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USE OF TITANIUM CASTINGS WITHOUT A CASTING FACTOR

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NOTICE

This technical report has been reviewed and is approved for publication.

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13. ABSTRACT *(Maximum 200 words)*
The "Use of Titanium Castings Without a Casting Factor" program was conducted to establish "A" and "B" allowables for Ti-6Al-4V. Taguchi methods were used to develop a more restrictive chemistry and annealing condition to provide parts with less variability in properties. "A" and "B" design allowables that were determined for full scale Ti-6Al-4V missile fins and step plates produced using these new parameters showed very low variability; the standard deviations of these data were less than 2 ksi. The "A"-basis allowables are F_{tu}=125 ski and F_{ty}=120 ksi. A nondestructive inspection technique was developed to correlate measurement of microstructural features to mechanical properties. This was found to be of limited value because of the narrow property band that was established. A new AMS specification that included the new allowables, the microstructural inspection criteria, and the more refined chemistry and post-casting treatments was established for investment cast Ti-6Al-4V. Limited fracture mechanics evaluation was also performed on the cast fins.

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FOREWORD

This program was conducted by the McDonnell Douglas Missile Systems Company (MDMSC) in cooperation with Schlosser Casting Company under Contract Number F33615-89-C-5627. Under this effort "A" and "B" design allowables were determined for Ti-6Al-4V castings. A new microstructural inspection techniques and a new AMS specification were established for investment cast Ti-6Al-4V.

Mr. Steven R. Thompson managed the program for Wright Laboratory. His guidance on the program is greatly appreciated. Funding for the program was provided by Wright Laboratories Materials Directorate.

We are also grateful for the support provided by the members of the MIL-HDBK-5 Titanium Casting Task Group, for their inputs and support of this program. Their guidance was invaluable to the program.

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INTRODUCTION AND SUMMARY

Casting has been demonstrated to be a cost-effective means of manufacturing aerospace parts compared to other fabrication processes such as machining or forging. The casting process produces net or near net shape parts that require little or no machining. For titanium alloys castings are particularly cost-effective for several reasons. Since the raw material cost of titanium is high, efficient use of the raw material as in castings results in little waste. Using traditional methods to machine titanium is expensive. Elimination of machining would further reduce costs.

Although castings have been found to be cost-effective, their usage in critical aircraft structures is limited due to the imposition of a margin of safety (i.e., casting) factor. In early casting technology, poor controls over the material composition resulted in parts with entrapped gas or inclusions. Lack of process control produced castings with shrinkage, cold-shuts, and hot tears. Many parts had coarse, nonuniform microstructure and chemical segregation. These defects caused variabilities in the mechanical properties of castings. This led to the institution of an added margin of safety for castings, or a casting factor, that is still used in the design of cast components despite the advancements that have been made in casting technology that have increased the reliability and quality of parts.

Foundries have focussed on several parameters in order to improve the quality of castings. Refinement of chemistries has been performed to increase consistency in processing as well as in the final product. Analysis of casting design has provided information for the optimization of gating and mold fill to prevent the formation of flaws during casting and to improve producibility. Heat treatment of castings has been developed to modify microstructures to improve properties as verified by tests of separately cast bars or prolongations. Extensive nondestructive inspection techniques have been developed to verify quality in castings. These techniques and inspection criteria have been tailored to the criticality of castings in use. While the better inspection methods increase confidence in the quality of the parts being used, they also add to the cost of using castings. Despite all these improvements in foundry practice, the process controls are not well enough established to permit the establishment of design allowables.

1.1 BACKGROUND

Aircraft companies have been reluctant to use castings (primarily aluminum) due to their inconsistent mechanical properties and quality. To compensate for the scatter in properties, a margin of safety (i.e., a casting factor) of 1.33 was defined for missiles (Reference 1) and aircraft (Reference 2). During the 1960s, aluminum foundries demonstrated that the property scatter could be reduced by providing better control of the process. To eliminate the uncertainty that properties of separately cast test bars did not reflect those of castings, strength was verified using specimens excised from parts. While the use of separately cast bars provides a good means of checking chemistry and heat treatment response, it is not representative of the properties of the part since the solidification environment is different. In 1970, MIL-A-21180 (Reference 3) was issued and addressed the problem of variability in properties by requiring more detailed inspection criteria. Even with improvements in foundry practice, variability in mechanical properties was still considered excessive. In 1985 acceptance criteria based upon measurement of dendrite arm spacing (DAS) of aluminum castings was established (Reference 4). Subsequently, the Society of Aerospace Engineers (SAE) issued an Aerospace Recommended Practice, ARP 1947, (Reference 5) describing the procedure for determining DAS and relating it to tensile strength and also issued a material specification, AMS 4241 (Reference 6), that specified a more restrictive chemistry for aluminum alloy 357.

Despite the advances that have been made in titanium foundry technology, there is a reluctance to eliminate the casting factor because of the history of property variability in aluminum castings. In titanium alloys, hot isostatic pressing and appropriate heat treatment have been shown to offer the potential of near-wrought properties, including fatigue-resistance and ductility. For these reasons and because of the cost effectiveness of using these castings, there has been an increased interest in using and establishing design allowables for these parts. In response to this need, in 1986, the Military Handbook 5 Coordination Committee established an ad hoc committee to compile data from investment cast Ti-6Al-4V for the purpose of determining "A" and "B" design allowables. Data from suppliers and users supplied to the Titanium Casting Task Group showed that investment cast Ti-6Al-4V parts supplied to the aerospace industry could not be represented by a single set of "A" and "B" design allowables (Reference 7).

Figure 1 demonstrates this point. This figure shows the mechanical property distribution by supplier for an investment cast Ti-6Al-4V elevon housing supplied to the Boeing Corporation (Reference 8). Data from each supplier can be represented by its own population distribution. The implication is that foundry practices significantly affect the variability of mechanical properties in castings. However, the differences in properties in no way compromise the quality of the parts since mechanical properties of the parts met the minimum values specified in the Boeing specification (BMS 7-181). Attempts to determine "A" and "B" basis design allowables from data with such a large variation in properties would result in conservative values.

The Task Group concluded that the casting and processing of Ti-6Al-4V needed to be reduced to a standard practice that was tightly controlled by a specification in order to reduce the variability in mechanical properties. Only when the variability was reduced and meaningful "A" and "B" allowables established, could reduction or elimination of the casting factor be considered.

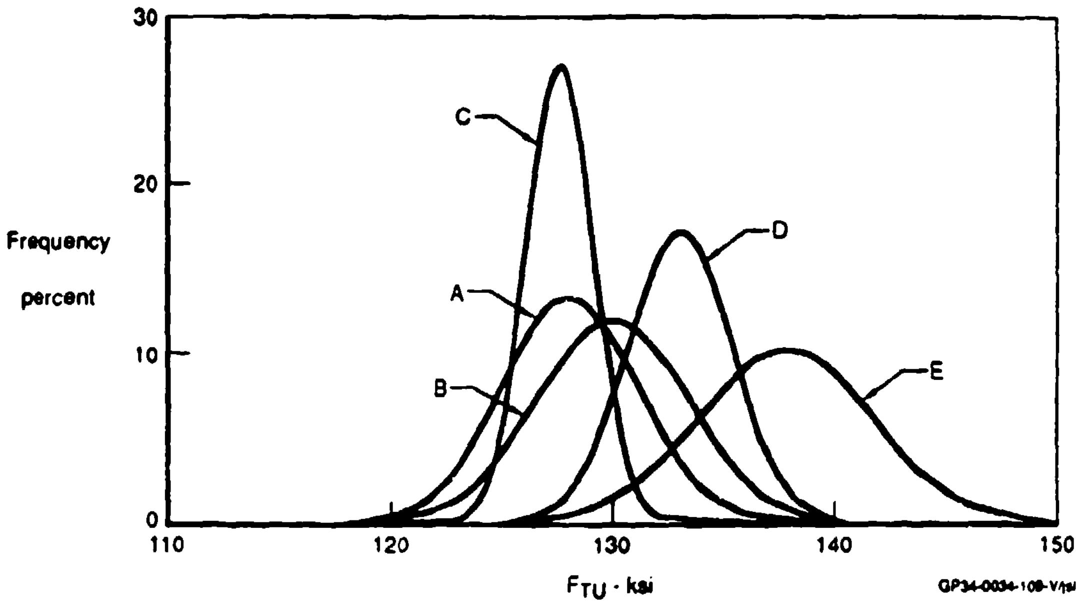


FIGURE 1. VARIATION IN MECHANICAL PROPERTIES OF TI-6AL-4V CASTINGS FROM DIFFERENT SUPPLIERS

The primary objective of our program was to establish meaningful "A" and "B" design allowables for Ti-6Al-4V castings. It is important to emphasize that this did not necessarily result in obtaining castings with the highest properties, but rather the most consistent. We employed the strategy of first reducing the variability in mechanical properties by imposing tighter restrictions on chemistry and post-casting treatment. We also utilized a microstructural nondestructive technique to verify properties of castings. Castings produced to these tightened parameters would then be controlled by a new specification and a microstructural nondestructive inspection technique. The technical program consisted of the following phases: control of variability, preproduction analysis, nondestructive inspection, specification establishment, establishment of

"A" and "B" allowables, and damage tolerance. The program flow is shown in Figure 2.

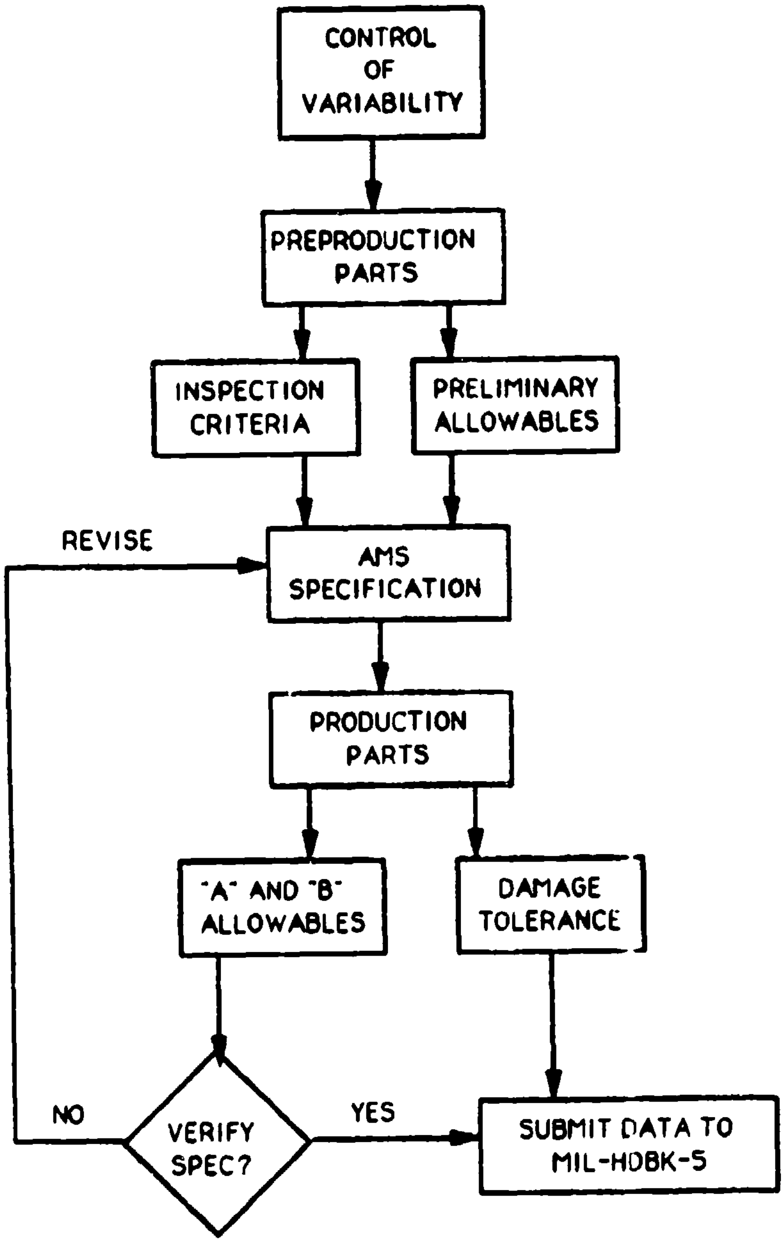


FIGURE 2. PROGRAM FLOW

1.2 PROGRAM PHASES

In Phase I, we used Taguchi methods to determine the sources of variability in Ti-6Al-4V castings. The primary factors that were investigated in this study were the chemical composition and post-casting treatment. These factors were defined with the intent of producing castings with small variability in mechanical properties.

In Phase II, we analyzed mechanical properties of preproduction missile fins and step plates produced using the composition and post-casting treatment defined by the results of the Taguchi study. We also utilized a nondestructive inspection (NDI) technique developed by MDMSC to correlate physical and mechanical properties of castings with features such as prior beta grain size, alpha colony size, and grain boundary alpha.

In Phase III, a new AMS specification was written to incorporate the refined chemistry and post-casting treatment. Mechanical property testing of specimens from of step plates and preproduction fins was used to provide "S" basis allowables.

In Phase IV, specimens from production lots of parts were tested to determine "A" and "B" allowables for these castings. Compression, bearing, and shear properties were also determined for the establishment of reduced ratios. These properties were used to revise the AMS specification.

Finally, in Phase V, fracture mechanics testing of specimens from the castings was performed.

SECTION 2

CONTROL OF VARIABILITY

In Phase I, we utilized Taguchi methods to identify the causes of and minimize the variation in the tensile strength of titanium castings. We applied Taguchi analysis of means and variance methods to the test data provided by the Boeing Corporation as well as other available data. As a result of this analysis, we were able to discern the individual effects of chemistry, HIPing, and heat treatment on the average and variance of the mechanical properties for Ti-6Al-4V castings. It was considered beyond the scope of this program to include analysis of other factors such as cooling rates (due to differences in mold temperature prior to casting), weld repair conditions, and heat treatments above the beta transus.

2.1 COMPOSITIONAL VARIABILITY

In this task we used Taguchi methods to define compositional limits for Ti-6Al-4V castings to provide more consistent mechanical properties. The relative strengthening effect of each alloying element was taken into account in our analysis. A detailed description of this analysis can be found in Appendix A.

Based on our findings, we felt that a tightening of allowable chemistry variations was feasible for the alloying elements in Ti-6Al-4V. Because of extensive experience obtained in the production of titanium alloys over the last 30 years, control of alloy chemistry is fairly routine. Of the interstitials, carbon and nitrogen are usually not adjusted by the primary metal supplier and typically do not exceed 0.01 weight percent (w/o). Oxygen levels are usually higher than those for carbon and nitrogen primarily because the starting titanium sponge can contain oxygen levels as high as 0.08 w/o. Melting operations conducted by titanium foundries typically raise the oxygen content of the melt by approximately 0.02 w/o. With current commercial practice, therefore, it is possible to obtain a titanium alloy casting with well-controlled oxygen levels in the range 0.12-0.17 w/o.

As stated in Section 1, the intent of the program was to establish parameters to produce the most consistent properties and not necessarily the highest average properties. An example of this is shown below. Differences in chemical composition that were still within the limits of the current public specifications can produce variations in population distributions (Figure 3). If we target a tighter chemical composition, we obtain the population labelled "minimum variance." The average strength of the parts is approximately 134 ksi. On the other hand, if our target were to be a chemistry that would produce maximum average strength, the resultant mechanical properties would show a much larger spread in values. The "A"- and "B"-basis allowables (Table 1) for each of these groups verify the influence that population distribution has upon allowable values.

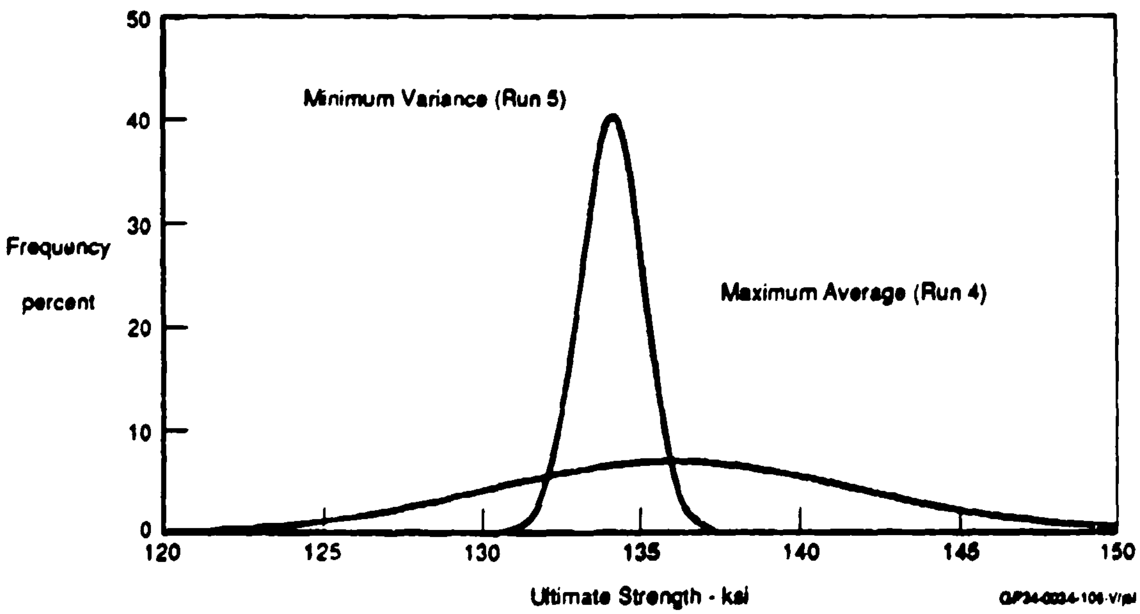


FIGURE 3. DIFFERENT CHEMISTRIES PRODUCE DIFFERENT STRENGTH LEVELS AND DISTRIBUTION OF POPULATION

TABLE 1. "A" AND "B" ALLOWABLES CORRESPONDING TO CURVES IN FIGURE 3

ALLOWABLE	MINIMUM VARIANCE	MAXIMUM AVERAGE
"A"-BASIS	128 KSI	117 KSI
"B"-BASIS	131 KSI	124 KSI

The Taguchi analysis of the Boeing data set identified an optimal chemistry for Ti-6Al-4V castings that would result in minimal variation in properties. Our optimized chemistry is shown in Table 2 and is compared to chemistries currently listed for Ti-6Al-4V castings. Ingot and casting suppliers were asked to review the findings of the Taguchi analysis. All felt that the optimized chemistry was too restrictive and supplied information that allowed us to define a chemical composition that was as close to the optimized composition as possible and still considered producible by the casting suppliers without incurring a significant cost penalty.

TABLE 2. PROPOSED CHEMISTRIES FOR TI-6AL-4V CASTINGS

ELEMENTS	MIL-T-81915	MDMSC PROGRAM	RMI	SUPPLIER 1	SUPPLIER 2	SUPPLIER 3	SUPPLIER 4
Ti	BALANCE	BALANCE	BALANCE	BALANCE	BALANCE	BALANCE	BALANCE
Al	5.5 - 6.75	6.0 - 6.3	6.0 - 6.5 or 5.9 - 6.4	6.0 - 6.4	5.75 - 6.5	5.8 - 6.3	5.8 - 6.3
V	3.5 - 4.5	3.6 - 4.4	3.6 - 4.3	3.6 - 4.4	3.5 - 4.5	3.8 - 4.3	3.6 - 4.4
Fe	0.30 MAX	0.11 - 0.21	0.11 - 0.21	0.10 - 0.21	0.25 MAX	0.25 MAX	0.11 - 0.21
C	0.08 MAX	0.02 - 0.03	0.03 MAX	0.01 - 0.03	0.07 MAX	0.04 MAX	0.015 - 0.035
H	0.015 MAX	0.0013 MAX	0.01 MAX	0.0035 MAX	0.01 MAX	0.01 MAX	0.003 MAX
O	0.20 MAX	0.13 - 0.16	0.12 - 0.16 or 0.13 - 0.17	0.13 - 0.16	0.13 - 0.17	0.17 - 0.20	0.18 - 0.20
N	0.05 MAX	0.008 - 0.017	0.017 MAX	0.008 - 0.017	0.01 - 0.03	0.008 - 0.015	0.008 - 0.017
Y	-	0.005	0.005 MAX	0.005 MAX	0.005 MAX	-	0.005
OTHER IMPURITIES	0.40 MAX	0.40 MAX (NO ONE ELEMENT OVER 0.10)	0.40 MAX (NO ONE ELEMENT OVER 0.10)	0.40 MAX (NO ONE ELEMENT OVER 0.10)	0.40 MAX (NO ONE ELEMENT OVER 0.10)	0.40 MAX (NO ONE ELEMENT OVER 0.10)	0.40 MAX (NO ONE ELEMENT OVER 0.10)

In our Taguchi analysis we also determined the contribution of each element to the variability of the mechanical properties. These data are shown in Table 3. The data indicate that aluminum is well-controlled

TABLE 3. CONTRIBUTION OF ALLOYING ELEMENTS TO MECHANICAL PROPERTY VARIABILITY

ELEMENT	CONTRIBUTION TO VARIABILITY OF: FTY	FTU
Al	1.57%	1.62%
C	0.97%	6.79%
H	15.08%	21.76%
Fe	19.87%	17.84%
N	7.65%	4.43%
O	15.25%	9.04%
TOTAL	60.39%	61.48%

and contributes very little to the mechanical property variability. However, our analysis showed that the other elements listed have a significant influence on the variability of the yield or tensile strength or both. These effects have been documented as shown in Figure 4, from which it can be observed that a small change in interstitial content can result in a large change in strength. In higher strength titanium alloys, oxygen and iron are intentional additions that result in higher strengths. While carbon and nitrogen can also be potent strengtheners, their content is kept to a minimum to avoid embrittlement. In our analysis we determined that in order to decrease the variability of the mechanical properties, the amounts of interstitial elements and iron need to be restricted to narrower ranges.

