4 and 28.6 MPa $\sqrt{m}$) on weld repaired test plates.[13] This is consistent with the previously referenced Northrop data which also included weld repaired material and showed no loss of K_Q in the weld.

6.5.1.6 *Summary of A357-T6 K_Q Data*

An analysis of the A357-T6 data from four different sources in Tables 6.18 through 6.22 is shown in Table 6.23. Data on all thicknesses is consolidated. Of these 41 K_Q values, six are valid K_{Ic} values per the ASTM E-399 requirements. The validity of these requirements for K_{Ic} is evident in that the variance in the valid data is only a fraction of that of the non-valid data. Even though the mean of the valid data is lower, an estimated design value at two standard deviations below the mean would actually be higher than if the non-valid K_Q data were considered.

6.5.1.7 *Ti6Al-4V*

Table 6.24 shows typical fracture toughness data on commercially available titanium castings that were available from several sources at the time of this report. Of these data, none were valid per ASTM K_{Ic}/yield thickness criteria. No crack curvature validity checks were made. The only ASTM valid data were data on material which had been subject to noncommercial proprietary thermal processing.[13] These valid K_{Ic} values (which are not shown in Table 6.24) ranged from 53 2 KSI $\sqrt{in}$ (58.5 MPa $\sqrt{m}$) to 73 6 KSI $\sqrt{in}$ (80 9 MPa $\sqrt{m}$) which are typical of transverse and longitudinal K_{Ic} values for STA titanium plate. Had larger specimens been used on the conventionally processed and HIPed castings it can probably be assumed that values would fall between those shown as K_Q numbers in Table 6.24 and the proprietary processed material, e g. 70—90 KSI $\sqrt{in}$ (77—99 MPa $\sqrt{m}$). Such assumed values are typical for Ti 6Al-4V wrought annealed material

It should be noted that the failure to obtain a significant amount of valid fracture toughness data on Ti castings was generally due to the relatively high K_Q/yield strength ratio of titanium and not due to difficulties in the pre-cracking process as has been the case with aluminium castings. This same K_Q/yield strength problem arose during the initial development of K_{Ic} data on wrought Ti plate and specimens as thick as 3" (76 2 mm) were necessary to obtain valid data on re-crystallized annealed material. It has been estimated that 2" thick specimens would be necessary to obtain valid data for most of the cast material listed in table 6 24. Hopefully, such data will become available in the near future to expedite the application of a damage tolerant analysis to Ti castings.

6 6 METALLOGRAPHIC CONTROLS

It is a common observation that a finer microstructure will improve tensile properties. Chills are commonly employed to obtain a finer structure in critical casting areas. While a finer structure is desirable from a tensile property standpoint, it is difficult to non-destructively measure or inspect the microstructure from a quality control standpoint. A major step in this direction was work at ALCOA[18], followed by an effort by Boeing in the CAST programme to relate dendritic arm spacing in aluminium to the tensile allowables. Results from the experimental bulkhead used in the CAST programme resulted in the allowables shown in Table 6 25.[19]

Since then, Northrop has also shown that tighter controls on soundness, heat treatment and composition will significantly improve the consistency of the dendritic arm spacing to tensile property relationship.[9] Figure 6 26 shows some of the Northrop results.

Subsequently, Boeing has reported that cell size of the microstructure combined with silicon particle aspect ratio and porosity may be a more reliable metallographic quality control tool than dendritic arm spacing alone.[20] Cell size measurement may also be more amenable to automated techniques on the production floor than measuring dendritic arm spacing.

As previously shown, mechanical properties approaching those for wrought products can be obtained on a cast structure, but not on a consistent basis. The proposed metallographic controls should result in more consistent metallographic structure and static properties although they may not necessarily increase the maximum strength level. While the effect metallographic controls will have on fracture toughness is unknown, techniques that will increase product uniformity should also increase the consistency in fracture toughness. Specification ARP-1947 has been published to provide a procedure for dendrite arm spacing measurement and control of high strength A357 aircraft structural castings.

Somewhat similar effort has been conducted on Ti 6Al-4V relating alpha platelet thickness to mechanical properties.[19] This effort would indicate that a similar procedure might be developed for an industry wide specification for titanium castings.

6.7 DESIGN ALLOWABLES

Design allowables for military and civilian aircraft manufactured in the US are contained in MIL-HDBK-5, which has been maintained and updated continuously since 1938.[21] The "A" allowables in MIL-HDBK-5 represent values for which at least 99 percent of the population is expected to equal or exceed with a confidence of 95 percent "B" allowables represent 90 percent exceedance at a confidence limit of 95 percent Common practice is to require "A" allowables for primary load path structure. In order to ensure statistical reliability of the values from one lot of material to another, MIL-HDBK-5 requires, among other things, the existence of an industry wide approved specification to ensure that future production will be consistent with that material from which the allowables were developed In addition at least 10 lots of material and 100 specimens are required. Using these criteria, numerous attempts have been made to develop allowables for castings. In the past, these efforts had been unsuccessful due to the wide variation in properties that can be obtained both within a casting and from one casting design to another. As a result, each casting had its own statistical population group with a rather wide spread. The computed allowables not only failed to meet the MIL-HDBK-5 "A" and "B" allowables requirements for a single population group, but if all data were grouped, the resultant allowables would have been too low to be useful, even though most of the casting strengths were quite high. The AMS specifications previously referenced (AMS 4241 and AMS 4242) were developed to control the uniformity of the cast product and may be a breakthrough to the allowables problem. They control uniformity through tigher controls on chemistry and the use of metallography e.g., grain size or Dendritic Arm Spacing controls. The metallographic limitations relate to solidification rate which in turn relate to tensile properties Using these new specifications, a proposed set of "A" and "B" allowables for D357 have been developed and are being considered for publication in MIL-HDBK-5. However, the use of these new specifications and allowables are not without additional effort, understanding and cost on the part of both the foundry and user. This is because appropriate metallographic limitations for critical areas in the casting must be established and each production casting must be non-destructively inspected to insure that the microstructure conforms with these limitations.

6.8 CASTING FACTORS

For many years castings have not been associated with the quality level and consistency of product necessary for critical aircraft components. As a result, both civilian and military authorities have implemented somewhat arbitrary casting factors to increase the margin of safety for castings over that required for other products. Unsuccessful efforts to develop design allowables on castings have, until now reflected this inconsistency and verified the use of such factors.

For civilian aircraft in the United States, these factors are specified in Federal Aeronautics Regulation (FAR) 25. These regulations require a factor from 1.25 to 2.00 depending on various degrees of inspection to which the casting is subjected and to the criticality of use. The US Air Force requires a margin of safety of .33 (1.33 in FAA terminology) as specified in MIL-A-008860A. The US Navy requires no casting factor as long as the castings are procured under MIL-A-21180 MIL-A-21180 covers A357, A201 and several other aluminum cast alloys. This specification does not include metallographic controls.

During the last decade the state-of-the-art for premium quality casting has rapidly advanced. Several thousand castings are commonly used in each aircraft. However, with very few exceptions, none of these castings are used in primary load carrying structures Those that are used in non-primary loaded structures are almost always stiffness or modulus-critical rather than load-critical. This is because the implementation of a casting factor simply makes the casting non-competitive in a strength critical application In the past, use of these casting factors has been justified However, with the quality level available today, casting factors become redundant if statistically derived design allowables are available and if the material is obtained under a specification which embodies effective metallographic, heat-treatment, chemistry and NDI controls. The elimination of a casting factor will not be easily accomplished. Different controlling authorities will undoubtedly have different criteria for approving non-factor use or acceptance. Generally, however, it will first require the development of A and B design allowables on a given cast alloy Until recently, this had not been possible as discussed in Section 6.7 Once allowables are developed, the second step will be the implementation of foundry level control of the metallographic structure of each casting. The first production casting will have to be cut up to establish a tensile strength-metallographic acceptance criterion Each subsequent production casting will have to be metallographically examined to ensure continuing quality. Prolongations on each casting to further confirm heat-treatment response will also be required.