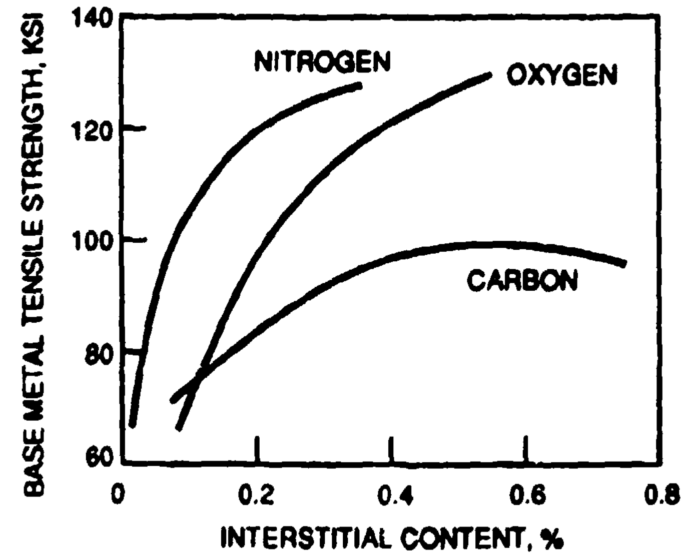


FIGURE 4. EFFECTS OF INTERSTITIAL ALLOYING ELEMENTS ON UNALLOYED TITANIUM (REFERENCE 9)

Using the supplier information, we selected two suppliers that could meet restrictive chemistries and the rigorous program schedule. Supplier 1 set their chemistry limits, labelled as Chemistry "B" (Table 4) as being producible at a cost competitive to current Ti-6Al-4V castings. Their parts were centrifugally cast. Supplier 2, who used a static casting method, felt that Chemistry "A" (Table 4), which was less restrictive than Chemistry "B" was more producible. In order to obtain comparisons between the suppliers as well as between chemistries, Supplier 2 was required to produce half of their parts to Chemistry "A" and the other half to Chemistry "B."

TABLE 4. PROGRAM CHEMISTRY

ELEMENT	TAGUCHI ANALYSIS	CHEMISTRY "A" (LESS RESTRICTIVE)	CHEMISTRY "B" (MORE RESTRICTIVE)
Ti	BALANCE	BALANCE	BALANCE
Al	6.0 - 6.8	5.75 - 6.5	6.0 - 6.4
V	3.6 - 4.4	3.6 - 4.5	3.6 - 4.4
Fe	0.11 - 0.21	0.25 MAX	0.10 - 0.21
C	0.02 - 0.03	0.07 MAX	0.01 - 0.03
H	0.0013 MAX	0.01 MAX	0.0035 MAX
O	0.13 - 0.16	0.13 - 0.17	0.13 - 0.16
N	0.008 - 0.017	0.01 - 0.03	0.008 - 0.017
Y	0.005 MAX	0.005 MAX	0.005 MAX
OTHER IMPURITIES	0.40 MAX (NO ONE ELEMENT OVER 0.10)	0.40 MAX (NO ONE ELEMENT OVER 0.10)	0.40 MAX (NO ONE ELEMENT OVER 0.10)

2.2 POST-CASTING TREATMENT

The data in Table 3 show that approximately 60% of the variability in mechanical properties of Ti-6Al-4V castings is a result of chemical composition. The other 40% is due to other factors such as post-casting treatment. In this task we applied Taguchi methods to a variety of heat treatment data that had been compiled by the MIL-HDBK-5 Titanium Casting Task Group (Appendix A). The objective of this task was to identify HIP and annealing treatments for Ti-6Al-4V castings that would result in more consistent mechanical properties. The data came from a variety of sources including both suppliers and users. Because these treatments are not identical, the castings produced by each foundry can be expected to exhibit slightly different mechanical properties due to the sensitivity of the microstructure of titanium alloys to elevated temperature exposure.

Selection of a specific HIP cycle is primarily dependent on the section size and microstructure of the casting. HIP temperatures for Ti-6Al-4V castings are never above the beta transus (1825°F) to avoid the formation of undesirable microstructural constituents. These include the formation of large beta grains during the isothermal portion of the cycle and precipitation of thick grain boundary alpha phase during the long cool down portion of the cycle. Although large prior beta grain size has been shown (References 10-13) to exert a beneficial effect on fracture toughness, creep resistance, and resistance to fatigue crack propagation, it is detrimental for low- and high-cycle fatigue resistance. Grain boundary alpha is undesirable because it has been found to cause premature fatigue crack initiation (Reference 14).

Heat treatment of titanium alloy castings is used to modify certain microstructural features and affect an improvement in mechanical properties. In Ti-6Al-4V, heat treatment alters the grain boundary alpha phase, the large alpha platelet colonies, and the morphology of the alpha platelets. These treatments can be done both above and below the beta transus temperature. Heat treatment above the beta transus is known to improve fatigue resistance while maintaining strength properties, but careful control of exposure times and cooling rate, especially in thick section castings, must be maintained to achieve optimum results. Beta heat treatments offer additional problems with distortion induced by alpha/beta phase transformation; these problems can be minimized through the use of rigid fixtures. Because the majority of titanium castings are typically annealed below the beta transus, more data are available on the properties of these castings. For this reason, the use of beta heat treatments was not considered for this program.

Details of the Taguchi analysis performed to optimize post-casting treatment are described in Appendix A. When one examines the phase relationships (Figure 5), it would appear that choice of annealing temperature for Ti-6Al-4V castings in the range that is currently called out in the public specifications (1330°F-1550°F), would have little effect on the microstructure and mechanical properties. However, our analysis indicates that narrowing this range would decrease the variability in properties. The results of our analysis indicated that hot isostatic pressing at 1650°F/15 ksi/2 hours and annealing at 1550°F/2 hours would produce the least variability in strength. The materials and parts suppliers agreed that these parameters were reasonable, and parts used in this program were produced to these parameters.

The results of the Taguchi analyses were used to produce cast step plates and missile fins for specification determination and design allowable determination. Specimens from these parts were used to establish NDI and mechanical property data bases for the remainder of the program.

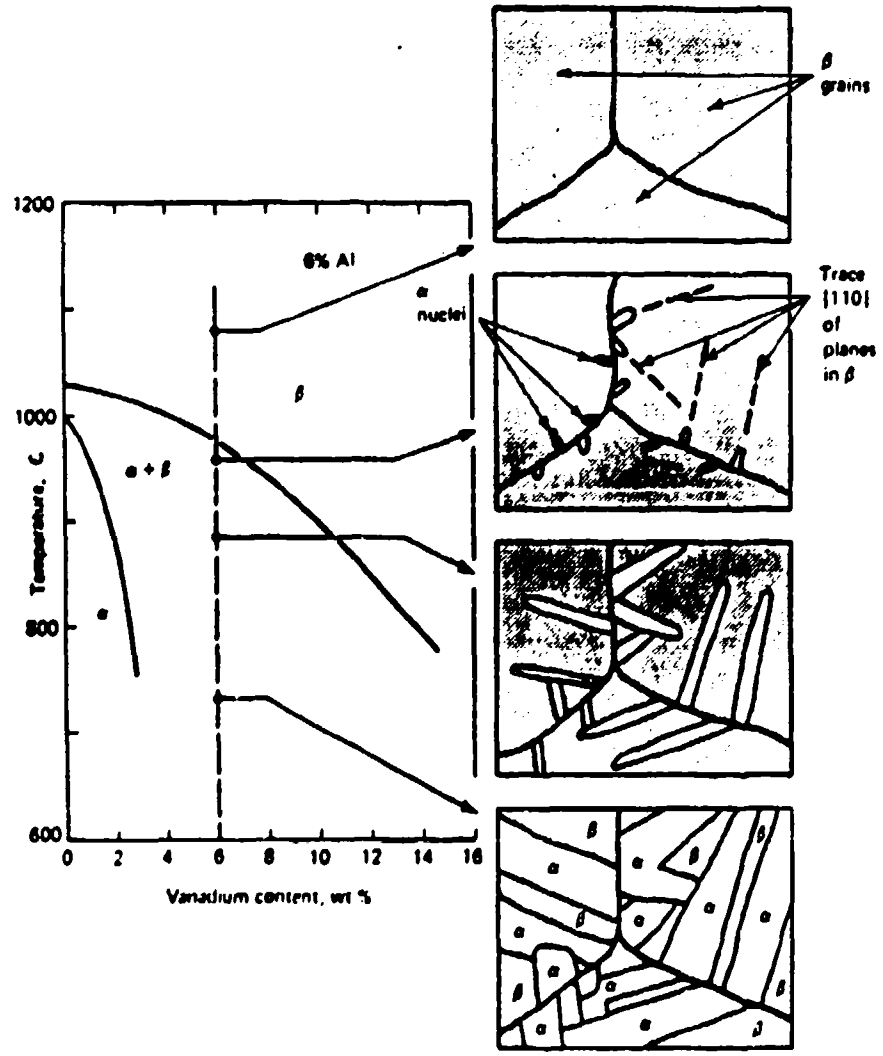


FIGURE 5. THE TI-6AL-V PHASE DIAGRAM (REFERENCE 9)

SECTION 3

PREPRODUCTION PART ANALYSIS

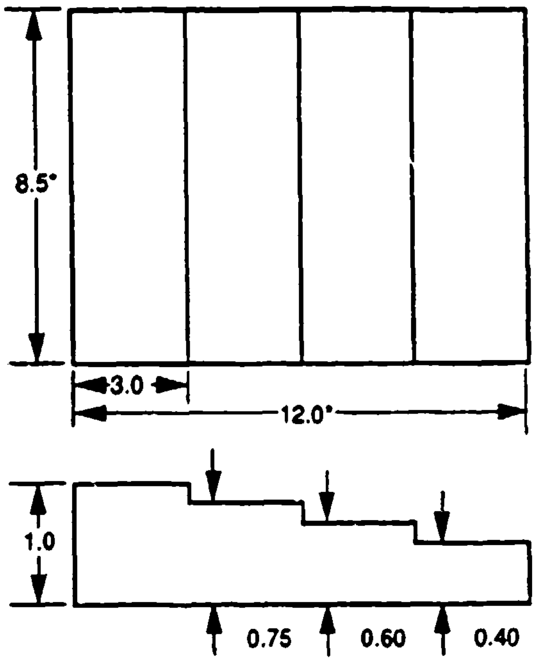
In Phase II of the program, we performed mechanical property testing and microstructural nondestructive inspection of cast step plates (Figure 6) and preproduction missile fins (Figure 7) produced using the 2 chemistries shown in Table 4. Parts were to be supplied by two foundries (Supplier 1 = Wyman-Gordon; Supplier 2 = Schlosser Casting Company). The data generated were used to establish a new AMS specification for investment cast Ti-6Al-4V.

3.1 MECHANICAL PROPERTY TESTING

Twelve specimens were excised from each step plate and 9 specimens from the 2 preproduction fins for a total of 33 test specimens. Specimen orientation with respect to part geometry is shown in Figure 8. Testing was performed at 75°F in accordance with ASTM E8 (Reference 15), and the data are contained in Appendix B.

Data in this section represent parts produced by Supplier 2. Parts from Supplier 1 did not meet the program requirements and were not incorporated into the base plan because these castings had been annealed for more than 2 hours in order to lower the hydrogen content. Data from parts procured from Supplier 2 were used in later analyses for heat treatment comparison.

When we examined the differences in strength as a function of chemistry, we noted that there was a difference in the mechanical properties of the castings that was related to the chemistry of the parts (Figure 9). Step plates made to the more restrictive Chemistry "B" (Table 4) had higher properties than those cast to the less restrictive Chemistry "A." The differences varied from 0.5 to 3 ksi, and the trends with respect to thickness were the same. When we look at the actual chemistries of the step plates (Table 5), we see that the chemistries of both plates were tightly controlled and are very similar. There are differences noted in the quantities of iron, vanadium and aluminum. Both plates met the highly restrictive chemical composition established using the Taguchi analysis. This indicates that there will always be some variability in properties even when using a highly restrictive chemistry.



NOTE: ALL DIMENSIONS IN INCHES
*MINIMUM DIMENSIONS

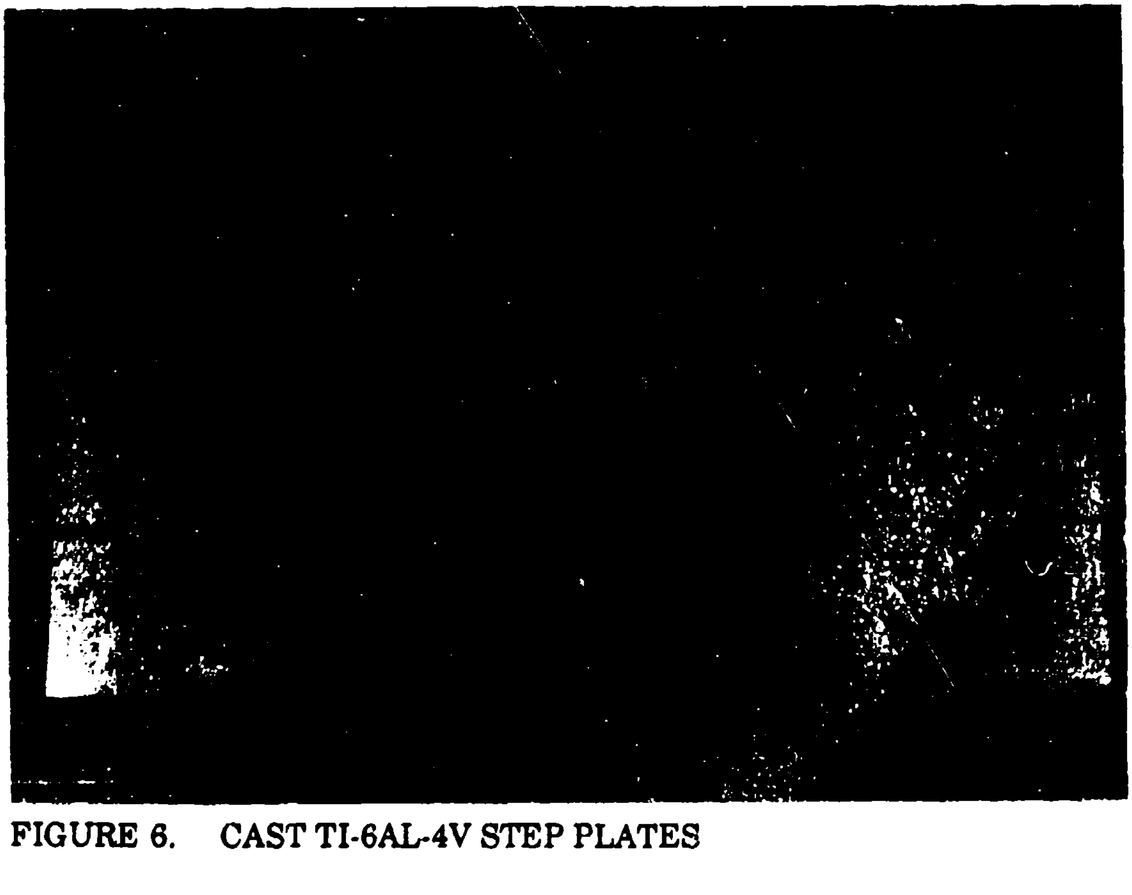
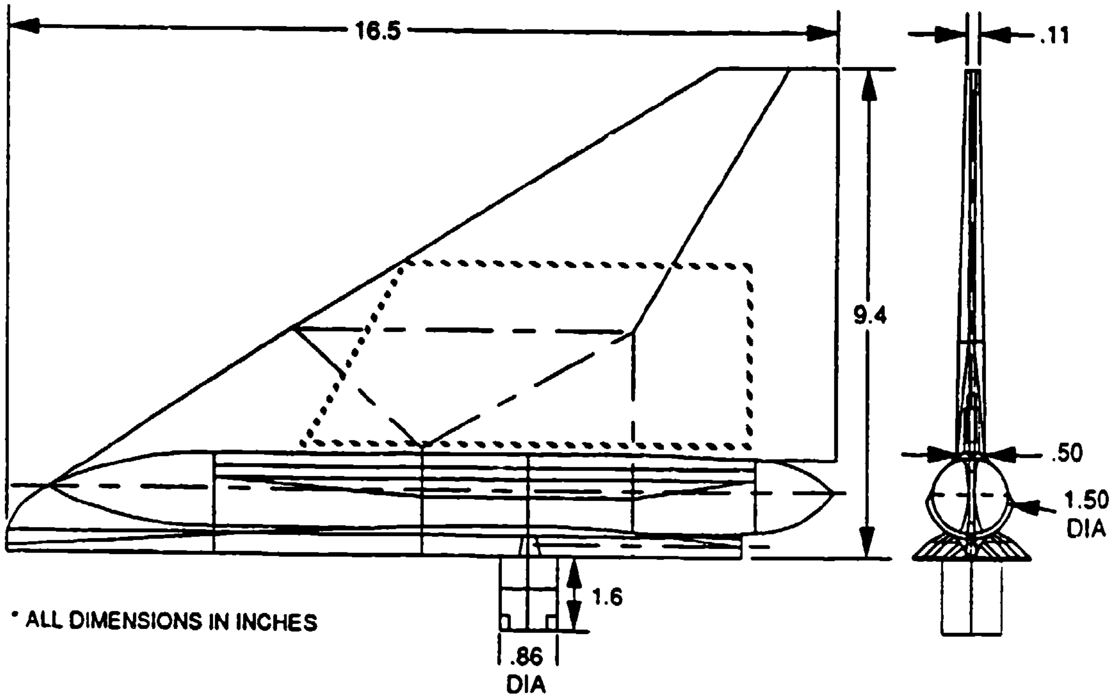


FIGURE 6. CAST TI-6AL-4V STEP PLATES



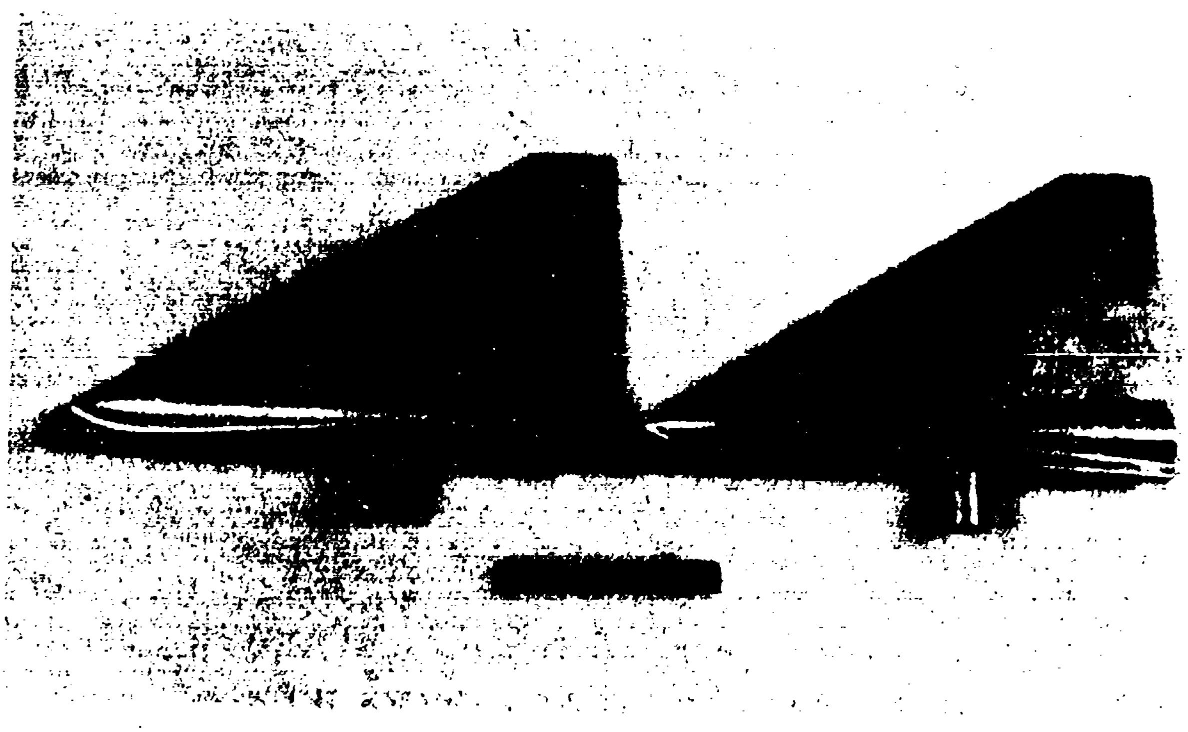


FIGURE 7. CAST TI-6AL-4V MISSILE FINS

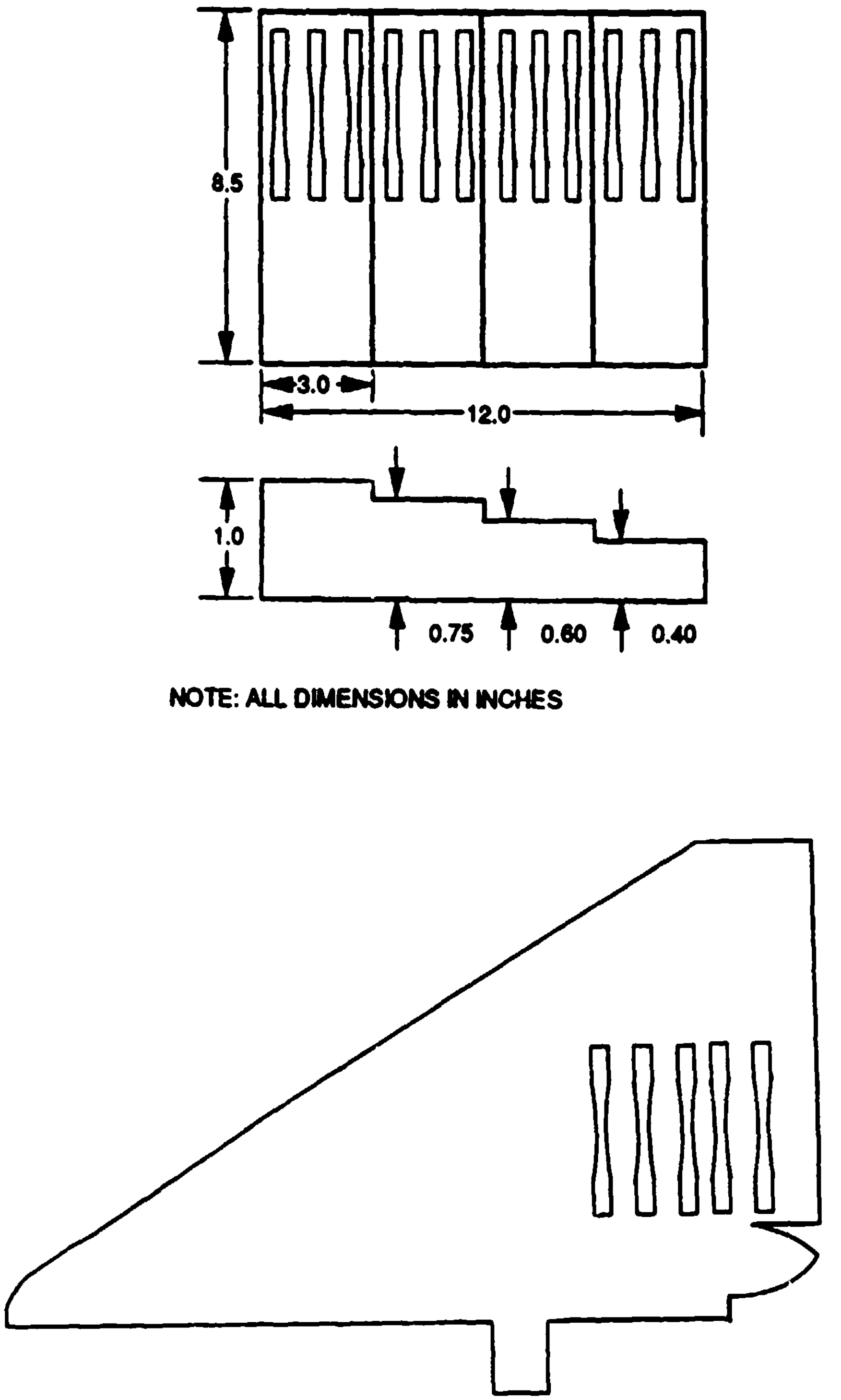


FIGURE 8. LOCATION AND ORIENTATION OF TENSILE SPECIMENS EXCISED FROM PREPRODUCTION FINS AND STEP PLATES

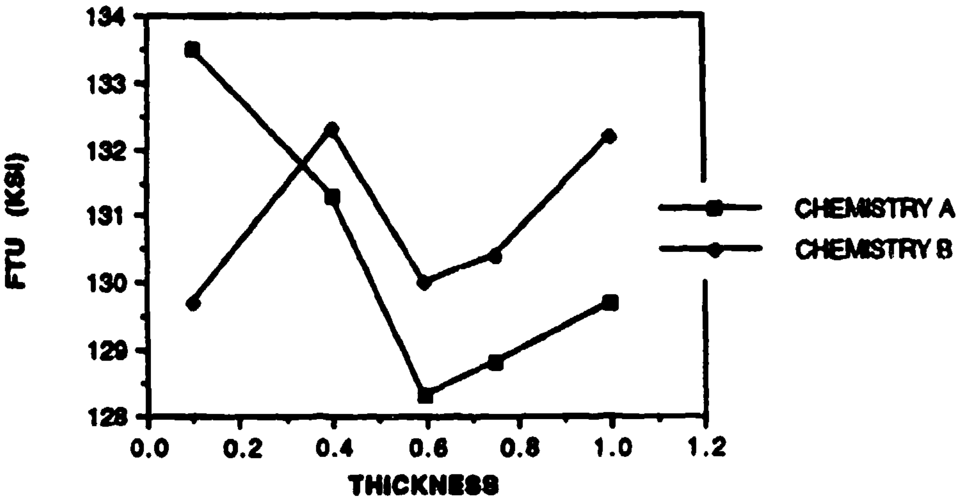


FIGURE 9. RELATIONSHIP OF CHEMISTRY TO STRENGTH

TABLE 5. ACTUAL CHEMISTRIES OF PREPRODUCTION PARTS

ELEMENT	CHEMISTRY "A"		CHEMISTRY "B"	
	PLATE	FIN	PLATE	FIN
Al	6.33	6.0	6.2	6.2
V	3.9	4.2	3.9	4.1
Fe	0.17	0.2	0.18	0.2
C	0.03	0.02	0.02	0.02
H	0.0009	0.0008	0.004	0.0028
O	0.17	0.16	0.18	0.15
N	0.008	0.008	0.007	0.006
Y	0.001	0.001	0.001	0.001

The "F" ratio comparison of variances and "t" test for comparison of means indicated that parts from Chemistry "A" and "B" could be considered part of the same population. The data from parts made using the 2 chemistries were combined into a single population. The strength of the parts varied very little with part thickness (Figure 10). Standard deviations were less than 2 for both tensile and yield strengths. These data were compared with other data provided by Titech (Reference 16) or derived from MDMSC IRAD studies of Ti-6Al-4V castings (Reference 17). This comparison shows that the average strength obtained with the restrictive chemistry is lower than that obtained using process controls contained in current public specifications (Figure 11). Our data also showed far less variability than the other data sets.

Data from the preproduction parts were then used to calculate preliminary "S"-basis allowables using the computational procedure described in MIL-HDBK-5 (Reference 18). The preliminary allowables are F_{tu}= 125 ksi and F_{ty}= 120 ksi.

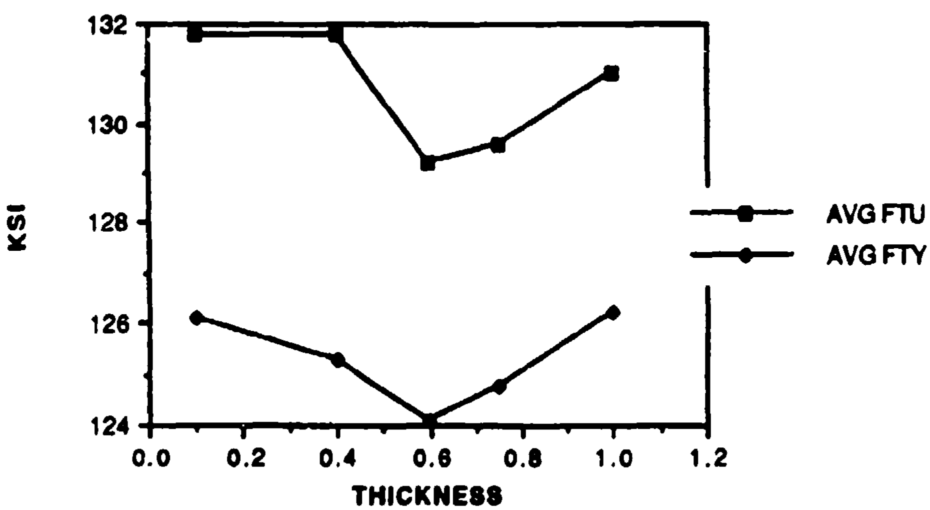


FIGURE 10. RELATIONSHIP OF THICKNESS TO TENSILE STRENGTH

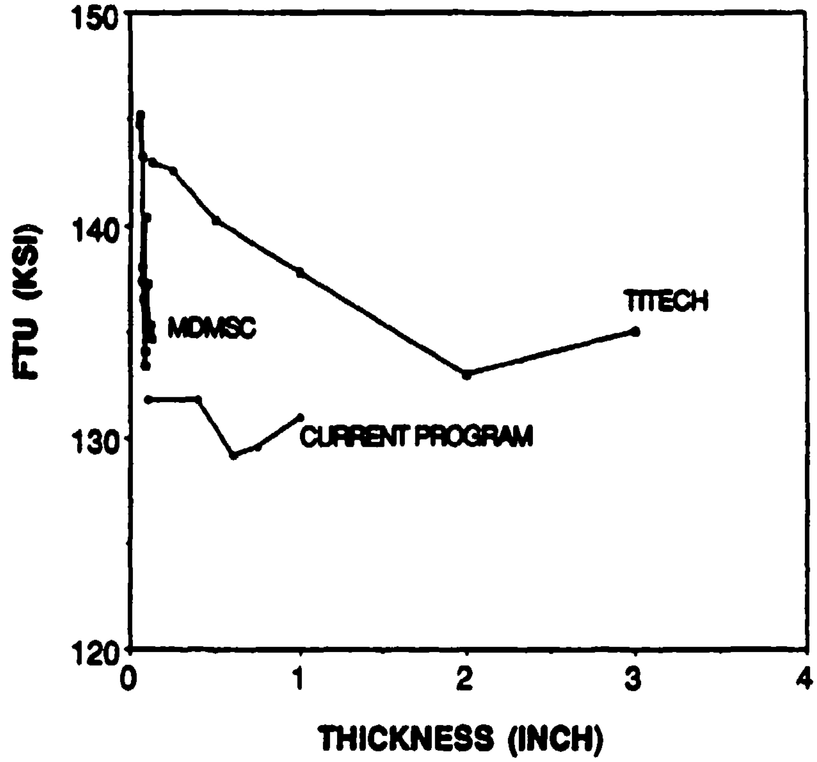


FIGURE 11. DATA GENERATED FROM PARTS CAST TO MORE RESTRICTIVE CHEMISTRY AND POST-CASTING TREATMENT SHOW LESS VARIABILITY THAN DATA GENERATED FROM PARTS CAST TO CURRENT PUBLIC SPECIFICATIONS

3.2 NONDESTRUCTIVE INSPECTION

The Ti-6Al-4V alloy microstructure contains nearly all alpha phase with 5-10% beta phase. Typical cast microstructures consist of alpha platelets separated by thin beta lathes or ribs (Figure 5). The alpha platelets are transformation products of the beta phase when cooled below the beta transus. During slow cooling the alpha platelets grow and coarsen, and if cooling rates are sufficiently slow, adjacent platelets may form colonies of similarly aligned platelets sharing a common crystallographic orientation. Larger colonies are developed by slow cooling rates through the beta transus with the upper size boundary for these colonies being the prior beta grain size.

Titanium castings typically exhibit large prior beta grains separated by continuous grain boundary alpha. The prior beta grain size is determined by the time spent in the beta phase upon cooling, with longer times giving larger grains. During slow cooling through the alpha + beta phase field grain boundary alpha forms on prior beta grain boundaries with larger and more continuous alpha forming at slower cooling rates.

MDMSC has developed NDI techniques (Reference 19) to correlate microstructural features of investment cast titanium to mechanical properties. Incorporation of metallographic examination of microstructure as a reliable NDI method for determining mechanical properties rather than relying solely on tensile prolongations has several advantages. There are many difficulties in trying to relate the properties of prolongations to those of actual cast parts. Prolongations do not represent different section sizes in the castings and undergo different cooling rates than the actual casting. Different gating mechanisms may also be used for the prolongations than for the casting, resulting in different solidification rates and different microstructures and mechanical properties than those observed for the casting.

In this phase of the program, we utilized this technique to correlate the surface microstructure of cast step plates and preproduction fins with their mechanical properties. The area of interest was polished with a Movipol-130 Electropolisher using an electrolyte solution consisting of perchloric acid, methanol, and butylcellosolve. A replica of the electropolished surface was made on acetate film and mounted for microscopy. Typical photomicrographs from replicas are shown in Figure 12. We measured prior beta grain size, colony size, alpha platelet spacing, and grain boundary alpha content of the cast step plates and preproduction fins.

In all cases the microstructural features under consideration increased in size with increasing section thickness (Figure 13). This is to be expected since thicker sections cool more slowly resulting in a coarser microstructure. Differences in chemistry also resulted in small differences in microstructural feature; however, these differences were not significant. When we examined the relationship of the mechanical properties to microstructural features, we could observe no obvious relationship between the two (Figure 14). As we have shown in Section 3.1, the tightened chemistry and post-casting treatments have produced parts with very small variances in mechanical properties. The same is true for the microstructural features. Because of this, it is not possible to correlate strength directly with microstructural feature in this thickness range (0.1 inch - 1.0 inch). Maximum sizes for the microstructural features measured can be specified for this narrow range of mechanical properties (Table 6). This data will be incorporated into the specification for Ti-6Al-4V castings. However, more work is needed with sections thicker than 1 inch and with parts that do not meet the more restrictive processing to determine whether these maxima are unique to our castings