Requirements for casting factors in countries outside the US may vary. In Great Britain the requirements are included in various sections of Defence Standard 00-970. In essence, this standard requires the use of a casting factor only for flight critical structures where A and B allowables are not available. Under such conditions, a factor of 1 6 is required for aluminium sand castings. In West Germany, a casting factor of 1.33 is specified for Military, and 1 25 for civilian aircraft

6.9 REFERENCES

1. "USAF Damage Tolerant Design Handbook. Guidelines for Analysis and Design Damage Tolerant Aircraft Structure", AFWAL-TR-82-3073, May 1984.
2. "Damage Tolerant Design Handbook: A Compilation of Fracture and Crack Growth Data for High Strength Alloys", MCIC-HB OIR, December 1984.
3. Garver WR, Lee DY, Koepsel KM
"Initial Quality of Advanced Joining Concepts", AFWAL-TR-84-3066, December 1984.
4. Tirpak JD
"Constant-Load-Amplitude Fatigue Crack Growth Testing of Cast Aluminium Alloys A201-T7 and A357-T6", AFWAL-TR-85-4096, July 1985.
5. Gunther CK
"Cast Aluminum Structure Technology (CAST) Structural Test and Evaluation (Phase V) Part II-Fatigue and Fracture Properties of Cast Aluminum Bulkheads", AFWAL-TR-80-3021 Part II, April 1980.
6. Tirpak, JD
"The Variability of Fatigue Crack Growth Life of Cast Aluminum Alloy A357-T6", as AFWAL-TR-86-4115.
7. "Cast Aluminum Primary Aircraft Structure", AFWAL-TR-84-4070, Vols I and II, September 1985.
8. Schwarmann Luder
"Comparison of Aluminum Alloys Concerning Strength and Damage Tolerance", UT-111/85, Report TE 374/0723/85, MBB-UT Bremen, Aug 1985.
9. Oswalt KJ
"Manufacturing Methods for Process Effects on Aluminum Casting Allowables", AFWAL-TR-84-4117, March 1985
10. Brahler and Leupp
"Summary of Fracture Toughness Data" (ALUSUISSE Test Report 16/83 in German), Jan 1985.
11. "Cast Aluminum Structures Technology (CAST)", Quarterly Test Report D180-20159-4, April-June 1977, and D180-20159-7, January-March 1978.
12. "Mechanical Properties, Fracture Characteristics and Fatigue Tests of Premium-Engineered Casting Alloys", ALCOA Premium Casting Div Dept No Date.
13. Misra MS, Lemeshewski SD, Bolstad DA
"Fracture Toughness Evaluation of Premium Quality A357-T6 Castings", Martin Marietta Aerospace Test Report, No Date.
14. Eylon D, Froes FH, Gardiner RW
"Developments in Titanium Alloy Casting Technology", Journal of Metals, Vol 35, No 2, Feb 1983.
15. Soltesz SM, Smickley RJ, Dard LE
"Proceedings, Fifth International Conference on Titanium", Vol 1, Sep 1984
16. Baxter, WJ
"Evaluation of Ti 6Al-4V ELI Investment Casting", Martin Marietta Aerospace, Michoud Division, Test Report ETTR-132, Dec 1982
17. Sigur WA
"Properties of Ti-6Al-4V Titanium Alloy Rammed Graphite Castings", Martin Marietta Aerospace, Michoud Division, Test Report ETTR-95, Sep 1982
18. Spear RE, Gardner GR
"Dendrite Cell Size" Transactions of the American Foundrymen's Society, Vol.71, 1963, pp 209–215
19. Faber JW
"Cast Aluminum Structures Technology (CAST) Technology Transfer (Phase VI) Summary Technical Report", AFWAL-TR-80-3020, April 1980.
20. McLelland DL, Tuttle MM
"Manufacturing Methodology Improvement for Aluminum Casting Ductility", AFWAL-TR-82-4135, December 1982.
21. "Metallic Materials and Elements for Aerospace Vehicle Structures", MIL-HDBK-5D, Naval Publications and Forms Center, June 1983.

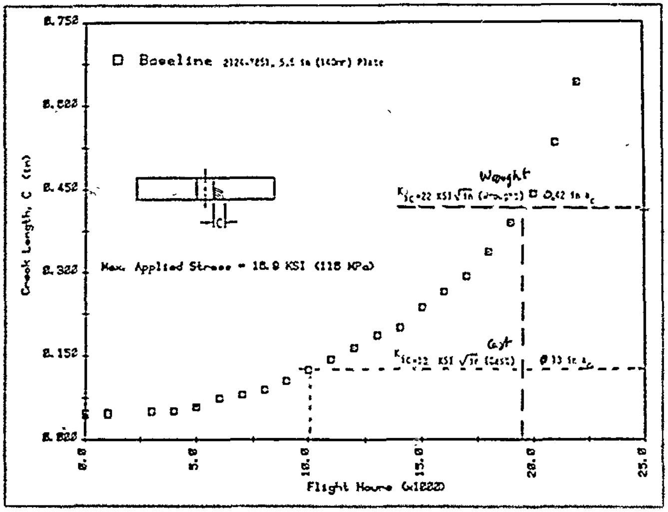


Fig 6 1 Spectrum crack growth of 2024-T851 wrought plate projecting life at two K_{Ic} values relative to critical crack size

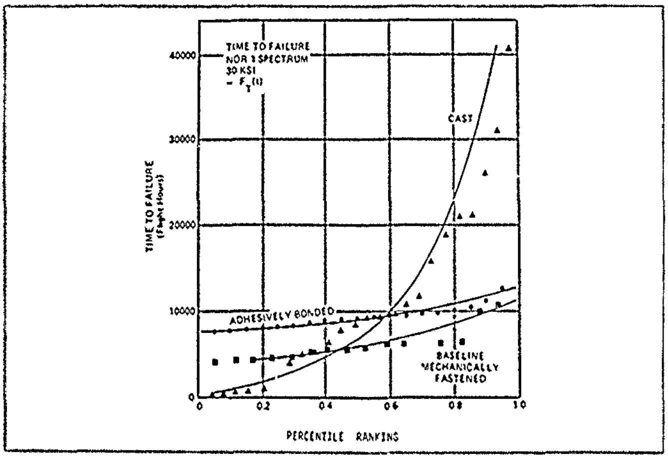


Fig 6 2 Percentile ranking of spectrum life to failure of three groups of specimens representing different manufacturing processes (3)

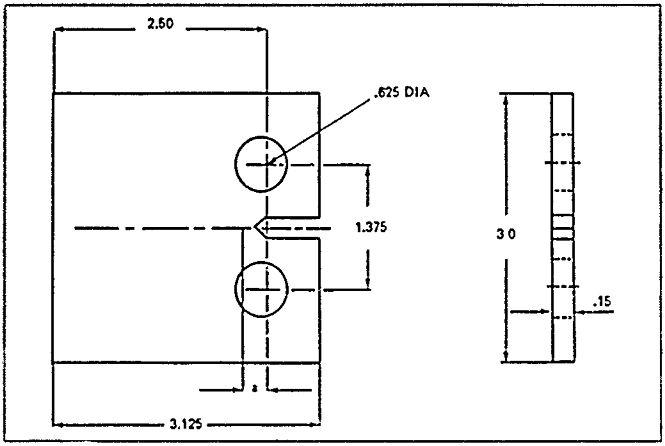


Fig 6 3 Typical crack growth rate specimen

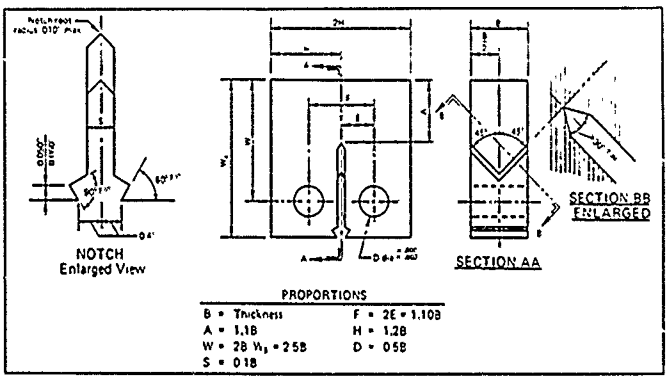


Fig 6 4 Compact tension fracture toughness specimen

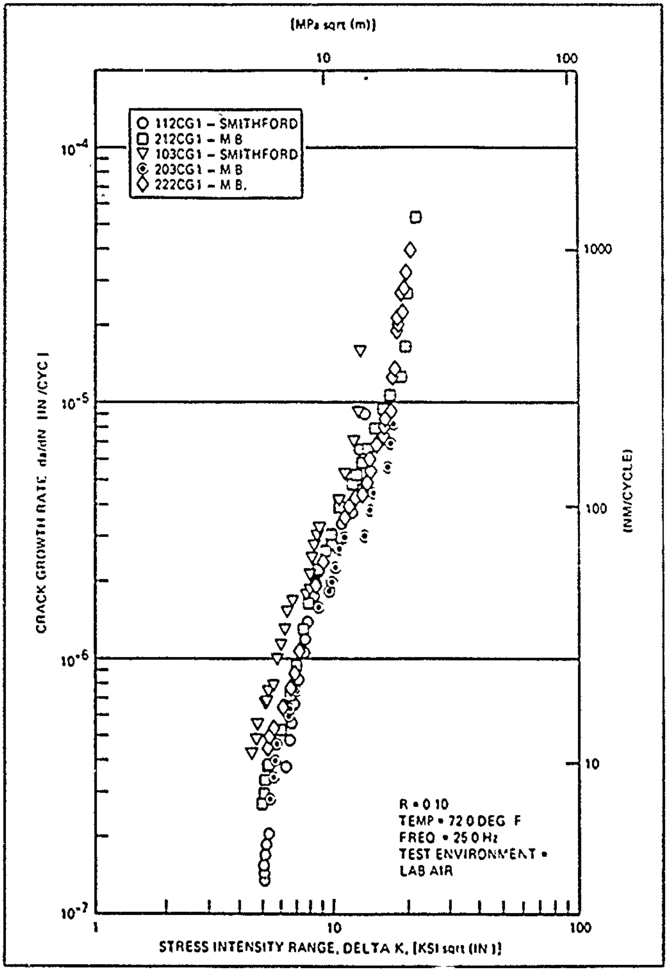


Fig 6.5 Crack growth data on A201-T7 from step block castings made by two producers and tested at AFWAL (4)

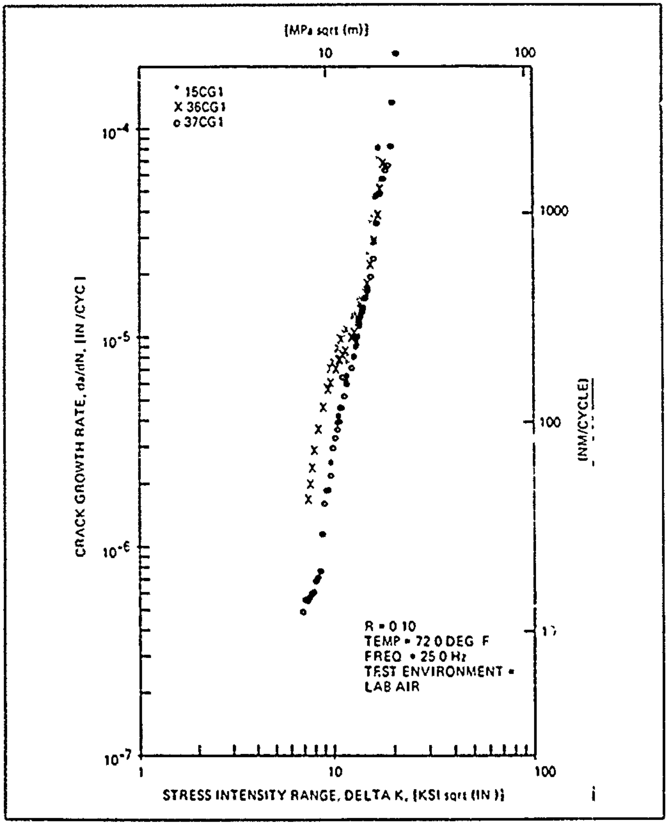


Fig 6 6 Crack growth data on A357-T6 from producer B's step block castings and tested at AFWAL (4)

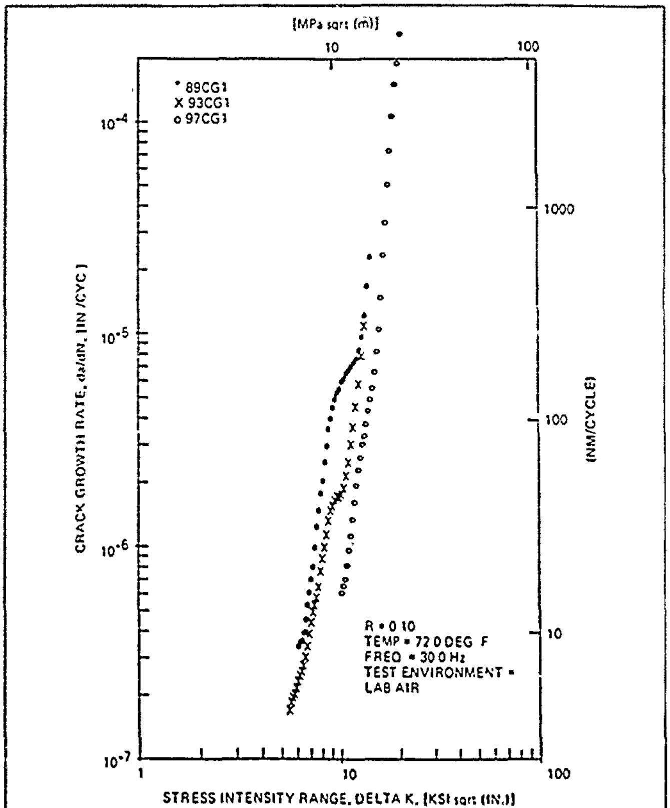


Fig 6 7 Crack growth data on A357-T6 from producer A's step block castings and tested at AFWAL (4)

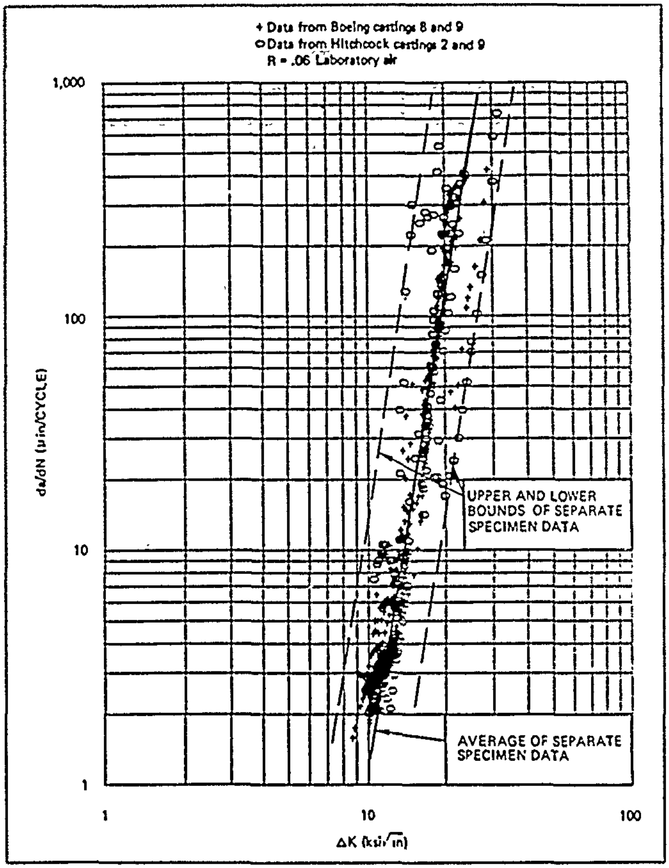


Fig 6.8 Crack growth data on A357-T6 specimens taken from specimens taken from several experimental Boeing bulkheads, compared with scatter band from Boeing step block castings. Tested at Boeing (5)

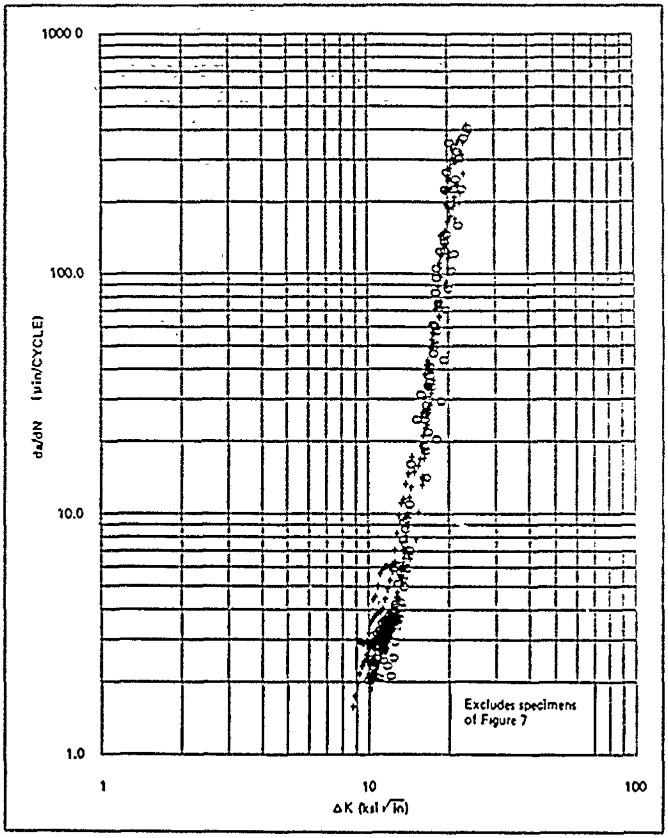


Fig 6.9 Selected crack growth data on A357-T6 from several Boeing experimental bulkhead castings tested at Boeing (5)

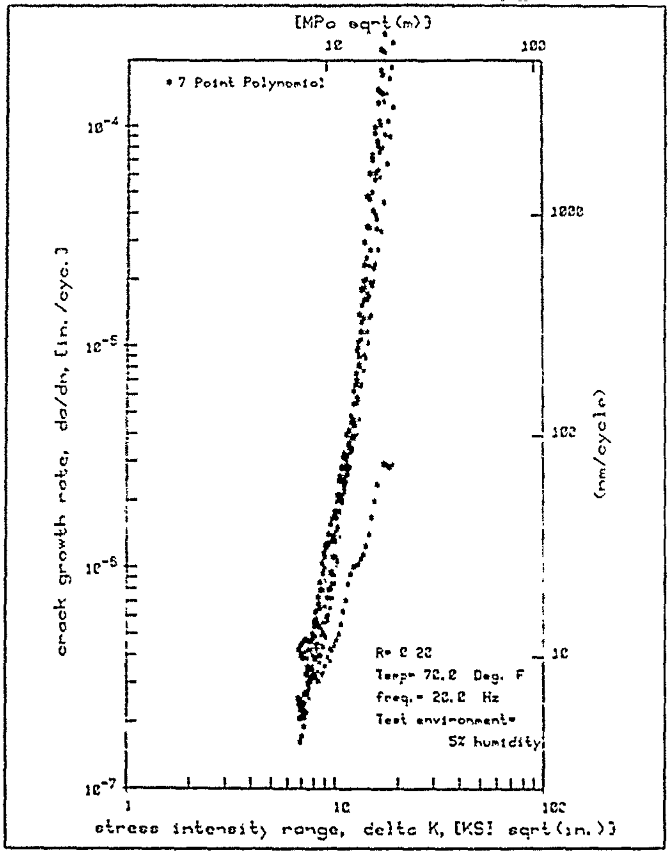


Fig 6.10 Crack growth data on A357-T6 specimens taken from a single Boeing experimental bulkhead and tested at AFWAL (6)