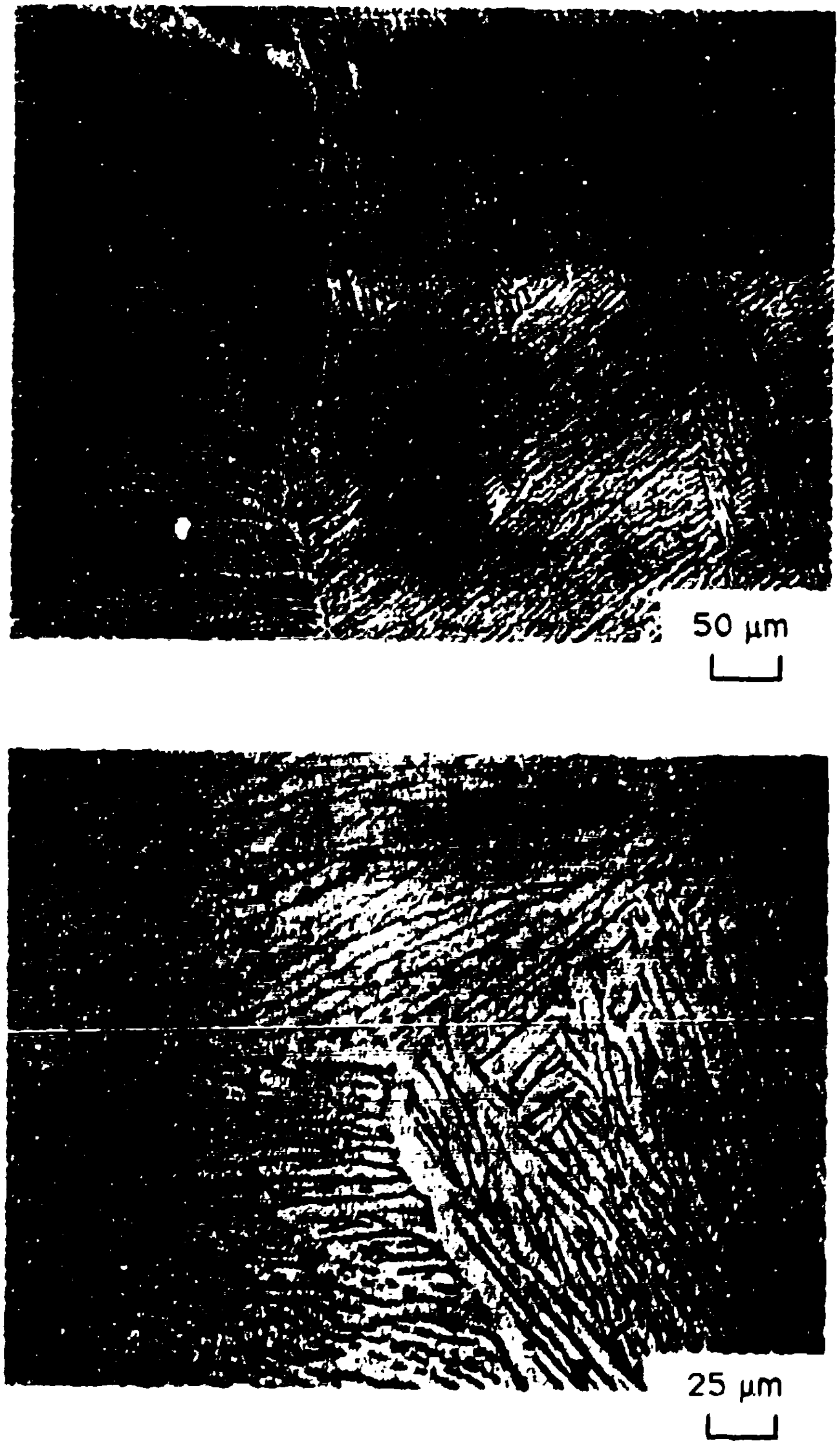


FIGURE 12. TYPICAL PHOTOMICROGRAPHS OF REPLICAS TAKEN FROM TI-6AL-4V CASTINGS

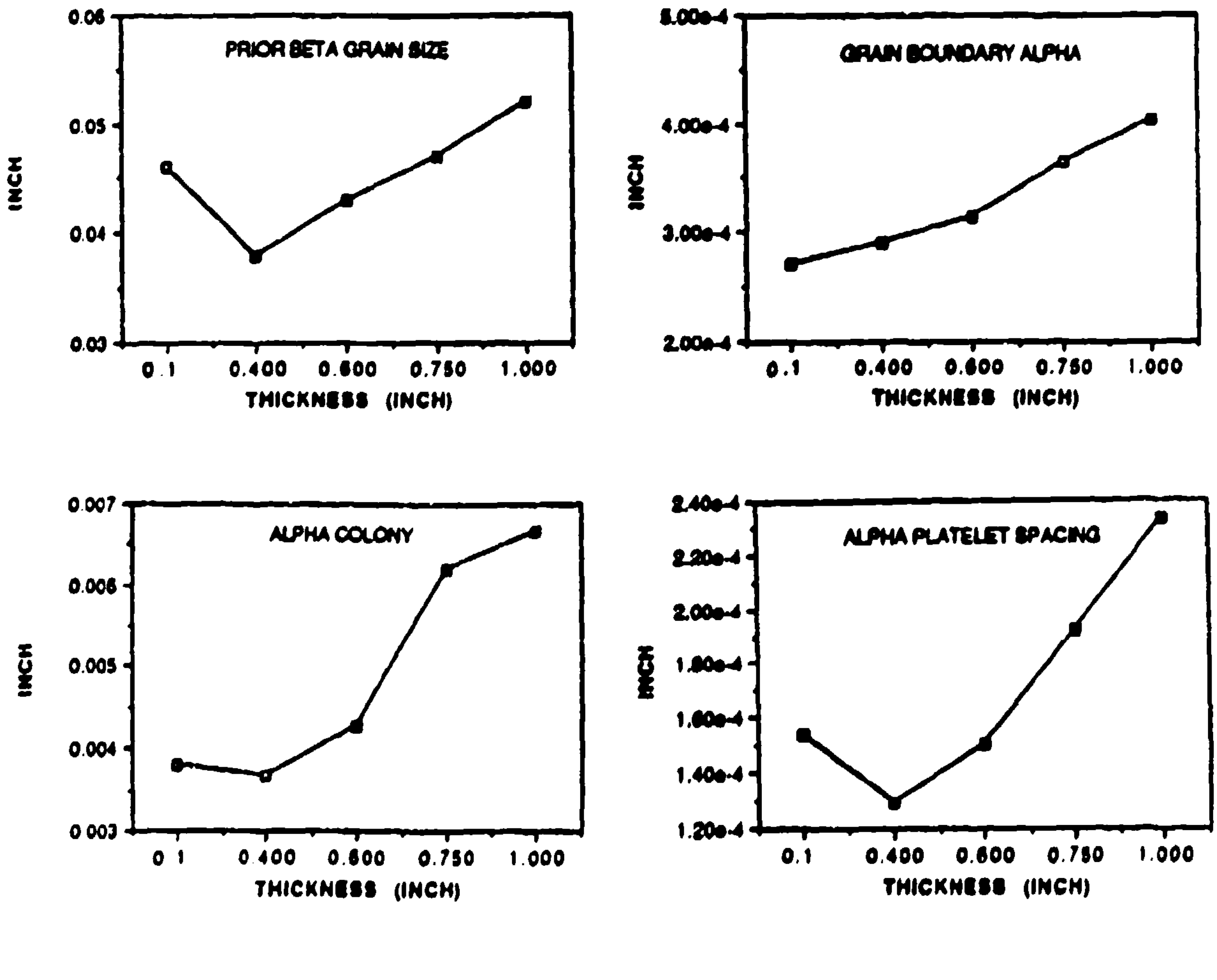


FIGURE 13. VARIATION OF MICROSTRUCTURAL FEATURE WITH PART THICKNESS

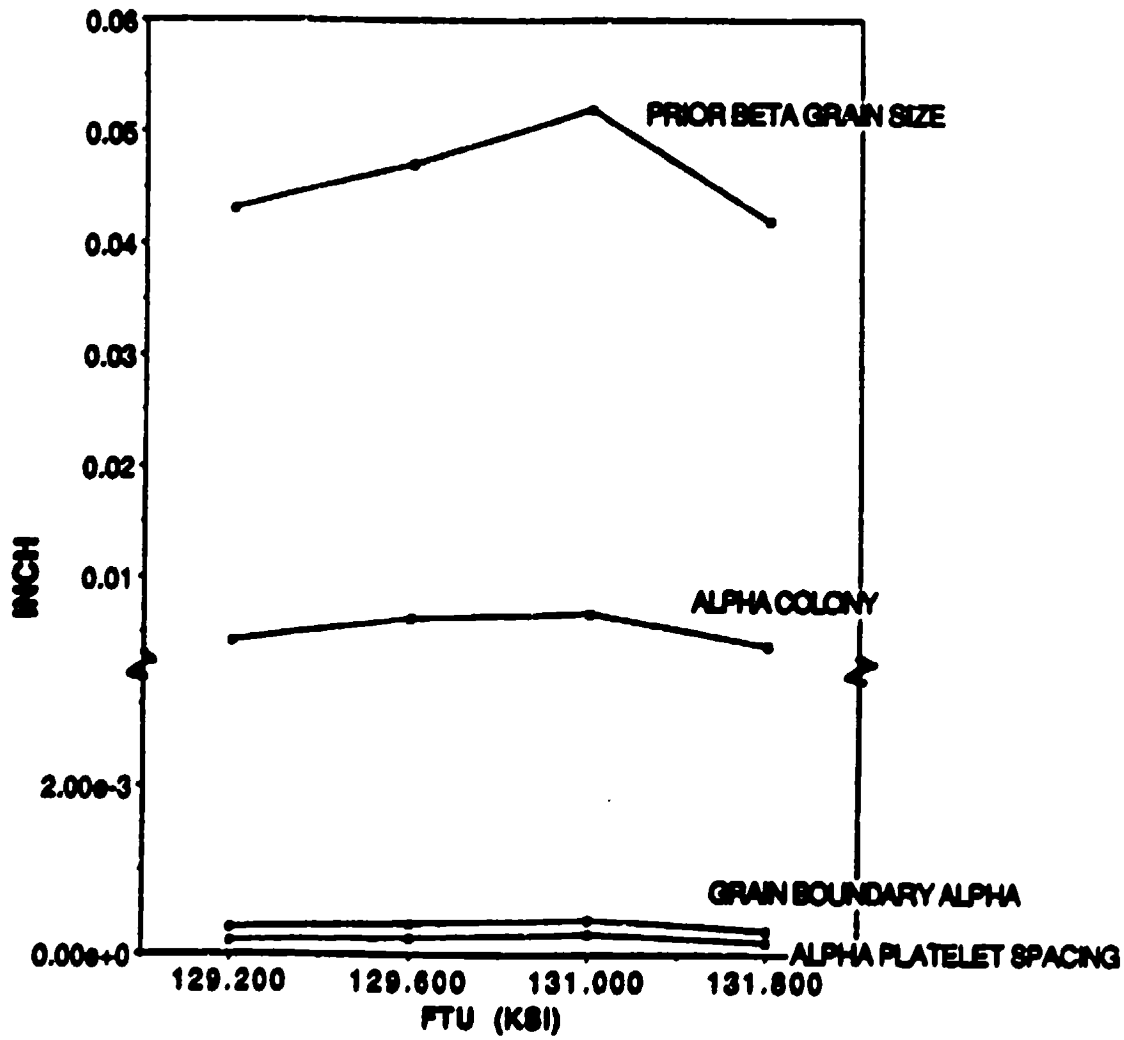


FIGURE 14. SIZES OF THE MICROSTRUCTURAL FEATURES VARY LITTLE OVER THE NARROW PROPRTY RANGE SEEN IN THESE CASTINGS

TABLE 6. MICROSTRUCTURAL FEATURES - MAXIMUM LIMITS

MICROSTRUCTURAL FEATURE	MAXIMUM SIZE (INCH)
PRIOR BETA GRAIN SIZE	0.057
GRAIN BOUNDARY ALPHA	0.000325
ALPHA COLONY	0.001
ALPHA PLATELET SPACING	0.000357

SECTION 4

ESTABLISHMENT OF SPECIFICATION

Public specifications are necessary to provide users with reliable data for specified product forms. Aerospace engineers need reliable information to design minimum weight airframe structures, optimize materials selection for their products, and to inform suppliers of the preferred practices needed to deliver parts with consistent properties. There are curr ıtly 3 public specifications that are used for procurement of titanium castings: AMS 4985, AMS 4991, and MIL-T-81915 (References 20-22). Specifications AMS 4985 and AMS 4991 cover Ti-6Al-4V castings and tensile properties for separately cast specimens, prolongations, or specimens from castings. MIL-T-81915 covers cast Ti-6Al-4V as well as commercially pure titanium, Ti-5Al-2.5Sn, and Ti-6Al-2Sn-4Zr-2Mo and contains properties for tensile specimens cut from castings. There is some variability in the minimum properties that are specified in each of these documents. Various radiographic grades are also specified in the different specifications. In-house company specifications are often used to procure Ti-6Al-4V castings. While many have the same chemistry requirements as found in the public specifications, they may contain provisions not contained in the public specifications, such as the parameters for hot isostatic pressing.

Under this phase of the proposed program, we prepared a more comprehensive and stringent specification for Ti-6Al-4V castings using chemical limits and post-casting treatment established in our Taguchi analysis and NDI criteria. The specification was drafted in accordance with AMS guidelines (Reference 23). We performed both "F" ratio of variance analysis and "t" test for comparison of means (Reference 18) on data sets representing both chemistries "A" and "B".

Our findings indicated that parts produced from these two chemistries did not differ significantly with respect to their average strengths and that the variability was not significantly different. We listed Chemistry "B" in the specification since it was less restrictive than Chemistry "A". Combining data from parts using both chemistries resulted in a population with a standard deviation of 2 ksi. The post-casting conditions called out in the specification are HIP at 1650°F/15 ksi/2 hours and annealing at 1550°F/2 hours. Using data from step plates and preproduction fins, we determined the preliminary "S"-basis allowables to be F_{tu}= 125 ksi and F_{ty}= 120 ksi. We included the NDI criteria listing the maximum coarseness for the microstructural features measured (Table 6, Section 3.2). A copy of the AMS specification is included as Appendix B. The AMS specification shown in Appendix B is a draft specification and may not resemble the final copy. Features of the new specification are compared with corresponding items in the current public specifications in Table 7.

TABLE 7. COMPARISON OF FEATURES OF SPECIFICATIONS FOR CAST TI-6AL-4V

FEATURE	MIL-T-81915	AMS 4985	AMS 4991	PROGRAM SPECIFICATION
CHEMISTRY	CURRENT BASELINE (CARBON = 0.08)	SAME AS MIL-T-81915 EXCEPT CARBON = 0.1	SAME AS MIL-T-81915 EXCEPT CARBON = 0.1	MORE RESTRICTIVE THAN BASELINE FOR ALL ELEMENTS
HEAT TREATMENT	PER MIL-H-81200	ANNEAL 1300°-1650°F/2-4 HR	ANNEAL 1300°-1650°F/2-4 HR	ANNEAL 1650°F/ 2 HR
HOT ISOSTATIC PRESSING	NO CALL-OUT	NO CALL-OUT	NO CALL-OUT	HIP 1650°F/ 15 KSI/2 HR
QUALITY	RADIOGRAPHIC PER ASTM E155 (GRADES A,B,C)	RADIOGRAPHIC PER AMS 2635	RADIOGRAPHIC PER AMS 2635 (GRADES A,B,C,D)	MICROSTRUCTURAL INSPECTION
"S"-BASIS FTU				
· SEP. CAST BARS	N/A	130 KSI	130 KSI	N/A
· PROLONGATIONS	N/A	130 KSI	130 KSI	N/A
· PARTS				
DESIGNATED	125 KSI	130 KSI	130 KSI	125 KSI
NONDESIGNATED	125 KSI	125 KSI	127 KSI	125 KSI

SECTION 5

"A" AND "B" ALLOWABLES

5.1 ALLOWABLES DETERMINATION

Using the chemistry and post-casting treatments identified in Phase I of this program, 2 suppliers were to produce enough fins to establish a data base that would be an accurate representation of the actual material properties. Figure 15 shows the production run from Supplier 2. In designing our test program, we used criteria presented in MIL-HDBK-5 (Reference 18) to insure that supporting data would meet the requirements for "A" and "B" allowables. Specifically, we conducted more than 100 tests representing 12 lots of castings from two suppliers. One of the original suppliers (Supplier 1) was unable to produce parts to the original conditions specified. They annealed their parts for an additional 2 hours than specified to lower the hydrogen content to the specified level. We chose not to use these castings for the original determination of "A" and "B" allowables, but we did measure properties for comparison and assessment of combinability with the established data base. Since there was a requirement to generate the data base using parts from two suppliers, we were able to meet this requirement by using surplus MDMSC fins cast by a third supplier. These parts were statically cast, had the same configuration as the program fins, and met the the chemical and post-casting requirements developed in Phase I of the program.

Upon receipt of the fins, MDMSC conducted metallographic NDI using the method described in Phase II. The areas examined were those from which the test specimens were excised (Figure 8). Room temperature tensile testing of these specimens was performed in accordance with ASTM E8 (Reference 15). Compression, bearing, and shear specimens were also excised from these areas of the fins to provide data for reduced ratios. The raw data is listed in Appendix D.

Once data was gathered, we computed "A" and "B" design allowables using software provided by the Boeing Corporation (Reference 24). The method of computation uses the Weibull approach and determines population distribution using the Anderson-Darling test for Weibullness. This test determines whether the test data can be approximated using a three-parameter Weibull curve. The software calculates "A" and "B" allowables using both normal and non-normal distribution function.

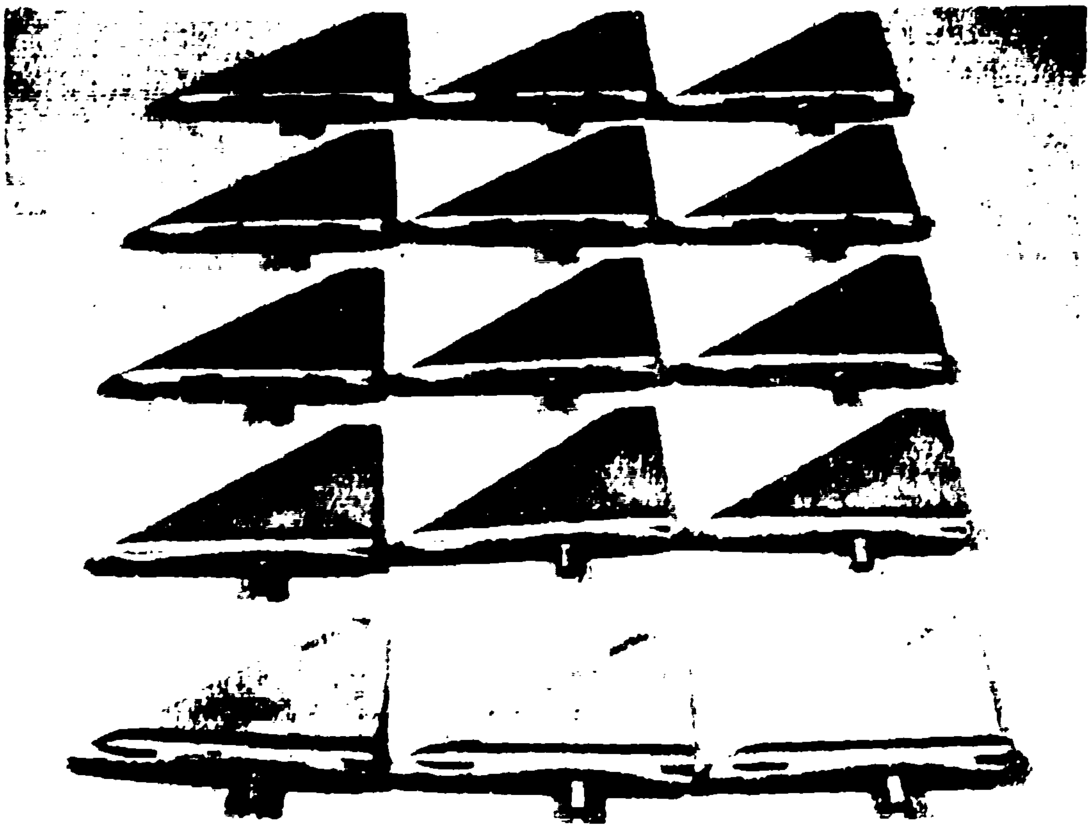


FIGURE 15. PRODUCTION FINS FROM SUPPLIER 2

We performed the "F" ratio test for analysis of variance and "t" test for analysis of means (Reference 18) to determine whether the fins produced by Suppliers 2 and 3 represented the same population. The results of these tests showed that both the variances and means were representative of the same population and that the data could be combined. The complete results of the data analysis are contained in Appendix D.

A summary of the allowables determination from the production fins from Suppliers 2 and 3 is shown in Table 8. The analysis reveals that the data obtained for the fins from these two suppliers fit a normal distribution. However, the hypothesis of Weibullness was rejected for the tensile strength but not for yield strength. The "A" and "B" allowables are compared to "S"-basis values listed in MIL-T-81915 and allowables determined by Douglas Aircraft for the C-17 program (Reference 25). The C-17 castings were supplied to AMS 4985 in the hot isostatically pressed and annealed condition.

TABLE 8. "A" AND "B" ALLOWABLES

BASIS	SOURCE	F_{ty} (KSI)	F_{tu} (KSI)
A	WEIBULL	120	125
	NORMAL	121	126
	DAC	109	123
B	WEIBULL	123	128
	NORMAL	123	128
	DAC	116	128
S	MDMSC	120	125
	MIL-T-81915	115	125

We tested 10 tensile specimens from 2 fins cast by Supplier 1. These fins met the chemistry requirements, but did not meet the post-casting conditions since they had been annealed for 4 hours rather than the specified 2 hours. The mean tensile strength and yield strength are 3-6 ksi lower than corresponding properties for Suppliers 2 and 3. The "F" ratio and the "t" tests showed that the fins produced by Supplier 1 could not be considered part of the same population as those produced by Suppliers 2 and 3. The differences in the data from parts produced by Supplier 1 could be due to the additional annealing time. Coarsening of the microstructure could bring about the lower properties in these parts. Another reason for the difference could be that these parts were centrifugally cast rather than statically cast as those produced by Suppliers 2 and 3.

5.2 REDUCED RATIOS

Direct computation is the desired method for determining derived properties such as bearing, shear, compression, and tensile properties in directions other than the original test direction. Because obtaining sufficient data for these properties is costly, a method of indirect computation to determine these values is used. This method utilizes pairing of individual ultimate shear or bearing values with ultimate tensile strengths. Compression and bearing yield strengths are paired with tensile yield strength. The basis for this computation is that the mean ratio of these paired observations represents the ratio of corresponding population means. In the ratios, the tensile strength or the tensile ultimate strength appears in the denominator.

We determined reduced ratios for Ti-6Al-4V castings by testing three compression, bearing and shear specimens from the fins. The corresponding data are shown in Table 9 and compared to those determined by Douglas Aircraft (Reference 25) and by the MIL-HDBK-5

Coordination Committee (Reference 26). Tested specimens are shown in Figure 16.

TABLE 9. REDUCED RATIOS FOR TI-6AL-4V CASTINGS

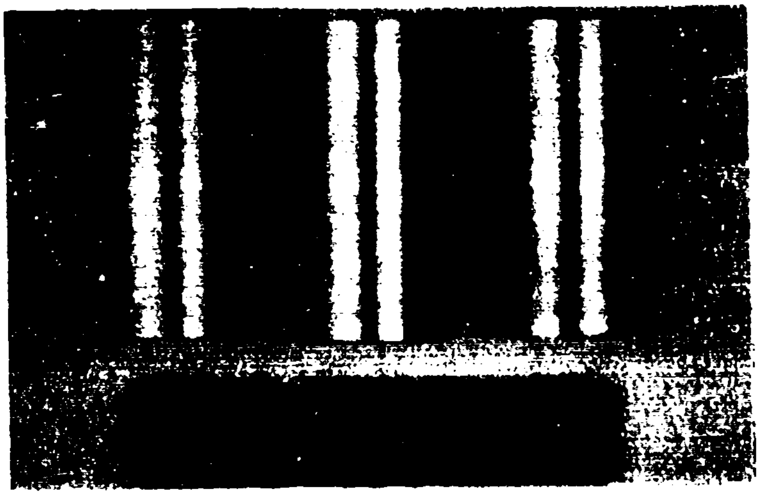
PROPERTY	MDMSC		DAC		MIL-HDBK-5	
	REDUCED RATIO	VALUE (KSI)	REDUCED RATIO	VALUE (KSI)	REDUCED RATIO	VALUE (KSI)*
CYS / FYS	0.999	120	1.059	114	1.058	122
SUS / FUS	0.687	86	0.694	82	0.695	83
BYS / FYS	1.509	181	1.561	169	1.562	180
BUS / FUS	1.701	212	1.635	193	1.634	196

*Determined from "S"-basis values in MIL-T-81915; F_{ty} = 115 ksi; F_{tu} = 120 ksi

A summary of the data is presented in MIL-HDBK-5 format in Figure 17. Since the allowables determined were the same as those estimated from the preproduction parts, there were no changes to the specification.