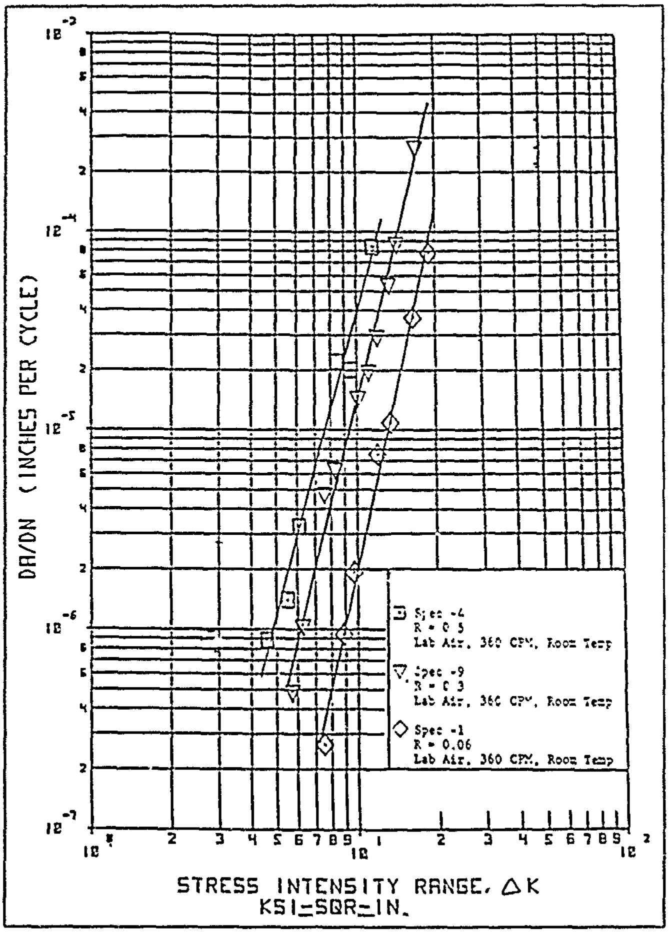


Fig 6 11 Crack growth data on A357-T6 specimens at various "R" ratios from an experimental F-16 vertical tail and tested at General Dynamics (7)

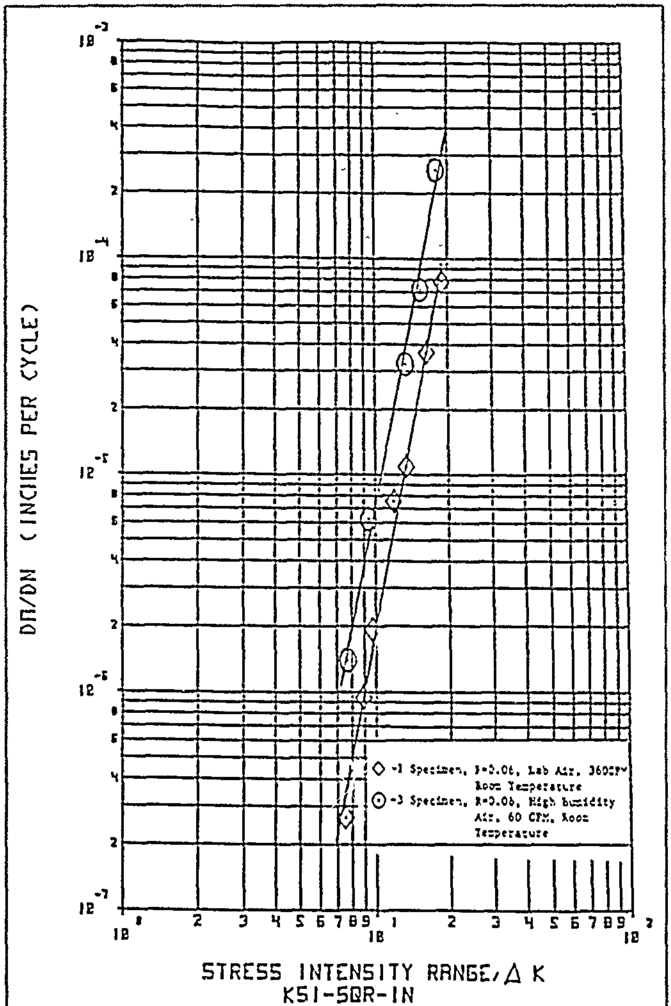


Fig 6 12 Crack growth data on A357-T6 specimens taken from an F-16 experimental tail and tested under various humidity levels at General Dynamics (7)

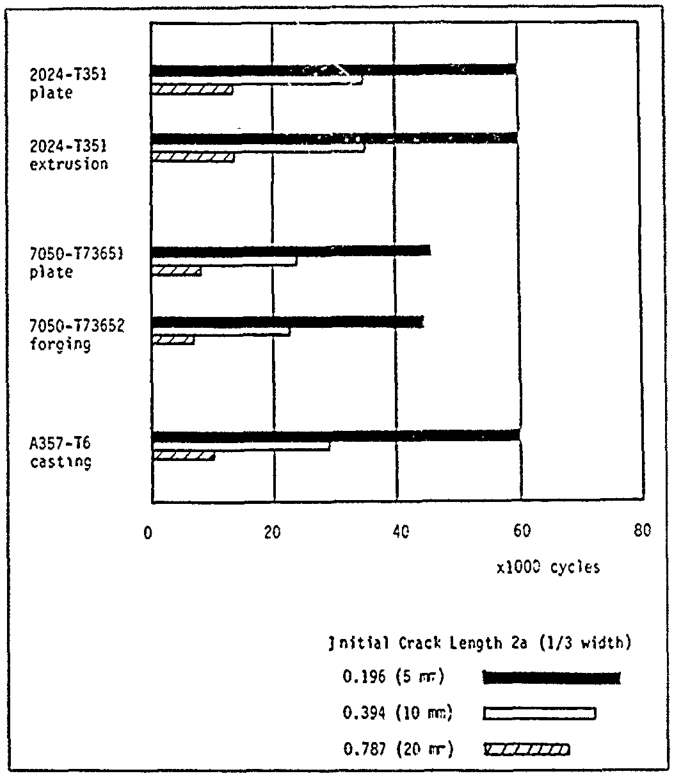


Fig 6 13 Influence of product form on crack growth life of A357 castings (8)

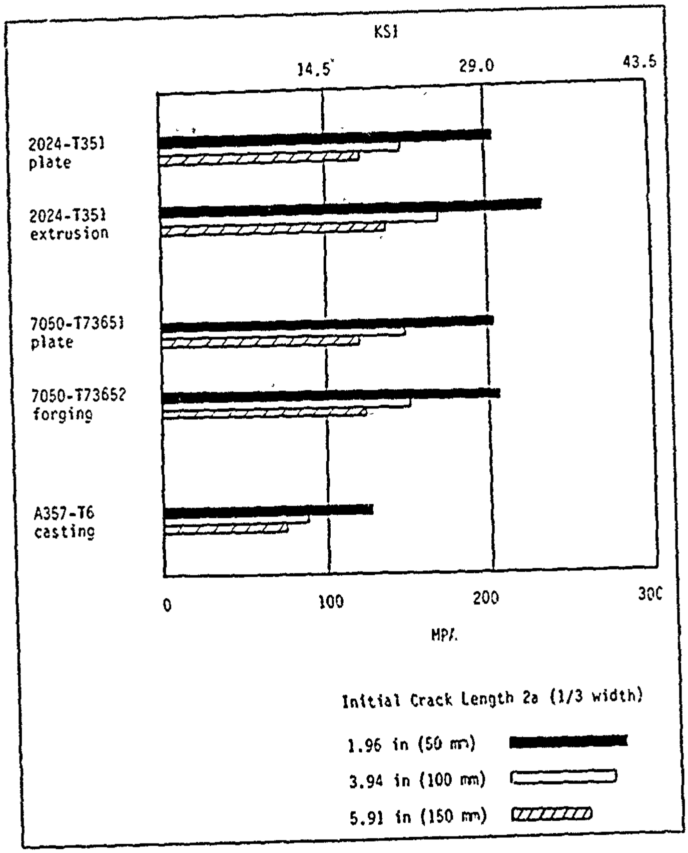


Fig 6.14 Influence of product form on residual strength of centre cracked panels (8)

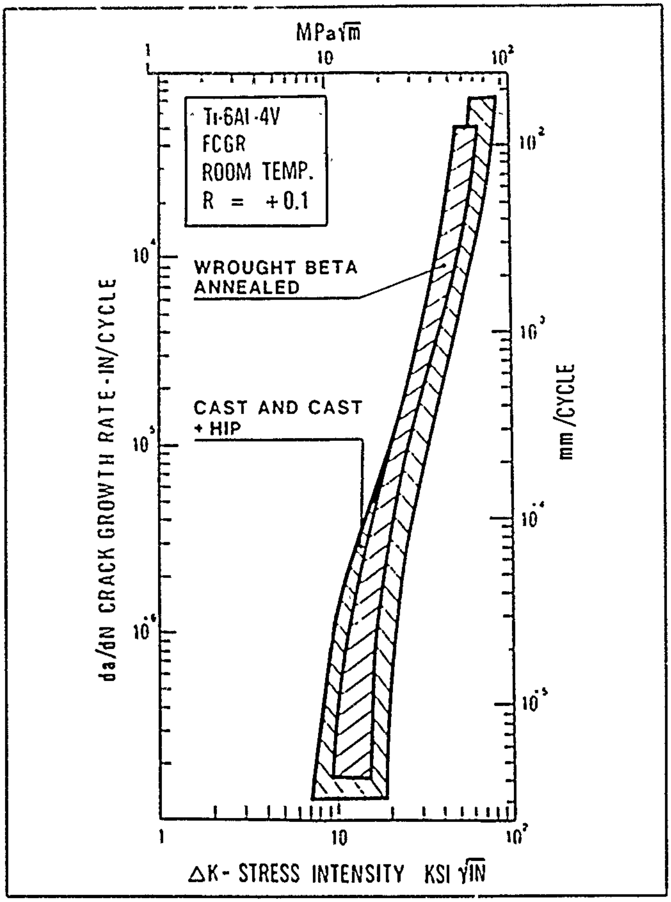


Fig 6 15 Scatterband comparison of room temperature fatigue crack growth rate of cast or cast+HIP Ti 6Al-4V with beta-annealed wrought material (14)

Table 6 16
Typical values of room temperature plane-strain fracture toughness of aluminium alloys

L-T					T-L						S-L					
No of Lots/ Specimens	Specimen Thickness Range Inch	K_{1C} ksi$\sqrt{in}$ Test Data Minimum	Test Data Average	Test Data Maximum	Product Thickness Range Inch	No. of Lots/ Specimens	Specimen Thickness Range Inch	K_{1C} ksi$\sqrt{in}$ Test Data Minimum	Test Data Average	Test Data Maximum	Product Thickness Range Inch	No of Lots/ Specimens	Specimen Thickness Range Inch	K_{1C} ksi$\sqrt{in}$ Test Data Minimum	Test Data Average	Test Data Maximum
					0 89	1/9	0 25-0 75	14	16	19	-	-	-	-	-	-
					4 5	1/10	0 25-0 75	16	17	18	-	-	-	-	-	-
6/21	0 5-1 0	19	22	26	1 0-1 75	5/24	0 5 1 0	19	21	24	1 5-3 0	3/6	0 5 1 0	16	18	19
5/13	0 75-2 0	24	32	48		5/11	0 75-2 0	19	22	30		1/3	1 0	17	18	26
3/9	0 75-2 0	27	31	44	0 5-2 0	2/3	0 5-2 0	26	29	34	2 0-3 25	3/7	0 75-1 0	18	22	26
3/6	1.5	34	36	37	3 0-5 0	3/6	1 5	23	25	26	3 0-5 0	2/4	1 0	21	23	[illegible]
8/45	0 5-1.5	15	21	26	1.0-3 0	4/21	0 62-1 4	18	20	23	1 4-5 0	3/7	0 5-1 5	16	17	18
11/26	0.75-2 0	19	27	37	2 0-7 0	10/20	0 75-2 0	14	19	26	4 0-4 0	4/11	0 25-1 0	15	16	17
4/4	1 5-2 0	39	41	43	1.5 3 5	2/3	1 5-2 0	37	37	38	-	-	-	-	-	-
27/75	0 5-2 0	21	28	37	1 5-6 0	31/80	0 5 1 5	20	24	31	1 5-4 0	20/62	0 5-1 5	17	22	27
2/4	0 5-0 75	29	29	29	1 6-2 0	3/6	0 5-0 75	19	21	22	-	2/3	0 75	18	19	19
1/4	1 0	30	31	31	-	-	-	-	-	-	-	-	-	-	-	-
2/8	0 5-0 7	24	27	29	0 5-0 9	3/16	0 25-0 75	17	20	24	-	1/4	0 5	16	17	17
-	-	-	-	-	4 5	1/8	0 25-0 75	20	23	25	-	-	-	-	-	-
10/32	0 5-2 0	20	26	29	0 5-2 0	15/76	0 5 2 0	18	22	27	1 4 - 3	14/31	0 5 1 0	15	18	20
2/4	1 5	30	32	34	3 0-5 0	2/4	1 5	18	19	19	-	-	-	-	-	-
11/31	0 5-1 5	23	28	32	0 7-3 0	12/33	0 5 1.5	18	23	28	3 5 5 0	3/8	0 25-1 0	17	19	22
1/5	0 75	20	29	29	0 75	1/6	0 75	23	23	24	-	-	-	-	-	-
3/11	1.0-1 5	29	32	39	1 0-4 0	3/13	1 0-1.5	20	23	27	3 0-14 0	4/10	1 0-1 5	19	22	28
1/3	0 5-0 7	23	26	28	0 75-1 0	3/17	0 25-0 75	19	21	25	1 0	1/4	0 5	18	19	20
9/26	0 75-2 0	27	30	33	1 5-4 0	7/25	1 0-2 0	22	30	48	1.4-4 0	7/16	0 5-1 5	18	23	38
11/26	0 63-2 0	31	35	43	0 7-3 5	13/38	0 5 1 7	12	23	33	1 0-7 0	10/15	0 25 1 0	17	26	23
-	-	-	-	-	4 6-7 0	2/4	1 0	19	20	21	4 6-7 0	2/4	1 0	18	19	21
5/13	0 75-2 0	30	34	40	2 0-4 0	3/12	0 75-2 0	22	26	29	4 0-6 0	2/4	0 25-1 0	18	21	27
1/3	1 0	36	37	37	1 0	1/4	1 0	32	32	32	-	-	-	-	-	-
1/3	2 0	34	35	37	-	1/4	1 7	24	27	29	-	-	-	-	-	-
12/42	0 5-2 0	22	27	34	0 5-2.0	31/96	0 5-2 0	21	23	26	2 0	6/16	0 3-0 7	18	19	21
9/18	0 6-2 0	27	32	40	1.25-2 0	9/40	0 8-2 0	20	23	34	1 4-2 0	2/4	0 7-0 8	16	20	22
3/9	0 75	30	35	37	4 9	3/10	0 75	20	22	23	-	-	-	-	-	-
4/17	0 25	26	26	31	0 75	4/17	0 75	21	22	28	-	-	-	-	-	-
6/14	0.75 1 0	24	32	36	0 0 1.25	5/15	0 75-2 0	18	21	24	-	-	-	-	-	-
* 2/4	0 5	32	35	36	0 5-1 0	2/3	0.5	21	24	26	-	3/9	0.5	19	21	22
3/9	0 75	30	34	37	4.9	3/8	0 75	21	23	25	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	1 0	1/4	0 5	20	27	28
11/30	0 75-1.4	33	34	36	0 75-1.5	11/32	0 75-1 4	26	28	30	[illegible]	2/6	0 5	22	23	23
8/26	0 75-1 0	27	33	40	0 8-1.25	8/31	0 75-1 0	23	25	27	-	4/20	0 5	17	19	22
-	3	-	-	-	3 0 3 0	3/5	1 0-1.3	25	27	29	2 0-3 0	2/3	1 0	22	22	23
6/11	0.5-1 5	22	25	33	-	5/11	0.5 1 5	21	24	32	-	11/26	0 5	20	26	31
1/4	0 75	31	34	37	4 9	1/8	0 75	21	23	26	-	-	-	-	-	-
4/12	1.5	31	32	33	1.5	4/11	1.5	24	25	26	-	-	-	-	-	-
13/35	0 0	20	32	34	0 6	9/30	0 6	23	27	28	-	-	-	-	-	-
3/20	0.75-1 0	21	32	38	0 8-1 25	5/23	0 75-1 0	22	25	26	-	2/8	0 5	17	18	19

Table 6 17

Specimen	Yield Strength (KSI)	Fracture Toughness (KSI-$\sqrt{IN}$)	Reason Not Valid	Producing Foundry
128P	63.2	23.2	Valid K_{IC}	Producer C
128A	59.4	24.9	Valid K_{IC}	Producer C
S/N 20	54.8	33.2	Valid K_{IC}	Producer D
S/N 30-1	60.1	30.7	Valid K_{IC}	Producer D
S/N 32-1	59.2	32.8	Valid K_{IC}	Producer D
Standard Deviation		4.62		
Mean		28.96		
Variance		17.08		