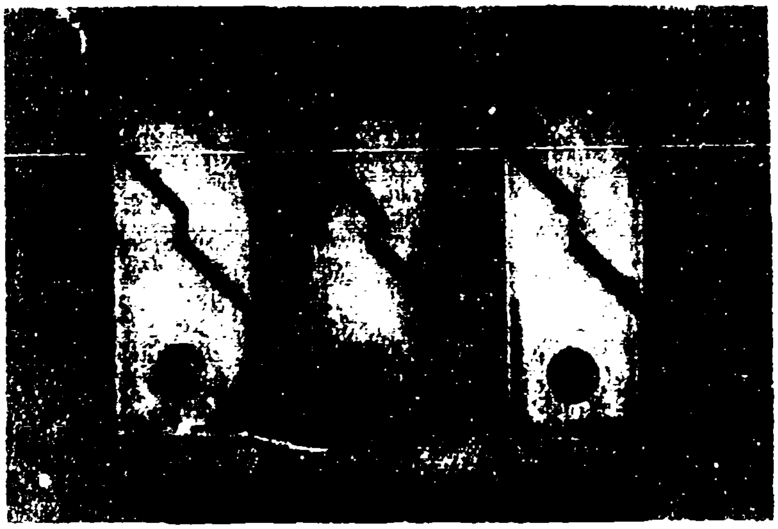
5.3 NONDESTRUCTIVE INSPECTION

Microstructural features were measured as described in Section 3 and the data verified the previous findings. There was only one minor change to the maximum limits; the maximum prior beta grain size changed from 0.57 inch to 0.60 inch. This change was incorporated into the specification.



COMPRESSION

BEARING



SHEAR

FIGURE 16. COMPRESSION, BEARING, AND SHEAR SPECIMENS FROM TI-6AL-4V CASTINGS

Mechanical & Physical Properties For
TI-64, Investment Cast

Specification			
Form	Investment Cast		
Temper	Annealed, HIP'd		
Thickness, or diameter, in			
Basis	Typical	B	A
Mechanical Properties			
F_{tu}, ksi	131	128	125
F_{ty}, ksi	125	123	120
F_{cy}, ksi			122
F_{su}, ksi			83
F_{bru}, ksi			180
F_{bry}, ksi			196
e, percent		5.5	
K_c, ksi•in$^{1/2}$			
E, 10^3 ksi		17	
E_c, 10^3 ksi			
G, 10^3 ksi			
m			
Physical Properties:			
w, lbs/in			
C, Btu/lb•F			
K, Btu/hr•ft•F			
a, 10^{-6}in/in.F			

Data source: Cast fins and step plates
Number of specimens: 115

FIGURE 17. SUMMARY OF ALLOWABLES FOR CAST TI-6AL-4V

SECTION 6

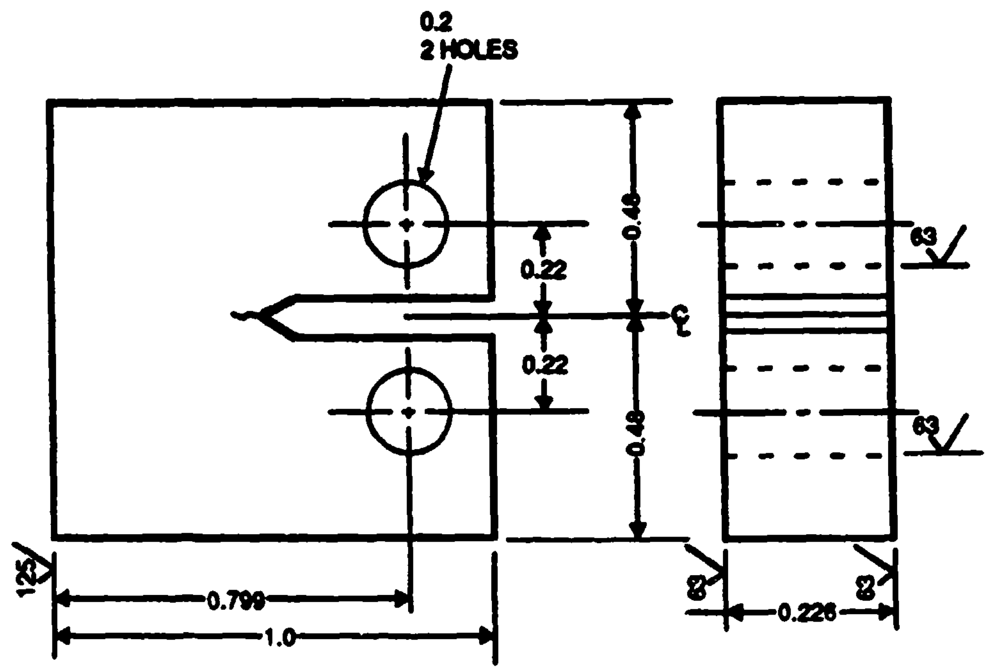
DAMAGE TOLERANCE

In Phase V, MDMSC conducted damage tolerance tests to generate plane-strain fracture toughness and constant amplitude crack growth data per ASTM methods. All test data for the fracture mechanics work is contained in Appendix E.

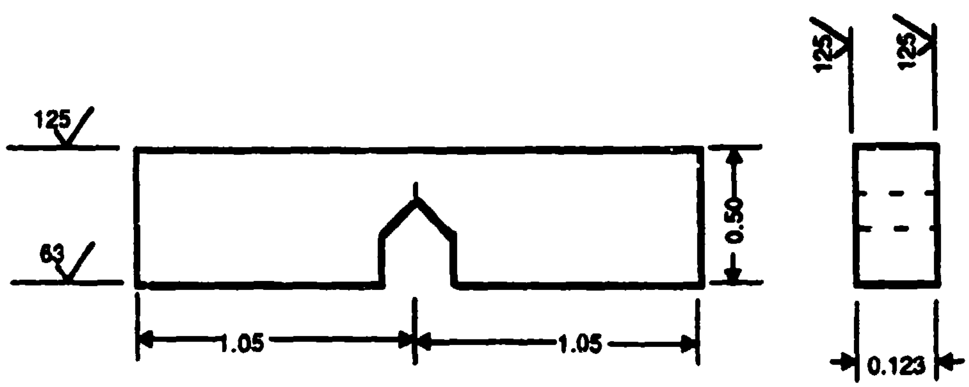
MIL-A-87221 defines durability and damage tolerance analysis requirements for aircraft structures (Reference 27). In the damage tolerance analysis of wrought alloys, the presence of a flaw is assumed to account for defects that may arise in critical areas of parts during manufacturing. In castings there are inherent flaws due to microporosities, microshrinkage, or contaminants. There is a lack of damage tolerance data that takes into consideration these casting flaws and the effects of the microstructural fractures on damage tolerance. This lack of data prevents widespread use of castings for fatigue-critical aircraft applications. In titanium castings, many of the flaws that occur as a result of the casting process are "healed" by hot isostatic pressing and thus are not commonly found. The performance of titanium castings is dominated by the unique cast microstructure. The typical as-cast titanium microstructure consists of beta grains that grow during slow cooling through the beta phase field (Figure 5). Larger beta grains are associated with improved fatigue crack growth. Alpha phase is located along the beta grain boundaries, and alpha plate colonies are located within the beta grains. Both grain boundary alpha and the alpha colonies have been shown to reduce fatigue life, crack initiation, and crack growth properties (Reference 28). Hot isostatic pressing will result in some coarsening of the alpha platelets leading to a lower fatigue strength but a higher fracture toughness.

6.1 FRACTURE TOUGHNESS

In this phase we excised (per ASTM E399) 3 C(T) compact tension specimens for K_{IC} determination and 3 SE(B) bend fracture toughness specimens (Figure 18) from the cast Ti-6Al-4V fins fabricated by Supplier 2. The C(T) specimens were precracked under the conditions shown in Table 9 and tested at 75°F (Reference 29). The results of the tests are shown in Table 10. Tests were considered invalid due to the thinness of the specimens which made the existence of plane-strain conditions questionable. However, the results of the testing of the compact



COMPACT TENSION SPECIMEN



BEND SPECIMEN

NOTE: ALL DIMENSIONS IN INCHES. DRAWING NOT TO SCALE.

FIGURE 18. COMPACT TENSION SPECIMENS AND BEND SPECIMENS USED FOR FRACTURE TOUGHNESS ASSESSMENT

TABLE 10. FRACTURE TOUGHNESS TESTS

SAMPLE	SPECIMEN TYPE	R	KMAX (KSI√IN)	PRECRACK CYCLES	KQ (KSI√IN)	VALIDITY
4AA-01	COMPACT TENSION	0.1	13.6	133080	70.6	INVALID
4AC-01	COMPACT TENSION	0.1	13.8	276730	66.8	INVALID
4G-02	COMPACT TENSION	0.1	12.2	181460	70.0	INVALID
4T-01	BEND	0.1	18.0	947000	48.3	INVALID
4P-02	BEND	0.1	17.1	300000	48.3	INVALID
4G-07	BEND	0.1	17.1	351000	46.6	INVALID

tension specimens fall in line with literature values for Ti-6Al-4V castings (Figure 19) although values as low as 40 ksi√in have been reported (References 30,31). The bend data may represent more of a threshold value that is closer to the plane-strain condition. As conditions approach plane-stress, values of fracture toughness increase to those seen in the compact tension specimens. Testing of thicker specimens is recommended in order to provide valid test results.

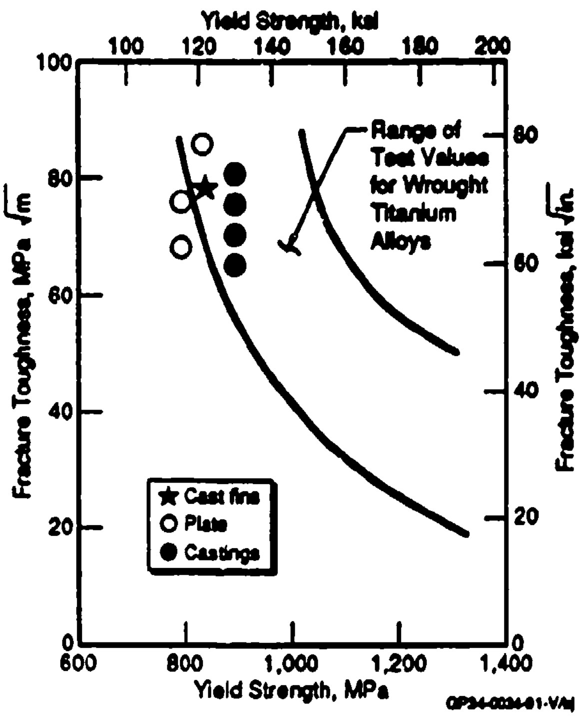


FIGURE 19. FRACTURE TOUGHNESS DATA FROM THE COMPACT TENSION SPECIMENS ARE COMPARABLE TO LITERATURE VALUES (REFERENCE 9)

R-Curve measurements were also made per ASTM E561 (Reference 33) for the 3 compact tension specimens listed in Table 10. The results are shown in Table 11. These measurements present the resistance to the crack propagation (K_R) as a function of crack extension beyond the initiation phase and K_{max} is the maximum K level in the test. In order for these results to be considered valid, the length of the uncracked ligament must be at least as great as $(4/p)(K_{max}/FTY)^2$ which is proportional to the size of the maximum expected plastic zone. For all 3 compact tension specimens tested, the length of the uncracked ligament was less than $(4/p)(K_{max}/FTY)^2$. Therefore, all tests were considered invalid.

TABLE 11. R-CURVE MEASUREMENTS

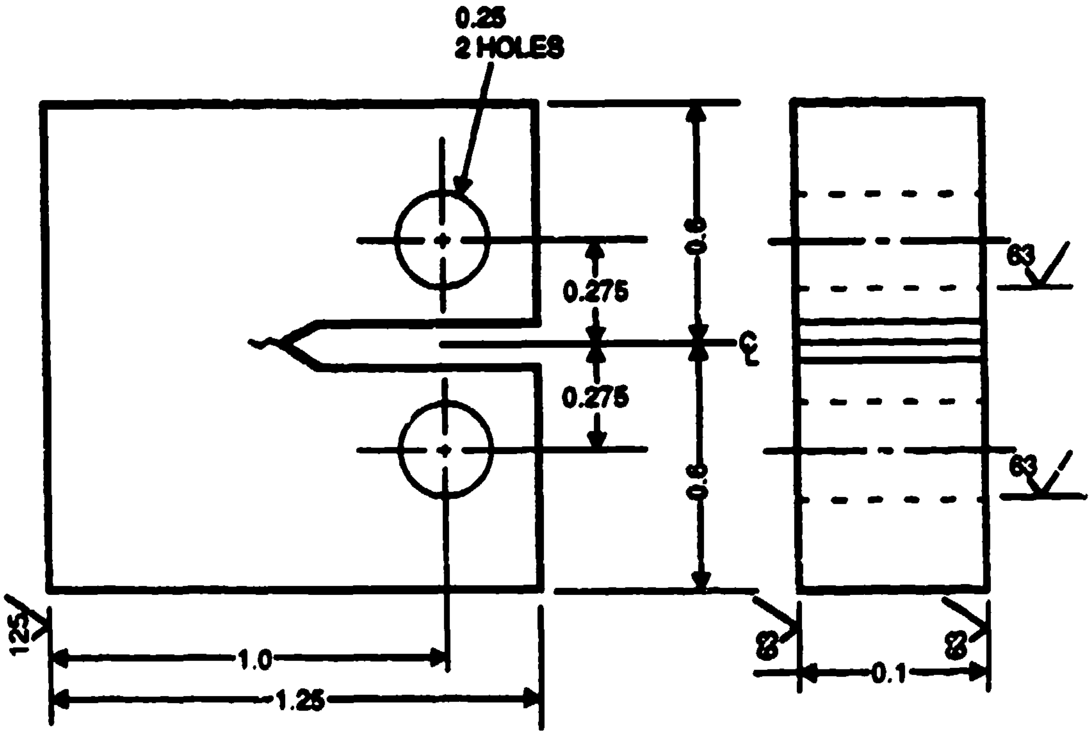
SAMPLE	K_R (KSI [illegible])	K_{MAX} (KSI√IN)	UNCRACKED LIGAMENT LENGTH (IN)	$(4/P)(K_{MAX}/FTY)^2$	VALIDITY
4AA-01	122.7	140.9	0.3957	1.7652	INVALID
4AC-01		112.7	0.4118	1.1230	INVALID
4G-02	118.6	125.0	0.3989	1.3815	INVALID

6.2 FATIGUE CRACK GROWTH

Just as K_{Ic} is important in determining loads that a structural member can carry in the presence of a flaw, it is also important to estimate the total operating life of components subjected to cyclic loading (i.e., fatigue) conditions. Generally, fatigue crack propagation behavior in titanium alloys parallels that for fracture toughness. As discussed in the beginning of this section, the cast titanium microstructure exerts a strong influence over fatigue behavior. Larger beta grains and alpha colonies will increase fatigue crack propagation resistance but degrade low- and high-cycle fatigue strength. The presence of grain boundary alpha is detrimental to fatigue crack initiation.

We excised 3 fatigue crack growth specimens (Figure 20) from cast Ti-6Al-4V fins and tested these compact tension specimens at 75°F in accordance with ASTM E647 (Reference 34) using a stress ratio (i.e., the ratio of minimum cyclic stress to maximum cyclic stress) of 0.1. The fatigue specimen precracking conditions are shown in Table 12. The fatigue crack growth rate as a function of stress intensity factor for all three specimens is shown in Figure 21. The curves agree with literature curves for Ti-6Al-4V with lower oxygen content (Figure 22), and all 3 were shown to be valid. There is minimal scatter in the data among the 3 specimens, presumably a result of the tight control over the chemistry.

Curves showing the crack growth versus constant-amplitude stress cycles for all three specimens are shown in Figure 23. Crack length measurements as well as other test procedures can produce variability in test results.



NOTE: ALL DIMENSIONS IN INCHES. DRAWING NOT TO SCALE.

FIGURE 20. FATIGUE CRACK GROWTH SPECIMEN

TABLE. 12 FATIGUE CRACK GROWTH CONDITIONS

SAMPLE	STRESS INTENSITY FACTOR RANGE (KSI√IN)
4T-01	7.090
4T-02	5.959
4P-02	7.081

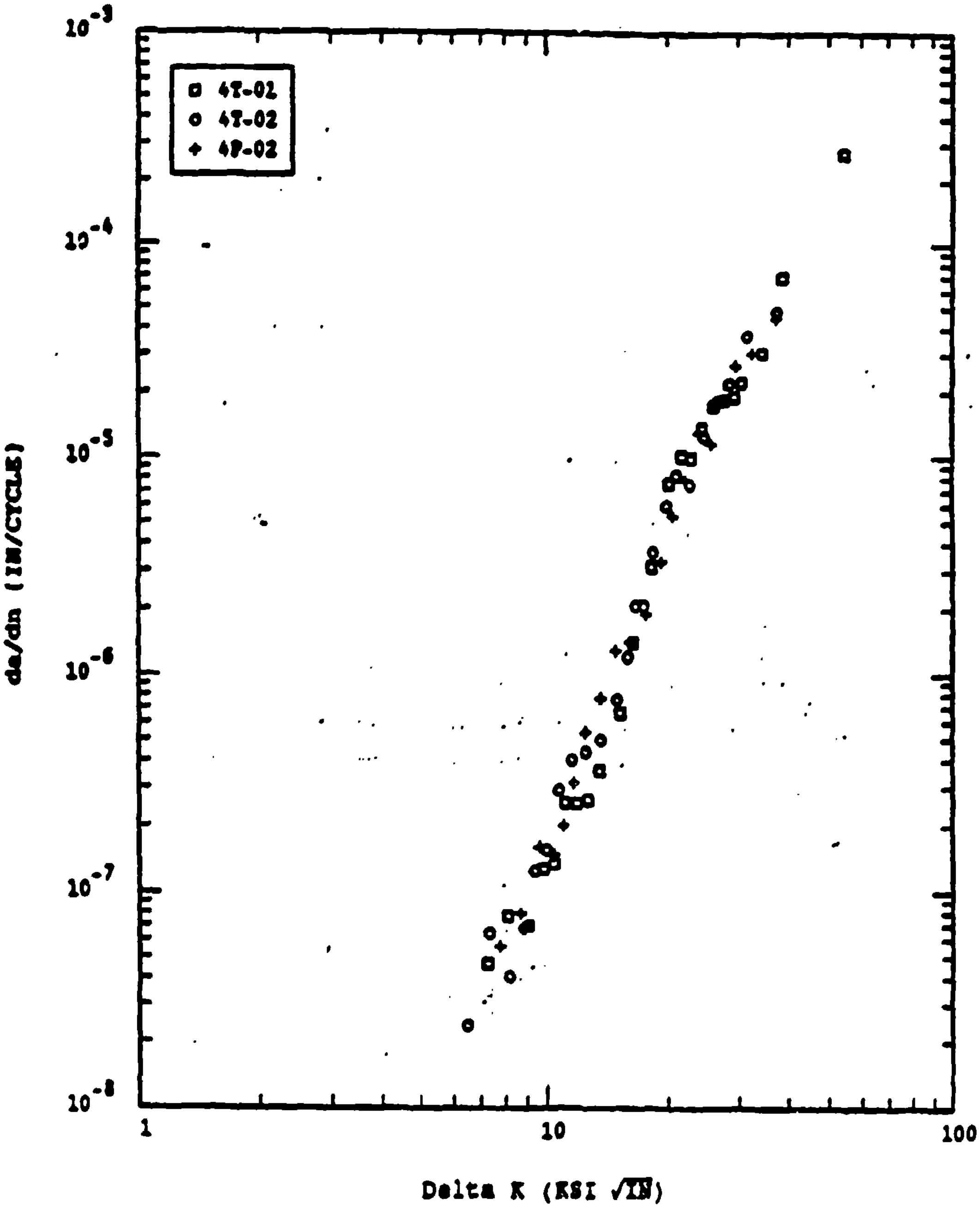
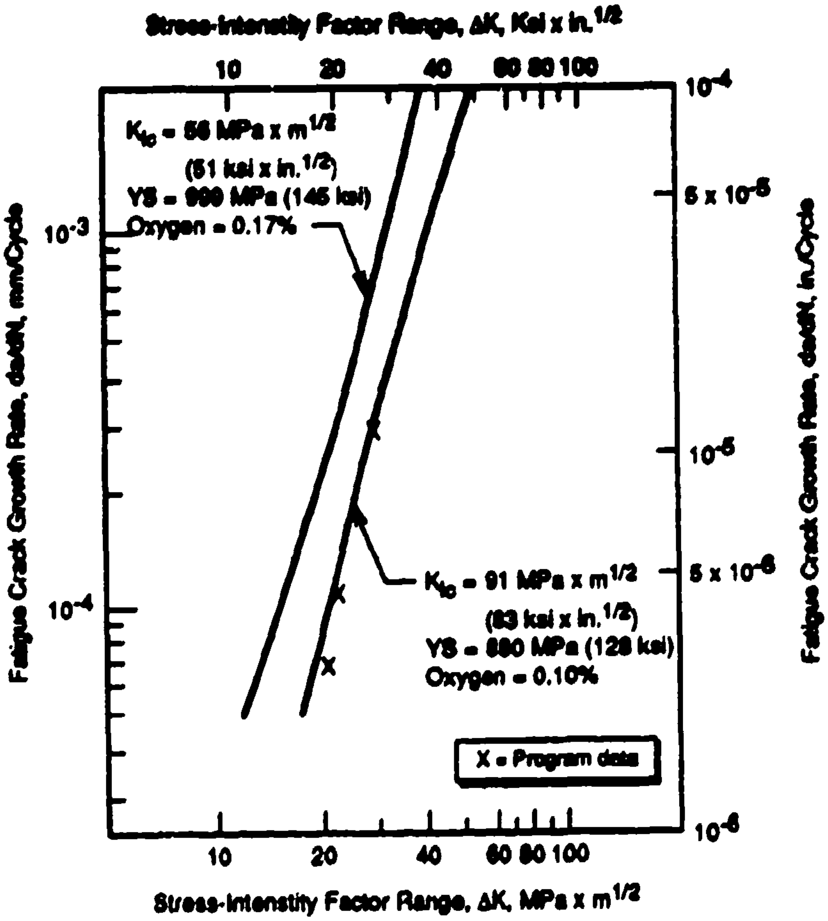


FIGURE 21. FATIGUE CRACK GROWTH RATE AS A FUNCTION OF STRESS INTENSITY FACTOR FOR ALL THREE SPECIMENS TESTED



R= 0.02; 10 Hz; Air, Argon and JP4 Environments Pooled:
Average of Six Tests Per Trend Line.

GP34-0084-60-V/4

FIGURE 22. COMPARISON OF FATIGUE CRACK GROWTH WITH LITERATURE CITATIONS (REFERENCE 32)

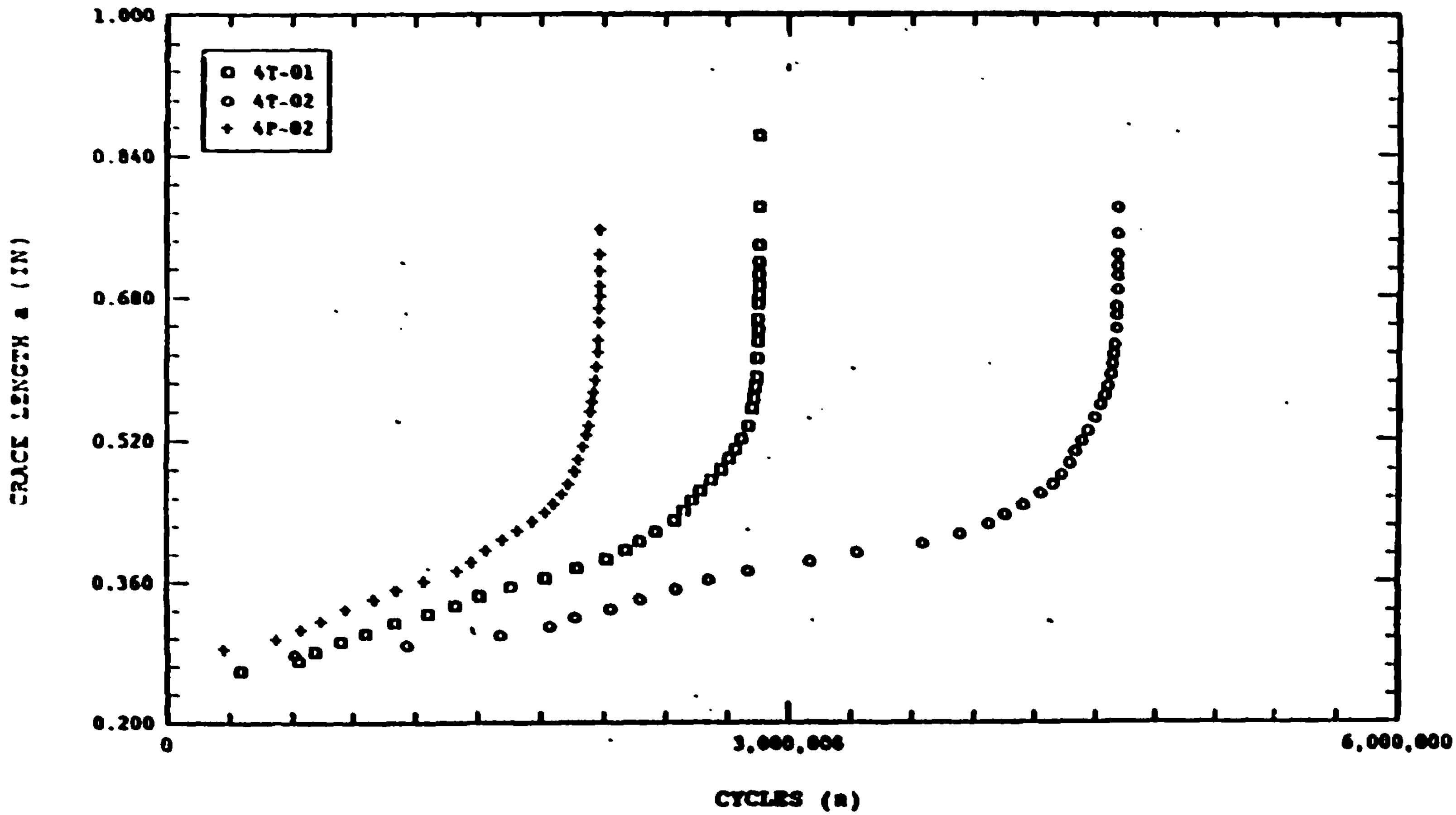


FIGURE 23. CRACK GROWTH VERSUS CONSTANT-AMPLITUDE STRESS CYCLES FOR THREE TI-6AL-4V CAST FINS

SECTION 7

CONCLUSIONS AND RECOMMENDATIONS

In this program we successfully reduced the variability of mechanical properties of Ti-6Al-4V castings by application of a more restrictive chemical composition and post-casting treatment. The use of Taguchi methods in determining these conditions provided an objective means of analyzing these parameters. We demonstrated that the more restrictive chemistries and post-casting treatments could be met in a production facility by more than one supplier in the production of step plates and missile fins. A data base was developed using these parts that permitted the establishment of meaningful "A" and "B" design allowables for investment cast Ti-6Al-4V. A new AMS specification was written to provide better control of the process. This specification incorporated the more restrictive chemistry and post-casting treatment including hot isostatic pressing, the new allowables, and criteria for nondestructive testing using measurements of microstructural features. Limited fracture mechanics testing was performed that indicated that these castings had fracture toughness and fatigue comparable to current cast and wrought Ti-6Al-4V. While this program accomplished the goals that it set out to achieve, there are still issues that remain to be resolved.

One recommendation is to increase the data base by using the new specification to cast other part geometries and thicknesses. This would allow verification and/or expansion of the current data base. Since we found that there was a very low variability in the range of thicknesses and section sizes investigated under this program, there needs to be more data to determine the effects of casting thicker sections on the mechanical properties and the microstructural features. The fracture mechanics work requires additional testing of thicker specimens to provide meaningful data.

We also need to determine the actual impact of producing parts in accordance with the new specification on the cost of the parts. Although the suppliers provided inputs to guide us in selection of chemistry and post-casting treatment that would be producible, there are no actual data on the cost impacts of these more restrictive parameters on production parts. Related to this, we need to also determine what the availability of this material would be and any cost impact due to availability issues.

Other aspects of processing need to be evaluated. Only statically cast parts were available for the data base development. Centrifugally cast parts as well as those produced using rammed graphite need to be investigated.

The influence of other parameters such as mold temperature, weld repair, and alternate heat treatment parameters also require additional study.

Finally, we need to apply these methods to other alloys that are being considered for use as castings. While these methods can be applied to currently available alloys, they should also be used in the development of new alloys.

SECTION 8

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APPENDIX A

CONTROL OF VARIABILITY
TAGUCHI ANALYSIS

APPENDIX A

CONTROL OF VARIABILITY TAGUCHI ANALYSIS

This appendix contains the rationale and methodology used in application of Taguchi methods in reduction of variability in Ti-6Al-4V castings. The problem to be solved was the tightening of chemistry and post-casting treatment to produce parts with minimal variability in mechanical properties. The information presented in this section presumes some knowledge of the design of experiments and will not include a discussion of the basics of Taguchi techniques. A bibliography is listed at the end of this section for the benefit of the reader.

A.1 CHEMICAL VARIABILITY

A data set, provided by the Boeing Corporation (Reference 8), was the basis of the analysis of the effect of composition on the variability of mechanical properties in Ti-6Al-4V castings. This data set consisted of 943 data points representing 43 heats of material. A summary of the data was shown in Figure A1. We confined our analysis to the use of L_8 matrices to simplify our analysis. Oxygen, nitrogen, and hydrogen were analyzed in one matrix, and carbon, iron, and aluminum or vanadium in another.

The first step in our analysis was defining two levels of composition for each element. This was accomplished by plotting the cumulative frequency as a function of concentration for each element and looking for natural breaks in the data to define a "high" and "low" level for each element. With hydrogen, iron, and carbon, the levels were easily identified. With nitrogen and oxygen, there were no natural breaks in the frequency distributions, and we assigned levels where 50% of the population fell on either side of the dividing value. We found from our frequency plots that both vanadium and aluminum were fairly tightly controlled. Suppliers had indicated to us that vanadium is very rigidly controlled because of its high cost.

Once the levels were defined, L_8 orthogonal arrays were designed. The matrices and preliminary data are shown for both the tensile strength (Figures A2 and A3) and yield strength (Figures A4 and A5). The Taguchi loss function used was "nominal is best" since we were trying to produce parts with strengths as close to a nominal value as possible. In the analysis, we used a Taguchi metric known as the signal-to-noise (S/N) ratio. The S/N ratio relates the magnitude of the response data (signal) to

CODE LETTER	AVERAGE FTU, KSI	AVERAGE FTY, KSI	AVERAGE ELONGATION	AVERAGE RA	Oxygen	Aluminum	Vanadium	2ND Nitrogen	4TH Carbon	5TH Iron	3RD Hydrogen
A	136060	123103	11.93	18.52	0.1730	6.00	3.90	0.0000	0.0300	0.1800	0.0036
B	134002	117000	10.60	19.00	0.1700	6.06	4.00	0.0000	0.0200	0.1800	0.0000
C	131200	119875	10.82	21.74	0.1640	6.10	4.10	0.0100	0.0310	0.2400	0.0120
D	131800	119400	10.50	20.10	0.1800	6.10	4.40	0.0120	0.0300	0.1300	0.0014
E	126720	116300	9.48	21.80	0.1620	6.00	4.20	0.0200	0.0200	0.1700	0.0083
F	129560	116400	11.30	21.70	0.1510	6.40	4.10	0.0040	0.0300	0.1800	0.0065
G	126204	116300	9.24	22.20	0.1400	6.00	4.00	0.0082	0.0300	0.1400	0.0087
H	132065	119335	11.28	20.75	0.1800	6.20	4.10	0.0083	0.0250	0.1300	0.0041
I	134050	119000	13.00	23.25	0.1750	6.05	3.70	0.0047	0.0200	0.1700	0.0047
J	132246	118318	11.78	19.81	0.1970	6.10	4.00	0.0140	0.0300	0.1400	0.0085
K	134600	124050	7.85	18.66	0.1605	6.00	4.00	0.0084	0.0370	0.1500	0.0034
L	125000	116450	9.40	24.00	0.1610	6.40	4.10	0.0040	0.0300	0.1800	0.0065
M	129007	119020	10.45	23.06	0.1746	6.10	4.20	0.0130	0.0300	0.2000	0.0081
N	127762	117625	9.82	22.33	0.1520	6.15	4.20	0.0170	0.0300	0.2100	0.0012
O	126200	118124	10.40	23.82	0.1554	6.06	4.20	0.0140	0.0300	0.1900	0.0073
P	125100	115017	9.82	23.40	0.1531	6.06	4.30	0.0083	0.0340	0.1200	0.0084
Q	124702	114870	9.84	23.64	0.1534	6.00	4.20	0.0081	0.0300	0.1800	0.0013
R	127042	115870	10.21	21.41	0.1530	6.20	4.10	0.0100	0.0400	0.1900	0.0079
S	129400	118113	9.30	21.40	0.1543	6.20	4.10	0.0120	0.0300	0.1100	0.0008
T	129267	117600	11.13	22.52	0.1406	6.10	4.10	0.0130	0.0310	0.1100	0.0015
U	127467	116307	11.85	20.85	0.1776	6.06	4.00	0.0110	0.0300	0.1100	0.0006
V	127426	119013	9.80	22.34	0.1632	6.20	4.10	0.0110	0.0300	0.1000	0.0000
W	125403	114630	10.63	23.16	0.1600	6.20	4.10	0.0110	0.0000	0.1000	0.0011
X	128003	117130	11.60	23.00	0.1654	6.20	4.00	0.0110	0.0200	0.1100	0.0007
Y	125360	114125	10.90	23.06	0.1617	6.06	4.00	0.0120	0.0000	0.1100	0.0011
Z	127542	119004	9.82	22.30	0.1720	6.10	4.00	0.0004	0.0000	0.1000	0.0014
AA	127976	119550	11.53	22.30	0.1400	6.30	4.20	0.0110	0.0200	0.1100	0.0000
BB	129220	119000	10.40	23.52	0.1046	6.20	3.90	0.0037	0.0300	0.1000	0.0000
DD	133066	123033	9.82	21.23	0.1700	5.70	4.90	0.0140	0.0530	0.1700	0.0022
EE	134384	123004	9.10	17.95	0.1634	5.70	4.30	0.0087	0.0000	0.1000	0.0010
FF	134083	125326	9.93	18.81	0.1984	5.50	4.40	0.0086	0.0430	0.1700	0.0016
GG	134500	124400	9.54	20.10	0.1776	5.90	4.40	0.0180	0.0570	0.2000	0.0007
HH	134313	124130	9.90	18.21	0.1640	5.90	4.30	0.0130	0.0610	0.1000	0.0006
LL	131617	122500	10.80	21.80	0.1400	6.10	4.20	0.0085	0.0300	0.1700	0.0030
MM	134237	124375	9.34	20.00	0.1615	5.80	4.10	0.0123	0.0635	0.1000	0.0000
NN	130026	119250	10.74	22.16	0.1641	6.20	4.30	0.0130	0.0600	0.1900	0.0007
RR	132500	122000	9.50	17.46	0.1650	6.10	4.40	0.0140	0.0400	0.2000	0.0000
TT	128200	118867	9.87	22.20	0.1720	5.85	4.10	0.0077	0.0400	0.1800	0.0000
UU	142100	129100	9.00	21.00	0.1900	6.30	4.00	0.0210	0.0100	0.1900	
VV	138420	123243	8.57	16.00	0.2300	6.47	4.06	0.0230	0.0100	0.1700	0.0062
WW	131617	119000	11.00	21.70	0.1710	6.47	3.90	0.0160	0.0200	0.1700	0.0022
XX	136857	125114	10.00	21.37	0.1800	6.47	4.06	0.0200	0.0100	0.1700	0.0020
YY	138400	123800	10.00	23.20	0.1800	6.47	4.06	0.0180	0.0100	0.2500	0.0075

FIGURE A1. BOEING DATA SET - MECHANICAL PROPERTIES OF CAST TI-6AL-4V ELEVON HOUSINGS

RUN NO.	OXYGEN CONTENT (1)	NITROGEN CONTENT (2)	OXYGEN NITROGEN INTERACTION (1X2)	HYDROGEN CONTENT (4)	OXYGEN HYDROGEN INTERACTION (1X4)	NITROGEN HYDROGEN INTERACTION (2X4)	(7)	CODE LETTER	AVERAGE (KSI)	SIGMA	NOMINAL SIGNAL TO NOISE RATIO (db)
1	.1565	.0085	1	.0018	1	1	1	G, AA, H, Q	126886	1539.4	38.28
2	.1565	.0085	1	.0054	2	2	2	LL, K, H, P, F, L, R	129497	3988.7	30.40
3	.1565	.0134	2	.00080	1	2	2	RR, MM, S, HH, X, V, Y, N, D, T	129380	3146.3	32.32
4	.1565	.0134	2	.00065	2	1	1	O, C	120748	4182.3	29.74
5	.1818	.0082	2	.00183	2	1	2	U, B, TT FF, EE, Z	131873	3588.7	31.25
6	.1818	.0082	2	.0053	1	2	1	A, I, M, BB	131302	4213.3	29.87
7	.1818	.01662	1	.00113	2	2	1	NN, GG, XX	133824	3848.3	30.62
8	.1818	.01662	1	.0051	1	1	2	WW, DD, YY, J	133785	3083.4	32.71

FIGURE A2. TENSILE STRENGTH - L_8 ORTHOGONAL ARRAY FOR OXYGEN, HYDROGEN, AND NITROGEN

RUN NO.	CARBON CONTENT (1)	IRON CONTENT (2)	CARBON IRON INTERACTION (1X2)	ALUMINUM CONTENT (4)	CARBON ALUMINUM INTERACTION (1X4)	IRON ALUMINUM INTERACTION (2X4)	(7)	CODE LETTER	AVERAGE (PSI)	SIGMA	NOMINAL SIGNAL TO NOISE RATIO (db)
1	.0253	.1273	1	6.07	1	1	1	G,U,Z Y,D,J	128402	2943.7	32.79
2	.0253	.1273	1	6.22	2	2	2	X,H,S BB,AA	129400	1871.9	36.80
3	.0253	.1027	2	6.04	1	2	2	B,I,LL E,N	130412	4200.1	29.84
4	.0253	.1027	2	6.40	2	1	1	UU,V,XX YY,WW,VV	135955	5703.1	27.42
5	.0405	.1550	2	5.70	2	1	2	FF,DD EE,HH	134049	981.8	42.70
6	.0405	.1550	2	6.04	1	2	1	A,K P,T	130982	5049.6	28.28
7	.0405	.1917	1	5.97	2	2	1	O,Q,TT RR,MM,GG	130056	4454.0	29.31
8	.0405	.1917	1	6.24	1	1	2	M,N,NN R,L,F	127012	1800.0	37.03

FIGURE A3. TENSILE STRENGTH - L_8 ORTHOGONAL ARRAY FOR CARBON, IRON, AND ALUMINUM

RUN NO.	OXYGEN CONTENT (1)	NITROGEN CONTENT (2)	OXYGEN NITROGEN INTERACTION (1X2)	HYDROGEN CONTENT (4)	OXYGEN HYDROGEN INTERACTION (1X4)	NITROGEN HYDROGEN INTERACTION (2X4)	(7)	CODE LETTER	AVERAGE YIELD (PSI)	SIGMA	NOMINAL SIGNAL TO NOISE RATIO (db)
1	.1565	.0005	1	.0010	1	1	1	G,AA, H,Q	115491	1000.3	40.50
2	.1565	.0005	1	.0054	2	2	2	LL,K,H, P,F,L,R	110517	3912.9	29.62
3	.1565	.0134	2	.00098	1	2	2	RR,MM,S, HH,X,V, Y,N,D,T	119211	3475.0	30.71
4	.1565	.0134	2	.00965	2	1	1	O,C	110000	3196.9	31.34
5	.1010	.0002	2	.00103	2	1	2	U,B,TT FF,EE,Z	119760	3989.0	29.72
6	.1010	.0002	2	.0053	1	2	1	A,I M,BB	110771	3431.6	30.70
7	.1010	.01662	1	.00113	2	2	1	NN,GG, XX	122941	3302.0	31.21
8	.1010	.01662	1	.0051	1	1	2	WW,DD, YY,J	120500	3040.5	29.92

FIGURE A4. YIELD STRENGTH - L_8 ORTHOGONAL ARRAY FOR OXYGEN, HYDROGEN, AND NITROGEN

RUN NO.	CARBON CONTENT (1)	IRON CONTENT (2)	CARBON IRON INTERACTION (1X2)	ALUMINUM CONTENT (4)	CARBON ALUMINUM INTERACTION (1X4)	IRON ALUMINUM INTERACTION (2X4)	(7)	CODE LETTER	AVERAGE YIELD (PSI)	SIGMA	NOMINAL SIGNAL TO NOISE RATIO (db)
1	.0253	.1273	1	6.07	1	1	1	G,U,Z Y,D,J	116065	1903.5	35.40
2	.0253	.1273	1	6.22	2	2	2	X,H,S BB,AA	117603	1191.0	39.00
3	.0253	.1027	2	6.04	1	2	2	B,I,LL E,W	117900	3281.7	31.11
4	.0253	.1027	2	6.40	2	1	1	UU,V,XX YY,WW,VV	122462	5113.0	27.50
5	.0405	.1550	2	5.70	2	1	2	FF,DD EE,HH	124265	769.6	44.16
6	.0405	.1550	2	6.04	1	2	1	A,K P,T	120162	5102.5	27.44
7	.0405	.1917	1	5.97	2	2	1	O,Q,TT RR,MM,GG	120102	4461.1	20.61
8	.0405	.1917	1	6.24	1	1	2	M,N,NN R,L,F	116760	1396.6	38.44

FIGURE A5. YIELD STRENGTH - L_8 ORTHOGONAL ARRAY FOR CARBON, IRON, AND ALUMINUM the magnitude of the standard deviation of the response data (noise). For a nominal is best characteristic, the signal-to-noise ratio is defined generically as:

$$S/N = 10 \, Log_{10} \left((\text{True Average})^2 / (\text{True Standard Deviation})^2 \right).$$

The resulting main effects from the analyses are shown in Figures A6 and A7 for the tensile strength and Figures A8 and A9 for yield strength. These graphs show that both oxygen and nitrogen have the strongest influence on the tensile and yield strengths within the range of values identified for this data set. All of the other elements had showed little effect on the strength of the castings in the ranges defined. The signal-to-noise ratios for all except carbon decreased with increasing concentration.