Fracture toughness results on 0 80" wide specimens from cast test blocks of A201-T7, Northrop data (9)

Specimen	Yield Strength MPa	Fracture Toughness MPa $\sqrt{m}$	Reason Not Valid	Producing Foundry
128P	441	25.5	Valid K_{IC}	Producer C
128A	415	27.4	Valid K_{IC}	Producer C
S/N 20	383	36.5	Valid K_{IC}	Producer D
S/N 30-1	420	33.7	Valid K_{IC}	Producer D
S/N 32-1	414	36.0	Valid K_{IC}	Producer D
Average	414	32.9		
Standard Deviation		5.08		
Mean		31.83		
Variance		18.77		

Fracture toughness results on 20 32 mm wide specimens from cast test blocks of A201-T7, Northrop data (9)

Table 6 18
Fracture toughness results on 25 4 mm wide specimens extracted from four cast bulkheads A357-T6 alloy, Boeing CAST programme (5)

Specimen I D	K_Q KSI $\sqrt{in}$	Valid K_{IC}
CH2L1	21.6	No
CH2L2	20.8	No
CH2L7	19.7	No
CH2L8	20.6	No
CH9L1	18.3	No
CH9L2	18.7	No
CH9L7	18.9	No
CH9L8	Precrack Failure	No
C8L1	24.4	No
C8L2	20.5	No
C8L7	20.6	No
C8L8	20.0	No
C9L1	Precrack Failure	No
C9L2	21.4	No
C9L7	21.6	No
C9L8	Precrack Failure	No

Specimen I D	K_Q MPa $\sqrt{m}$	Valid K_{IC}
CH2L1	145.9	No
CH2L2	143.2	No
CH2L7	135.8	No
CH2L8	142.0	No
CH9L1	126.2	No
CH9L2	128.9	No
CH9L7	130.3	No
CH9L8	Precrack Failure	No
C8L1	168.2	No
C8L2	141.3	No
C8L7	142.0	No
C8L8	137.9	No
C9L1	Precrack Failure	No
C9L2	147.5	No
C9L7	148.9	No
C9L8	Precrack Failure	No

Table 6 19

Specimen Identification	TYS (KSI)	B (IN)	a (IN)	P_{max} (LB)	P_Q (LB)	K_Q (KSI $\sqrt{IN}$)	Remarks
ACT 1-1	41.465	.710	.813	1695.	1625.	20.5	2
ACT 1-2	41.465	.713	.777	1000.	1000.	11.6	2
ACT 2-1	39.749	.700	.717	1795.	1665.	17.5	2
ACT 2-2	39.749	.707	.770	2240.	2160.	24.9	1
ACT 3-1	42.226	.762	.680	1625.	1590	14.3	2
ACT 3-2	42.226	.744	.667	1965.	1845.	16.6	Valid
ACT 4-1	40.535	.756	.640	1750.	1590.	13.5	2 3
ACT 4-2	40.535	.757	.660	19[illegible]5.	1830.	16.0	Valid
ACT 5-1	35.799	.690	.717	2115.	1930.	20.6	1
ACT 5-2	35.799	.690	.663	2000.	1775	17.2	3
ACT 6-1	38.996	.690	.803	2400.	2225.	28.3	1
ACT 6-2	38.996	.690	.800	2220.	2055.	25.9	1
ACT 7-1	41.587	.714	.737	1900.	1810.	19.4	Valid
ACT 7-2	41.587	.712	.757	1955.	1860	20.8	4
ACT 8-1	38.314	.752	.710	2050.	1885.	18.2	Valid
ACT 8-2	38.314	.735	.727	2155.	1950.	19 9	3

Fracture toughness results on 1½" wide specimens from CAST test plates. A357-T6 alloy, Boeing CAST program (11)

Specimen Identification	TYS (MPa)	B (MM)	a (MM)	P_{max} (KN)	P_Q (KN)	K_Q (MPa $\sqrt{M}$)	Remarks
ACT 1-1	286	18.0	20.7	7.54	7.23	22.5	2
ACT 1-2	286	18.1	19.7	4.45	4.45	12.7	2
ACT 2-1	274	17.8	18.2	7.98	7.41	19.2	2
ACT 2-2	274	18.0	19.6	9.96	9 61	27.4	1
ACT 3-1	291	19.3	17.3	7.23	7.07	15 7	2
ACT 3-2	291	18.9	16.9	8.74	8.21	18.2	Valid
ACT 4-1	279	19.2	16.3	7.78	7.07	14.6	2 3
ACT 4-2	279	19.2	16.8	8.87	8.14	17.6	Valid
ACT 5-1	247	17.5	18.2	9.41	8.59	22.6	1
ACT 5-2	247	17.5	16.8	8.90	7.90	18.9	3
ACT 6-1	269	17.5	20.4	10.68	9.90	31.1	1
ACT 6-2	269	17.5	20.3	9.88	9.14	28.5	1
ACT 7-1	287	18.1	18.7	8.45	8.05	21.3	Valid
ACT 7-2	287	18.1	19.2	8.70	8.27	22.9	4
ACT 8-1	264	19 1	18.0	9.12	8.38	20.0	Valid
ACT 8-2	264	18.7	18.5	9.59	8.67	21.9	3

Fracture toughness results on 968 mm wide specimens from CAST test plates A357-T6 alloy, Boeing CAST program (11)

Remarks Does not meet the ASTM E399-74 validity requirements because:

1 $2.5\,(K_Q/TYS)^2$ greater than a and b

2 K_f/K_Q greater than 0.60

3 P_{Max}/P_Q greater than 1.10

4 a/δ greater than 0.05

Table 6 20

No.	B (IN)	W (IN)	A (IN)	P_Q (LBS)	K_Q KSI(IN)$^{1/2}$	K_{IC}	Error
-2	0.295	1.995	0.987	1010	23.1	No	AB
-5	0.154	1.999	1.011	570	25.8	No	AB
-7	0.293	2.003	0.953	1050	22.7	No	AB
-10	0.248	2.002	0.921	1230	30.1	No	AB

Fracture toughness results on 2" wide specimens extracted from F-16 vertical tail casting A357-T6, General Dynamics program (7)

No.	B (MM)	W (MM)	A (MM)	P_Q (N)	K_Q (MPa $\sqrt{m}$)	K_{IC}	Error
-2	7.49	50.67	25.07	4493	25.4	No	AB
-5	3.91	50.77	25.68	2585	28.4	No	AB
-7	7.44	50.88	24.21	4671	24.9	No	AB
-10	6.30	50.85	23.30	5471	33.1	No	AB

Error Codes:

- A - Insufficient thickness
- B - P_{Max}/P_Q Exceeds 1.1, RSC is given
- C - Minimum Surface Crack Length is less than 90 percent.
- D - Crack Curvance is greater than 5 percent.

Yield Stress given as 36.000 KSI (248.22 MPa).

Fracture toughness results on 50 8 mm wide specimens extracted from F-16 vertical tail casting A357-T6, General Dynamics program. (7)

Table 6 21
Fracture toughness results on 0 8" wide specimens from cast test block of A357-T6, Northrop data (9)

Specimen	Yield Strength (KSI)	Fracture Toughness (KSI-$\sqrt{IN}$)	Reason Not Valid	Remarks
9193-1	46.1	25.4	b	Foundry A
9193-4	46.0	26.6	c, d	Foundry A
2237-3-7	44.1	26.7	a, b, c, d	Foundry B
2244-2-8	45.2	25.7	a, c, d	Foundry B
2258-4-9	44.1	26.4	a, b, c, d	Foundry B
		Average 26.1		

Specimen	Yield Strength (MPa)	Fracture Toughness (MPa $\sqrt{M}$)	Reason Not Valid	Remarks
9193-1	318	27.9	b	Foundry A
9193-4	317	29.2	c, d	Foundry A
2237-3-7	304	29.3	a, b, c, d	Foundry B
2244-2-8	312	28.2	a, c, d	Foundry B
2258-4-9	304	29.0	a, b, c, d	Foundry B
		Average 28.7		

a = Crack length 0.55 W

b = Crack length at surface 1 is less than 85 percent of average crack length

c = Crack length at surface 2 is less than 85 percent of average crack length

d = Thickness is less than $2.5 \frac{KQ}{YS}^2$

Table 6 22

Grain Orien-tation	Yield Strength,* KSI	Thickness, IN B	Nominal Width, IN W	Crack Length A_0	Load, kips P_Q	P_{Max}	K_Q KSI $\sqrt{IN}$	K_Q Valid K_{IC}
LT	43.2	0.75	1.50	0.73	1.93	2.00	19.3	Yes
LT	43.2	0.75	1.50	0.78	1.88	1.92	21.0	Yes
TL	43.3	0.75	1.50	0.74	1.90	1.98	19.6	No*
TL	43.3	0.75	1.50	0.68	1.82	1.93	16.8	No*

* Fatigue cracked not extended far enough from machined notch.