The interactions are shown in Figures A10-A12. The interactions shown agree with known effects of the different alloying elements. For instance, if there are 2 elements that are both alpha stabilizers, no interaction is shown (i.e., the interaction lines do not intersect). If the elements being compared have opposite effects (e.g., oxygen = alpha stabilizer and hydrogen = beta stabilizer), an interaction is indicated with intersecting lines. The point of intersection defines the levels where the intersection is strongest.

The results of the analysis of variance revealed the contribution of each element to the variability of the mechanical property in question. This is shown in Table A1. Since only 60% of the variability can be accounted for by the chemical composition, other factors such as processing and post-casting treatment are responsible for the other 40%.

TABLE A1 CONTRIBUTION OF ALLOYING ELEMENTS TO MECHANICAL PROPERTY VARIABILITY

	CONTRIBUTION TO VARIABILITY OF:	
ELEMENT	FTY	FTU
Al	1.57%	1.62%
C	0.97%	6.79%
H	15.08%	21.76%
Fe	19.87%	17.84%
N	7.65%	4.43%
O	15.25%	9.04%
TOTAL	60.39%	61.48%

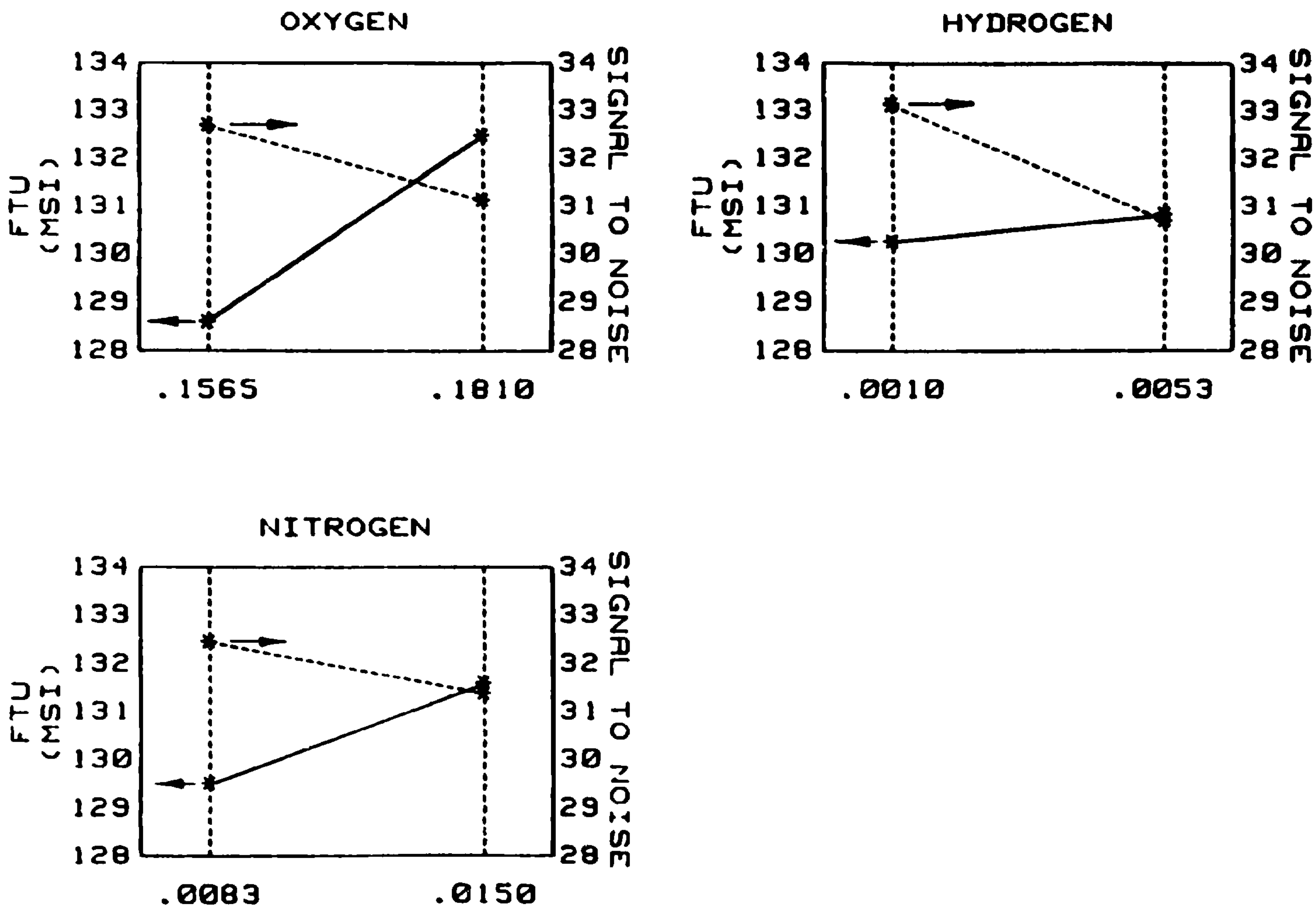

FIGURE A6. TENSILE STRENGTH - MAIN EFFECTS FOR OXYGEN, HYDROGEN, AND NITROGEN

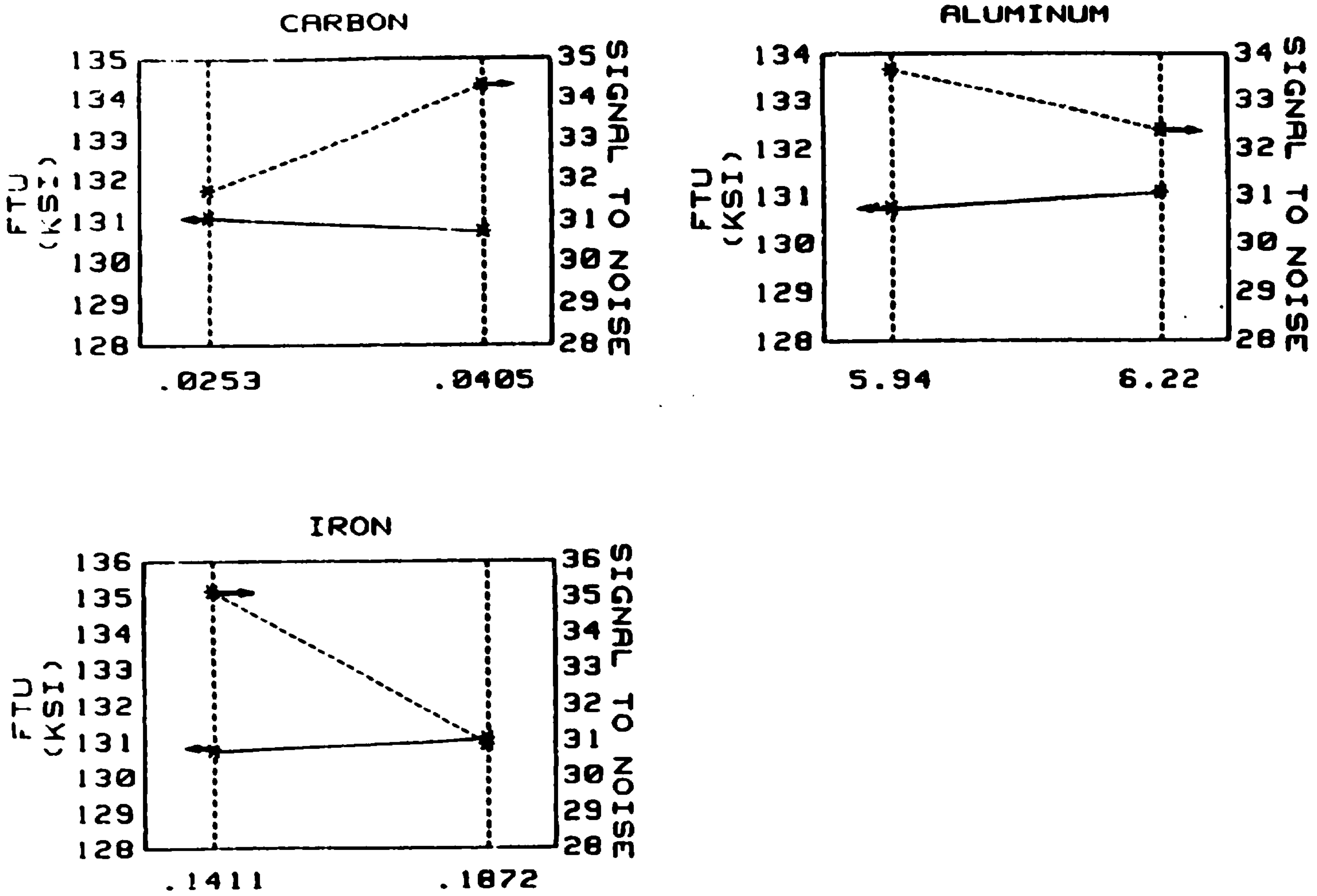

FIGURE A7. TENSILE STRENGTH - MAIN EFFECTS FOR CARBON, IRON, AND ALUMINUM

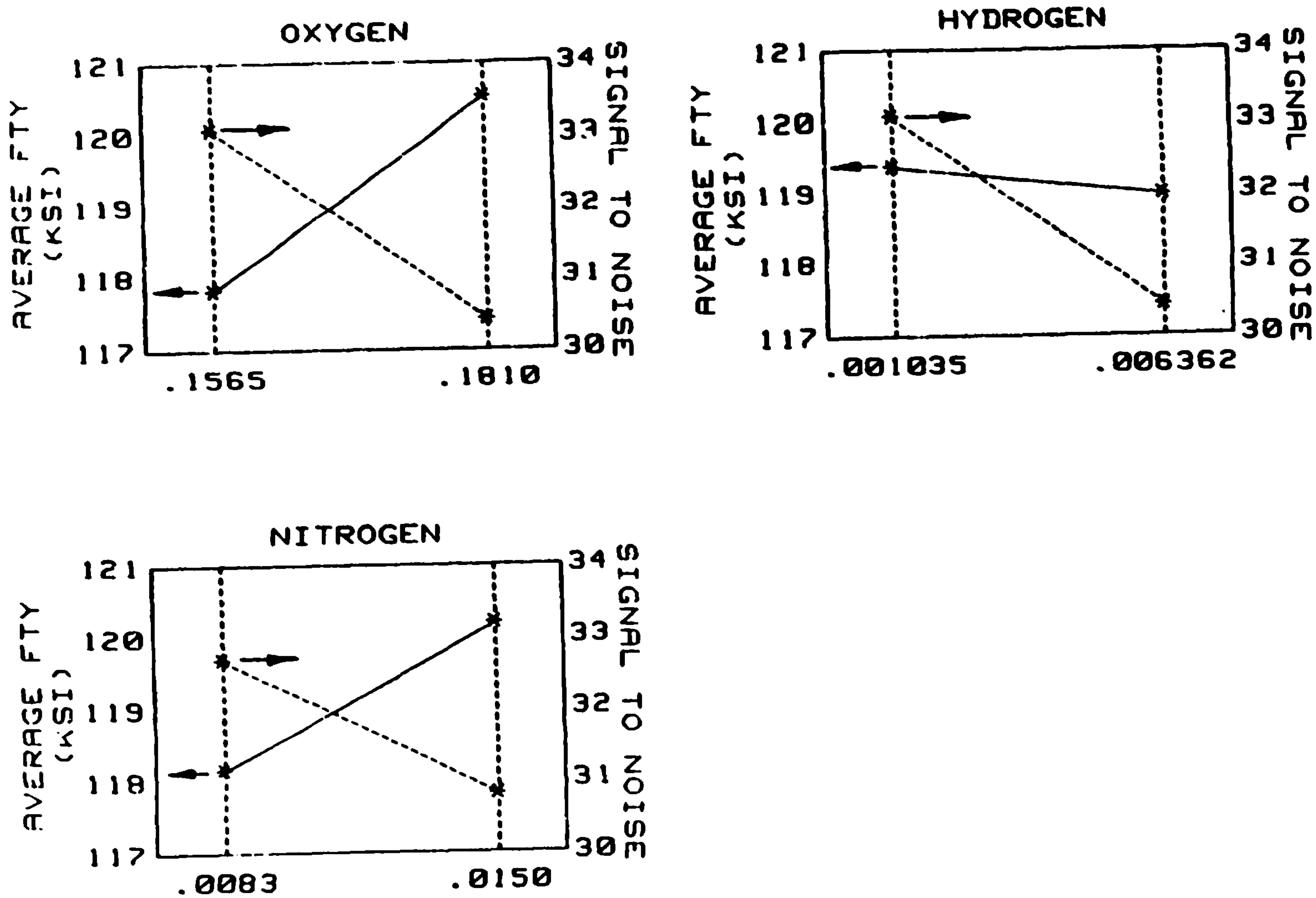

FIGURE A8. YIELD STRENGTH - MAIN EFFECTS FOR OXYGEN, HYDROGEN, AND NITROGEN

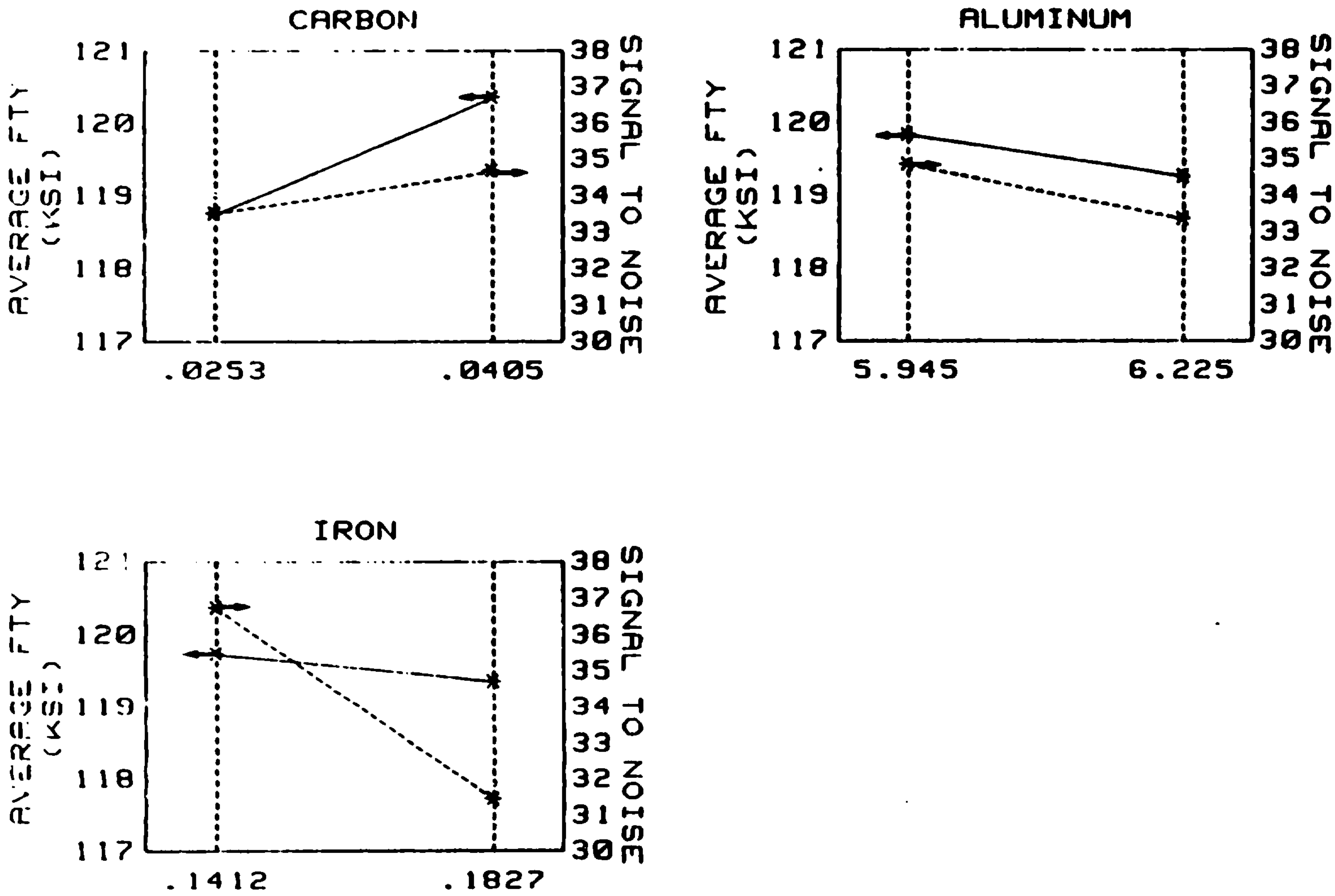

FIGURE A9. YIELD STRENGTH - MAIN EFFECTS FOR CARBON, IRON, AND ALUMINUM

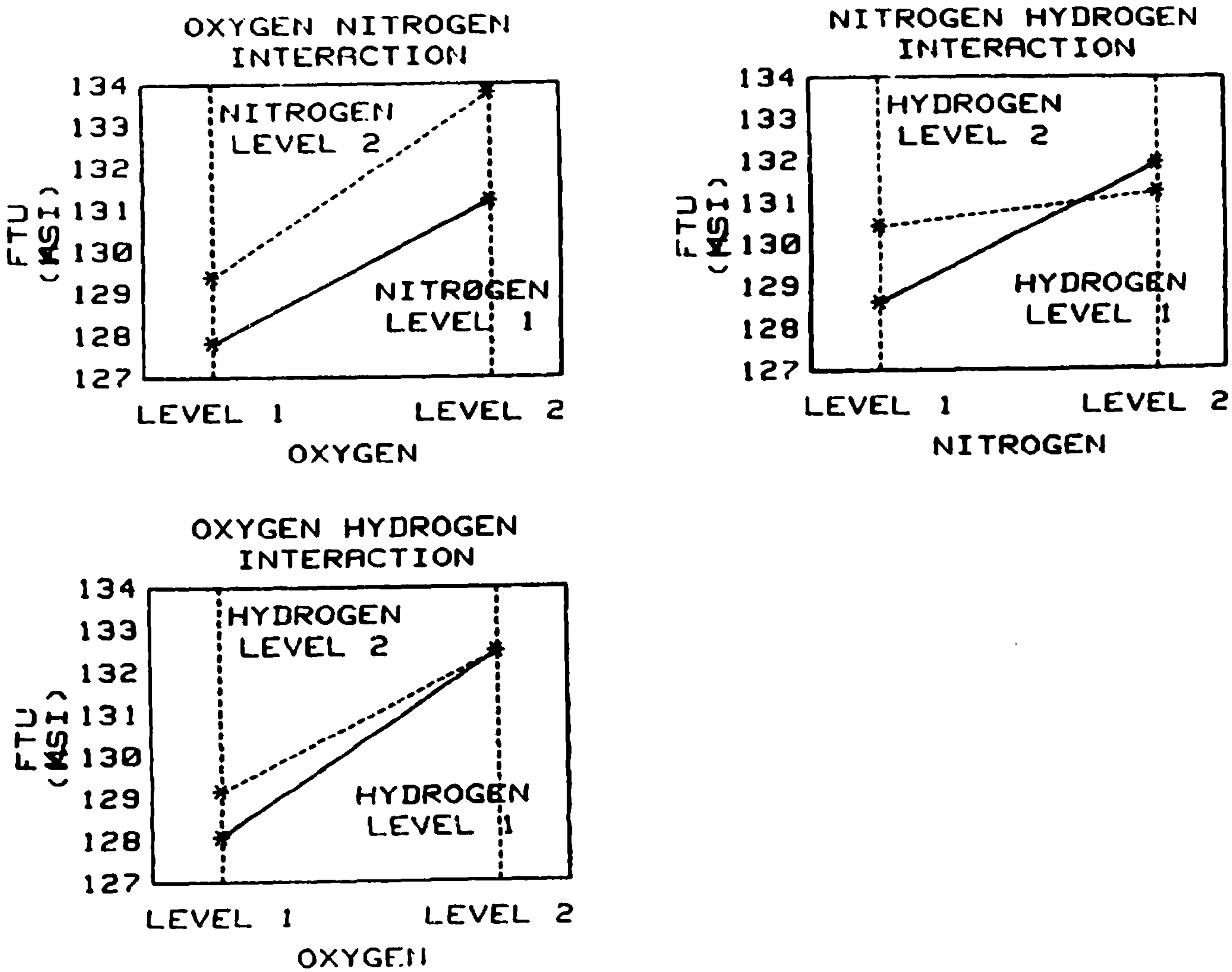

FIGURE A10. TENSILE STRENGTH - INTERACTIONS FOR OXYGEN, HYDROGEN, AND NITROGEN

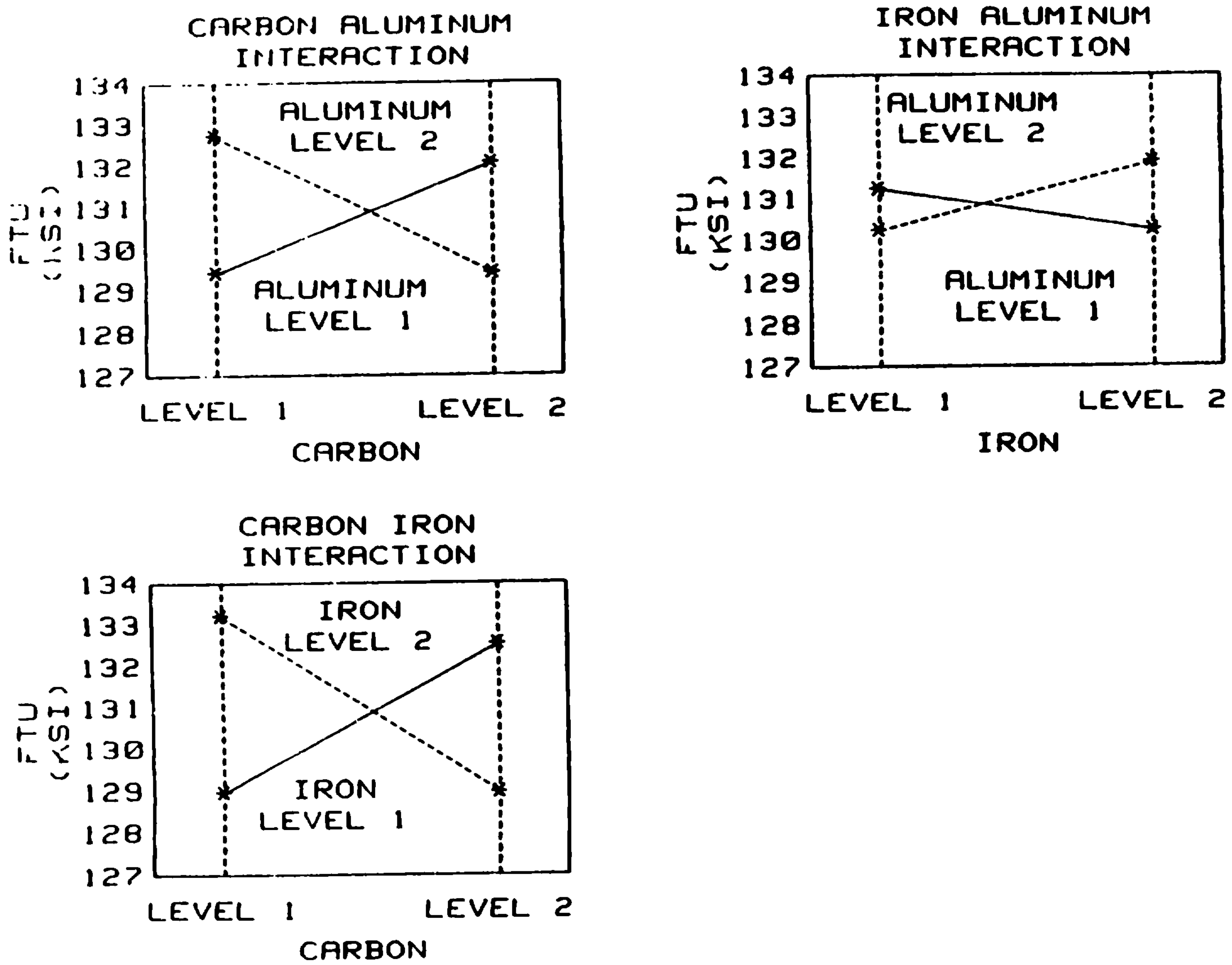

FIGURE A11. TENSILE STRENGTH - INTERACTIONS FOR CARBON, IRON, AND ALUMINUM

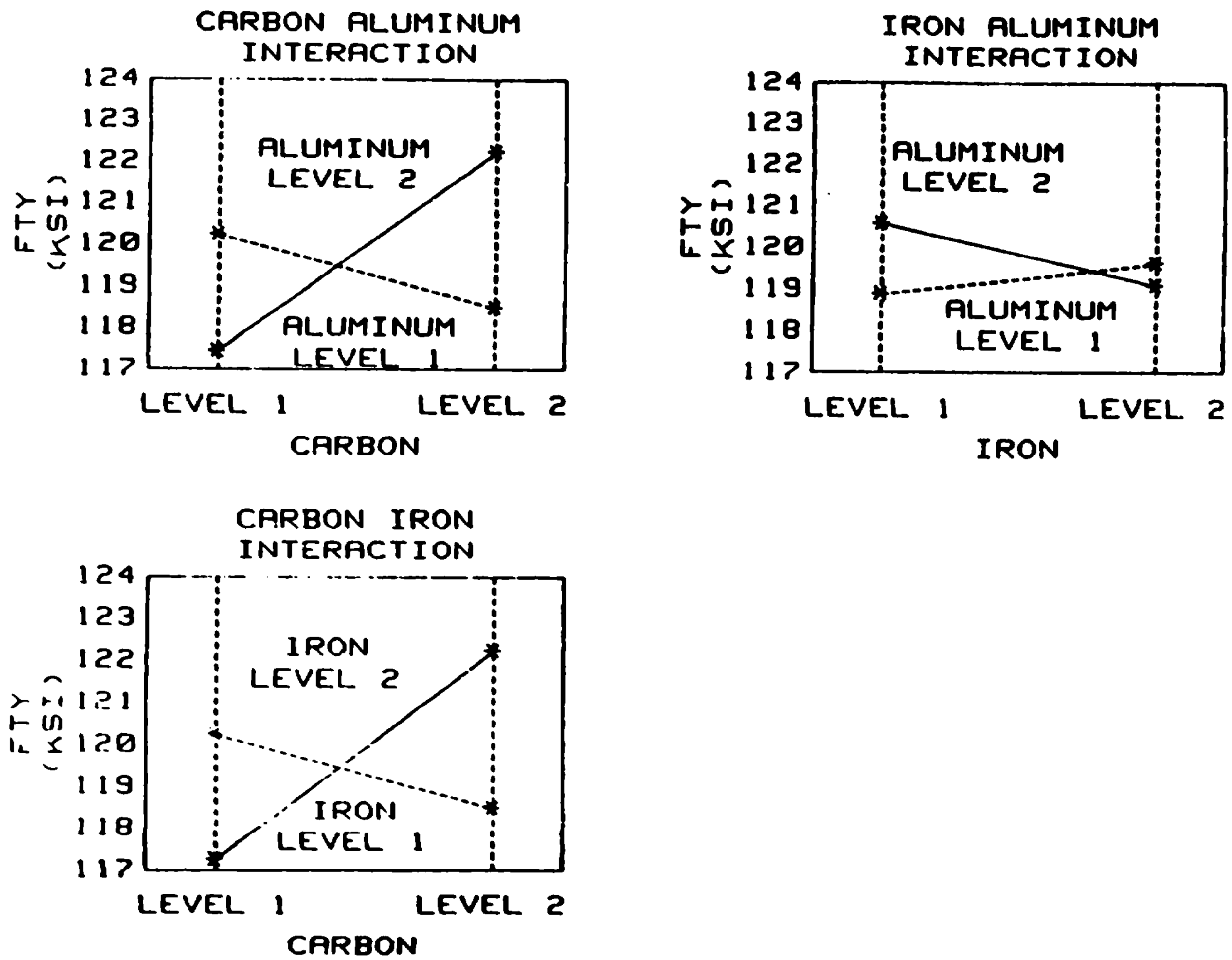

FIGURE A12. YIELD STRENGTH - INTERACTIONS FOR CARBON, IRON, AND ALUMINUM

A.2 POST-CASTING TREATMENT

In order to determine the effects of post-casting treatment (i.e., hot isostatic pressing and annealing) on the variability of mechanical properties of Ti-6Al-4V castings, we used the data set shown in Figure A13. This data was a compilation of data provided to the Titanium Casting Task Group by various sers and suppliers. The same techniques that were used in the chemical analysis were employed in the analysis of this data with the exception of using L_4 arrays (Figures A14, A15) for the heat treatment analysis. The results showed that minimum variance for tensile strength is favored by using a cold mold and annealing at 1550°F. The minimum variance for yield strength is favored by using a cold mold and annealing at 1300°-1350°F. We chose to optimize the process for tensile strength.

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MEAN FTY KSI	MEAN FTU KSI	THICKNESS INCH	HIP	HEAT TREATMENT	MOLD	SUPPLIER	N	
117.73	132.38	0.30-1.25	1650°F	1550°F	C	HOWMET	246	A
113.84	124.90	0.10-0.20	1650°F	1350°F	H	PCC (BOEING)	111	B
112.32	121.95	0.50-1.00	1650°F	1300°F	H	PCC (BOEING)	142	C
125.81	137.49	0.08-0.90	1650°F	1300-1550°F	?	LTV	174	D
123.57	134.05	0.20-2.00	1750°F	1750/1150	?	PW	309	E
124.01	135.17	0.25-0.50	1650°F	1550°F	C	HOWMET (DAC)	21	F
123.08	132.44	0.25-0.50	1650°F	1550°F	H	PCC (DAC)	21	G
122.66	134.58	0.25-0.50	1650°F	1550°F	C	TITECH (DAC)	32	H
125.51	135.01	0.14-1.375	1650°F	1550°F	C	TITECH (NORTHROP)	75	I
127.36	137.23	?	?	1350°F	C	TITECH	195	J
126.97	141.08	?	?	1325°F	C	SELMET	38	K
120.99	134.08	?	?	1350°F	H	PCC	47	L
117.26	133.77	?	?	1550°F	C	HOWMET	38	M

FIGURE A13. PROCESS AND POST-CASTING TREATMENT DATA

	ANNEALING TEMPERATURE (°F)	MOLD TEMPERATURE	CODE LETTER	AVERAGE TENSILE STRENGTH	S	S/N
1	1300-1350	COLD	J,K	139.16	2.72	34.17
2	1300-1350	HOT	B,C,L	126.98	6.33	26.05
3	1550	COLD	A,F,H,I,M	134.18	1.14	41.38
4	1550	HOT	G	132.44	5.33	27.91

FIGURE A14. TENSILE STRENGTH - L_4 ARRAY FOR PROCESS AND POST-CASTING TREATMENT

	ANNEALING TEMPERATURE (°F)	MOLD TEMPERATURE	CODE LETTER	AVERAGE YIELD STRENGTH	S	S/N
1	1300-1350	COLD	J,K	127.17	0.276	53.28
2	1300-1350	HOT	B,C,L	115.72	6.326	26.05
3	1550	COLD	A,F,H,I,M	121.43	3.738	30.23
4	1550	HOT	G	123.08	5.136	27.59

FIGURE A15. YIELD STRENGTH - L_4 ARRAY FOR PROCESS AND POST-CASTING TREATMENT

APPENDIX B

PREPRODUCTION PART ANALYSIS

APPENDIX B

PREPRODUCTION PART ANALYSIS

This appendix contains the results of tension tests of specimens excised from cast Ti-6Al-4V preproduction fins and step plates. Data from measurement of microstructural features using a nondestructive technique are also contained in this section.

MECHANICAL PROPERTY DATA

SAMPLE	CHEMISTRY	THICKNESS(IN)	FTU(KSI)	FTY(KSI)	MODULUS	ELONGATION
5B-021	B	0.40	133.4	126.1	16.8	12.7
5B-022	B	0.40	132.6	126.1	17.1	11.6
5B-023	B	0.40	130.8	124.6	17.1	12.1
5B-024	B	0.60	130.2	125.0	17.0	9.9
5B-025	B	0.60	130.1	125.1	17.2	9.9
5B-026	B	0.60	129.8	124.0	16.8	10.4
5B-027	B	0.75	129.9	125.5	16.9	9.8
5B-028	B	0.75	130.8	125.7	16.9	7.9
5B-029	B	0.75	130.4	124.9	16.7	9.1
5B-0210	B	1.00	132.0	126.5	16.8	8.5
5B-0211	B	1.00	133.5	128.2	17.0	9.6