Fracture toughness results on 3/4" wide specimens from cast A357-T6 alloy slabs, ALCOA report (12)

Grain Orien-tation	Yield Strength, MPa	Thickness, mm B	Nominal Width, mm W	Crack Length mm A_0	Load, kN P_Q	P_{Max}	K_Q MPa$\sqrt{m}$	K_Q Valid K_{IC}
LT	302	19.05	38.1	18.54	8.58	8.90	21.21	Yes
LT	302	19.05	38.1	19.81	8.36	8.54	23.08	Yes
TL	302	19.05	38.1	18.80	8.45	8.81	21.54	No*
TL	302	19.05	38.1	17.27	8.10	8.58	18.46	No*

Fracture toughness results on 19 05 mm wide specimens from cast A357-T6 alloy slabs, ALCOA report (12)

Table 6 23

	Non Valid	Valid
Data Points	36	6
Standard Deviation	4.10 KSI -$\sqrt{in}$ (4.51 MPa -$\sqrt{m}$	1.71 KSI -$\sqrt{in}$ (1.90 MPa -$\sqrt{m}$)
Mean	21.39 KSI -$\sqrt{in}$ (23.51 MPa -$\sqrt{m}$)	18.42 KSI -$\sqrt{in}$ (20.24 MPa -$\sqrt{m}$)
Variance	16.81 KSI -$\sqrt{in}$ (18.47 MPa -$\sqrt{m}$)	2.92 KSI -$\sqrt{in}$ (3.21 MPa -$\sqrt{m}$)

Analysis/summary of K_Q data on A357-T6 castings from all sources, all thicknesses

Table 6.24
Fracture toughness data on compact tension specimens machined from Ti-6Al-4V cast test plates

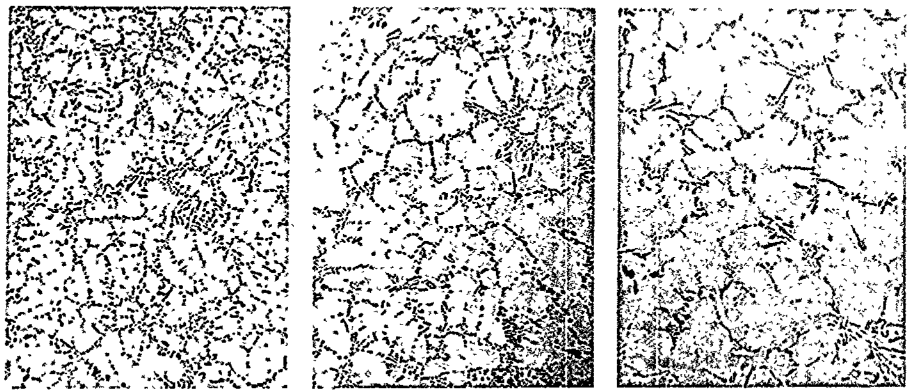
Material Condition	Yield Strength (ave)		Number of spec.	KQ		Reference
	KSI	MPa		KSI $\sqrt{IN}$	MPa $\sqrt{m}$	
STD Grade Investment Cast, PCP	119	820	10	103	113	16
ELI Grade Investment Cast, PCP	110	758	12	90	99	16
STD Grade Ramed Graphite Mold, Ti Tech	124	855	12	87	96	16,17
ELI Grade Ramed Graphite Mold, Ti Tech	114	786	12	93	102	16,17
Centrifically Investment Cast, Homet	120	827	3	94	103	15
Investment Cast, Howmet	126	870	2	83	91	14
Non-HIP'ed Investment Cast	130	895	2	65-70	71-77	14

Note:
1) All materials HIP'ed except where noted
2) None of the data was valid Kic data per ASTM 399
3) Where reported, all specimens were machined to within the 1" to 1½" thickness range.

Table 6 25
Tension allowables from Boeing Cast program (20)

Specimen DAS Range	Property	Specimen Soundness Grade (ASTM E-155)		
		A	B	C
Up to .0012	Ftu KSI	45.90	44.30	43.60
	Fty KSI	36.50	36.50	36.50
	e %	1.80	1.00	1.00
.0013 to .0018 in	Ftu KSI	44.20	42.90	42.10
	Fty KSI	36.50	36.50	36.50
	e %	1.30	.60	1.00
.0019 to .0024 in	Fty KSI	42.90	41.50	40.80
	Fty KSI	36.50	36.50	36.50
	e %	.80	.50	.50
.0025 to .0030 in	Ftu KSI	42.30	40.90	40.10
	Fty KSI	36.50	36.50	36.50
	e %	.60	.40	.40

Specimen DAS Range	Property	Specimen Soundness Grade (ASTM E-155)		
		A	B	C
Up to .0305 mm	Ftu MPa	316.48	305.45	43.60
	Fty MPa	251.67	251.67	36.50
	e %	1.80	1.00	1.00
.0306 to .0457 mm	Ftu MPa	304.76	295.80	42.10
	Fty MPa	251.67	251.67	36.50
	e %	1.30	.60	1.00
.0458 to .0610 mm	Fty MPa	295.80	286.14	40.80
	Fty MPa	251.67	251.67	36.50
	e %	.80	.50	.50
.0611 to .0762 mm	Ftu MPa	291.66	282.01	40.10
	Fty MPa	251.67	251.67	36.50
	e %	.60	.40	.40



A. DENDRITE ARM SPACING = 0.0014 INCH (0.035 mm)

Tus = 52 KSI (358 MPa)
Tys = 45 KSI (310 MPa)
El = 4%

B. DENDRITE ARM SPACING = 0.0019 INCH (0.048 mm)

Tus = 48 KSI (331 MPa)
Tys = 43 KSI (296 MPa)
El = 1%

C. DENDRITE ARM SPACING = 0.0035 INCH (0.089 mm)

Tus = 45 KSI (310 MPa)
Tys = 42 KSI (290 MPa)
El = 1%

Fig 6 26 Effect of solidification rate on the tensile properties of A357-T6 castings (9)

Appendix

In the following, foundries and users are listed who have contributed to the handbook or have attended some meetings. This list should be a help for potential users of castings to make initial contact.

1. AFWAL/MLSE
Att. C.L.Harmsworth
Wright Patterson AFB
Ohio 45433
United States

2 ALCOA
Premium Castings Division
Att. M R.Dunke
1450 Rincon Street
Corona CA 91720
United States

3. Boeing Company/
Military Airplane Comp.
Att. D L.McLellan
Mail Stop 45-11
P.O. Box 3707
Seattle, Washington 98124
United States

4. Cercast GmbH
Att. Gabriel
Postfach 14
4770 Soest
West Germany

5. Cercast Inc.
Att S.Kennerknecht
3905 Industrial B.
Montreal North
P.Q. H1H 2Z2
Canada

6. Consolidated Aluminium Corp.
Att. N.J Davidson
51 Archer Drive
Bronxville N.Y. 10708
United States

7. Fokker B.V.
Att. M O.T.H. Han
P.O. Box 7600
1117 ZJ Schiphol
Netherlands

8. General Dynamics Corporation
Att. B L. Ribeiro, MZ 2161
Metallic Materials and Processes
P.O. Box 748
Fort Worth TX 76101
United States

9. Haley Industries Limited
Att. H.J.Proffitt
Haley, Ontario K0J 1Y0
Canada

10. Hitchcock Industries Inc.
Att. F.H.Muehlegger
8701 Harriet Ave. South
Minneapolis, MN 55420-2787
United States

11. Honsel-Werke
Att. Dr Betz
5778 Meschede 1
Germany

12. Howmet Turbine Components
Corp.
Att. G.Askew
1600 South Warner Road
Whitehall, Michigan 49461
United States

13. Avery Kearney and Co.
2206 Linden
Valparaiso, IN 46383
United States

14. Lauzier Fonderie
Att. J Deborde
12, route de St.-Jean
38300 Bourgoin-Jallieu
France

15. MBB, Transport-
und Verkehrsflugzeuge
Att. D.Mietrach, TFB 51
Hünefeldstr. 1–5
P.O. Box 107845
2800 Bremen 1
Germany

16. Messier Fonderie d'Arudy
Att. J.P.Mannant
64260 Arudy
France

17. Montupet Fonderies
Att. Dr C.Planchamp
Recherches et Délevoppement
45, rue jean de la Fontaine
Nogent-Sur-Oise-60101
CREIL CEDEX
France

18 Northrop Corp. Aircraft Div
Att. K.J.Oswald
Orgn. 3872/62, Adv. Mfg. Tech.
One Northrop Ave.
Hawthorne CA 90250
United States

19. Precision Cast Parts (PCC)
Att. J.Thorne
4600 S.E Harney Drive
Portland OR 97206-0898
United States

20. Pechiney
Att. Ch.Fauvel
Département Aluminium Métal
Direction des Technologies
de Moulage
ALUVA, BP7
38240 Voreppe
France

21. Progress Casting Group
Att. D E Lettlen
V.P. Engineering
1457 Marshall Ave.
St. Paul MN 55104
United States

22. TITAL
Att. Dr Chr Liesner
Postfach 280
5780 Bestwig
West Germany

23. TiTech, International Inc.
Att. E.A.Williams
P.O. Box 3060
4000 West Valley Boulevard
Pomona, LA 91769
United States

24. Westland Helicopter Ltd.
Att. P.R.Wedden
Head of Materials and
Logistic Services
Yeovil, Somerset
United Kingdom

REPORT DOCUMENTATION PAGE

1. Recipient's Reference	2. Originator's Reference	3. Further Reference	4. Security Classification of Document
	AGARD-AG-299	ISBN 92-835-0455-0	UNCLASSIFIED

5. Originator Advisory Group for Aerospace Research and Development
North Atlantic Treaty Organization
7 rue Ancelle, 92200 Neuilly sur Seine, France

6. Title AGARD HANDBOOK ON ADVANCED CASTING

7. Presented at

8. Author(s)/Editor(s) Various Edited by D Mietrach

9. Date March 1991

10. Author's/Editor's Address Various See Flyleaf

11. Pages 188

12. Distribution Statement This document is distributed in accordance with AGARD policies and regulations, which are outlined on the back covers of all AGARD publications.

13. Keywords/Descriptors

Casting
Aircraft industry
Fabrication
Design
Mechanical properties
Utilization
Quality assurance
Damage

14. Abstract

The need to improve aircraft performance and, simultaneously, to reduce costs has led to a re-examination of the use of casting processes in aircraft manufacture. In this volume the Structures and Materials Panel of AGARD has provided practical information about design, mechanical values, applications, quality assurance and damage tolerance.

By providing the data in this form it is hoped that the designer will be encouraged to exploit the many recent advances in casting to optimum effect.

AGARDograph No.299 Advisory Group for Aerospace Research and Development, NATO AGARD HANDBOOK ON ADVANCED CASTING Edited by D.Mietrach Published March 1991 188 pages The need to improve aircraft performance and, simultaneously, to reduce costs has led to a re-examination of the use of casting processes in aircraft manufacture. In this volume the Structures and Materials Panel of AGARD has provided practical information about design, mechanical values, applications, quality assurance and damage tolerance. P.T.O	AGARD-AG-299 Casting Aircraft industry Fabrication Design Mechanical properties Utilization Quality assurance Damage

AGARDograph No.299 Advisory Group for Aerospace Research and Development, NATO AGARD HANDBOOK ON ADVANCED CASTING Edited by D.Mietrach Published March 1991 188 pages The need to improve aircraft performance and, simultaneously, to reduce costs has led to a re-examination of the use of casting processes in aircraft manufacture. In this volume the Structures and Materials Panel of AGARD has provided practical information about design, mechanical values, applications, quality assurance and damage tolerance. P.T.O	AGARD-AG-299 Casting Aircraft industry Fabrication Design Mechanical properties Utilization Quality assurance Damage

AGARDograph No.299 Advisory Group for Aerospace Research and Development, NATO AGARD HANDBOOK ON ADVANCED CASTING Edited by D.Mietrach Published March 1991 188 pages The need to imorove aircraft performance and, simultaneously, to reduce costs has led to a re-examination of the use of casting processes in aircraft manufacture. In this volume the Structures and Materials Panel of AGARD has provided practical information about design, mechanical values, applications, quality assurance and damage tolerance. P.T.O	AGARD-AG-299 Casting Aircraft industry Fabrication Design Mechanical properties Utilization Quality assurance Damage

AGARDograph No 299 Advisory Group for Aerospace Research and Development, NATO AGARD HANDBOOK ON ADVANCED CASTING Edited by D.Mietrach Published March 1991 188 pages The need to improve aircraft performance and, simultaneously, to reduce costs has led to a re-examination of the use of casting processes in aircraft manufacture. In this volume the Structures and Materials Panel of AGARD has provided practical information about design, mechanical values, applications, quality assurance and damage tolerance. PTO	AGARD-AG-299 Casting Aircraft industry Fabrication Design Mechanical properties Utilization Quality assurance Damage

By providing the data in this form it is hoped that the designer will be encouraged to exploit the many recent advances in casting to optimum effect.

ISBN 92-835-0455-0

By providing the data in this form it is hoped that the designer will be encouraged to exploit the many recent advances in casting to optimum effect.

ISBN 92-835-0455-0

By providing the data in this form it is hoped that the designer will be encouraged to exploit the many recent advances in casting to optimum effect.

ISBN 92-835-0455-0

By providing the data in this form it is hoped that the designer will be encouraged to exploit the many recent advances in casting to optimum effect.

ISBN 92-835-0455-0

AGARD
NATO OTAN
7 RUE ANCELLE · 92200 NEUILLY-SUR-SEINE
FRANCE
Téléphone (1)47.38.57.00 · Télex 610 176
Télécopie (1)47.38.57.99

DIFFUSION DES PUBLICATIONS AGARD NON CLASSIFIEES

L'AGARD ne détient pas de stocks de ses publications, dans un but de distribution générale à l'adresse ci-dessus. La diffusion initiale des publications de l'AGARD est effectuée auprès des pays membres de cette organisation par l'intermédiaire des Centres Nationaux de Distribution suivants. A l'exception des Etats-Unis, ces centres disposent parfois d'exemplaires additionnels; dans les cas contraire, on peut se procurer ces exemplaires sous forme de microfiches ou de microcopies auprès des Agences de Vente dont la liste suite.

CENTRES DE DIFFUSION NATIONAUX

ALLEMAGNE
Fachinformationszentrum,
Karlsruhe
D-7514 Eggenstein-Leopoldshafen 2

BELGIQUE
Coordonnateur AGARD-VSL
Etat-Major de la Force Aérienne
Quartier Reine Elisabeth
Rue d'Evere, 1140 Bruxelles

CANADA
Directeur du Service des Renseignements Scientifiques
Ministère de la Défense Nationale
Ottawa, Ontario K1A 0K2

DANEMARK
Danish Defence Research Board
Ved Idraetsparken 4
2100 Copenhagen O

ESPAGNE
INTA (AGARD Publications)
Pintor Rosales 34
28008 Madrid

ETATS-UNIS
National Aeronautics and Space Administration
Langley Research Center
M/S 180
Hampton, Virginia 23665

FRANCE
O.N.E.R.A. (Direction)
29, Avenue de la Division Leclerc
92320, Châtillon sous Bagneux

GRECE
Hellenic Air Force
Air War College
Scientific and Technical Library
Dekelia Air Force Base
Dekelia, Athens TGA 1010

ISLANDE
Director of Aviation
c/o Flugrad
Reykjavik

ITALIE
Aeronautica Militaire
Ufficio del Delegato Nazionale all'AGARD
3 Piazzale Adenauer
00144 Roma EUR

LUXEMBOURG
Voir Belgique

NORVEGE
Norwegian Defence Research Establishment
Attn: Biblioteket
P.O. Box 25
N-2007 Kjeller

PAYS-BAS
Netherlands Delegation to AGARD
National Aerospace Laboratory NLR
Kluyverweg 1
2629 HS Delft

PORTUGAL
Portuguese National Coordinator to AGARD
Gabinete de Estudos e Programas
CLAFA
Base de Alfragide
Alfragide
2700 Amadora

ROYAUME UNI
Defence Research Information Centre
Kentigern House
65 Brown Street
Glasgow G2 8EX

TURQUIE
Milli Savunma Başkanlığı (MSB)
ARGE Daire Başkanlığı (ARGE)
Ankara

LE CENTRE NATIONAL DE DISTRIBUTION DES ETATS-UNIS (NASA) NE DETIENT PAS DE STOCKS DES PUBLICATIONS AGARD ET LES DEMANDES D'EXEMPLAIRES DOIVENT ETRE ADRESSEES DIRECTEMENT AU SERVICE NATIONAL TECHNIQUE DE L'INFORMATION (NTIS) DONT L'ADRESSE SUIT.

AGENCES DE VENTE

National Technical Information Service (NTIS)
5285 Port Royal Road
Springfield, Virginia 22161
Etats-Unis

ESA/Information Retrieval Service
European Space Agency
10, rue Mario Nikis
75015 Paris
France

The British Library
Document Supply Division
Boston Spa, Wetherby
West Yorkshire LS23 7BQ
Royaume Uni

Les demandes de microfiches ou de photocopies de documents AGARD (y compris les demandes faites auprès du NTIS) doivent comporter la dénomination AGARD, ainsi que le numéro de série de l'AGARD (par exemple AGARD-AG-315). Des informations analogues, telles que le titre et la date de publication sont souhaitables. Veuiller noter qu'il y a lieu de spécifier AGARD-R-nnn et AGARD-AR-nnn lors de la commande de rapports AGARD et des rapports consultatifs AGARD respectivement. Des références bibliographiques complètes ainsi que des résumés des publications AGARD figurent dans les journaux suivants:

Scientifique and Technical Aerospace Reports (STAR)
publié par la NASA Scientific and Technical Information Division
NASA Headquarters (NTT)
Washington D.C. 20546
Etats-Unis

Government Reports Announcements and Index (GRA&I)
publié par le National Technical Information Service
Springfield
Virginia 22161
Etats-Unis
(accessible également en mode interactif dans la base de données bibliographiques en ligne du NTIS, et sur CD-ROM)

Imprimé par Specialised Printing Services Limited
40 Chigwell Lane, Loughton, Essex IG10 3TZ