5B-0212	B	1.00	131.2	126.4	16.9	8.8
4G-001	B	0.10	128.7	123.4	16.9	11.2
4G-012	B	0.10	130.1	124.0	16.8	9.3
4G-013	B	0.10	129.9	123.6	16.7	8.0
4G-015	B	0.10	130.1	125.1	16.8	8.6
SPA1	A	0.40	131.9	125.1	17.1	12.6
SPA2	A	0.40	131.6	125.4	16.7	11.3
SPA3	A	0.40	130.3	124.7	16.9	11.5
SPA4	A	0.60	129.2	124.3	16.6	6.2
SPA5	A	0.60	128.9	123.9	16.6	10.1
SPA6	A	0.60	126.8	122.5	16.6	5.6
SPA7	A	0.75	129.4	124.8	16.8	6.6
SPA8	A	0.75	128.2	124.1	16.7	8.1
SPA9	A	0.75	128.7	124.0	17.0	8.1
SPA10	A	1.00	129.4	125.1	16.6	8.0
SPA11	A	1.00	130.3	126.2	16.9	8.5
SPA12	A	1.00	129.5	124.6	17.0	6.3
4A-001	A	0.10	133.5	127.7	17.5	9.2
4A-012	A	0.10	134.1	129.2	17.3	8.4
4A-013	A	0.10	133.8	128.6	17.3	8.9
4A-014	A	0.10	134.1	-	-	-
4A-015	A	0.10	132.2	127.4	17.3	8.1
ADATA			FTU	FTY	E	ELONG
MEAN			130.7	125.5	16.9	8.6
STD DEV			2.3	1.9	0.3	2.0
N			17.0	16.0	16.0	16.0
BDATA						
MEAN			130.8	125.3	16.9	9.8
STD DEV			1.4	1.2	0.1	1.4
N			16.0	16.0	16.0	16.0
ALL DATA						
MEAN			130.7	125.3	16.9	9.1
STD DEV			1.8	1.6	0.2	1.8
N			33.0	32.0	32.0	32.0

INSPECTION DATA

SAMPLE	PBGS	GBA(E-4)	AC(E-3)	APS(E-4)
5B-021	0.043	3.125	2.73	1.79
5B-022	0.033	1.820	2.14	1.32
5B-023	0.047	3.125	3.36	1.14
5B-024	0.052	3.125	2.92	1.47
5B-025	0.037	3.125	7.08	1.56
5B-026	0.032	3.125	5.63	1.67
5B-027	0.041	3.125	8.13	1.92
5B-028	0.045	4.960	5.31	1.78
5B-029	0.050	3.125	10.00	2.50
5B-0210	0.040	3.020	7.08	2.08
5B-0211	0.041	4.780	9.18	2.27
5B-0212	0.045	6.250	4.06	2.08
4G-001	0.038	2.600	2.71	2.50
4G-012	0.048	3.520	2.38	1.47
4G-013	0.055	2.080	3.44	1.47
4G-015	0.043	2.340	2.75	1.56
SPA1	0.030	3.125	5.10	1.09
SPA2	0.044	2.813	2.50	1.32
SPA3	0.034	3.440	6.25	1.09
SPA4	0.055	3.125	2.50	1.19
SPA5	0.040	3.125	3.75	1.00
SPA6	0.040	3.281	3.75	2.08
SPA7	0.048	-	2.50	1.56
SPA8	0.057	3.910	3.75	2.08
SPA9	0.040	3.125	7.50	1.67
SPA10	0.043	3.125	5.00	3.57
SPA11	0.057	3.125	6.88	2.08
SPA12	0.028	3.910	7.80	1.92
4A-001	0.040	3.125	3.68	1.56
4A-012	0.053	3.125	4.06	1.32
4A-013	0.046	1.950	4.16	1.38
4A-014	0.050	2.500	4.00	1.25
4A-015	0.042	3.125	7.08	1.32
ADATA	PBGS	GBA	AC	APS
MEAN	0.044	3.121	4.72	1.62
STD DEV	0.009	0.464	1.77	0.62
N	17	16	17	17
BDATA				
MEAN	0.043	3.328	4.93	1.79
STD DEV	0.006	1.127	2.61	0.41
N	16	16	16	16
ALL DATA				
MEAN	0.044	3.227	4.89	1.70
STD DEV	0.008	0.855	2.18	0.53
N	33	32	33	33

PBGS = PRIOR BETA GRAIN SIZE
GBA = GRAIN BOUNDARY ALPHA
AC = ALPHA COLONY
APS = ALPHA PLATELET SPACING

APPENDIX C

ORIGINAL DRAFT OF
PROPOSED AMS SPECIFICATION
FOR
TITANIUM ALLOY CASTINGS, INVESTMENT
6AL-4V

APPENDIX C

ORIGINAL DRAFT OF PROPOSED AMS SPECIFICATION FOR TITANIUM ALLOY CASTINGS, INVESTMENT 6AL-4V

The specification in this appendix incorporates the data has has been generated by this program. This includes a more restrictive chemical composition, new mechanical property limits, and limits for a microstructural nondestructive inspection technique. The specification is being reviewed by the MIL-HDBK-5 *ad hoc* Titanium Casting Task Group and will be submitted to AMS for review.

This is a preliminary draft of the proposed AMS specification. It may not resemble the final version.

TITANIUM ALLOY CASTINGS, INVESTMENT
6Al - 4V, Aerospace Quality
Annealed

1. SCOPE:

1.1 Form:

This specification covers an aerospace quality titanium alloy in the form of investment castings cast using static methods.

1.2 Application:

This product has been used typically for parts of intricate design requiring a combination of good strength-to-weight ratio properties, and corrosion resistance up to 750°F (399°C), but usage is not limited to such applications.

2. APPLICABLE DOCUMENTS:

The following publications form a part of this specification to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order.

2.1 SAE Publications:

Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

AMS 2249	Chemical Check Analysis Limits, Titanium and Titanium Alloys
AMS 2360	Room Temperature Tensile Properties of Castings
AMS 2804	Identification, Castings
AMS 2750	Pyrometry

2.2 ASTM Publications:

Available from ASTM, 1916 Race Street, Philadelphia, PA. 19103-1187.

ASTM E 8	Tension Testing of Metallic Materials
ASTM E 120	Chemical Analysis of Titanium and Titanium Alloys
ASTM E 1320	Standard Reference Radiographs for Titanium Castings

2.3 Government Publications:

Available from Standardization Documents Order Desk, Building 4D, 700 Robbins Avenue, Philadelphia, PA. 19111-5094

MIL-H-81200	Heat Treatment of Titanium and Titanium Alloys
MIL-STD-453	Inspection, Radiographic
MIL-STD-2073-l	DoD Material Procedures for Development and Application of Packaging Requirements
MIL-STD-6866	Inspection, Liquid Penetrant
MIL-STD-2175	Castings, Classification and Inspection of

3. TECHNICAL REQUIREMENTS:

3.1 Composition:

Castings shall conform to the percentages by weight shown in Table 1, determined by wet chemical methods in accordance with ASTM E 120, by spectrochemical methods, or by other analytical methods acceptable to purchaser (see 8.2.1):

Table 1 - Composition

Element	min	max
Aluminum	5.75	6.50
Vanadium	3.60	4.50
Iron	--	0.25
Oxygen	0.13	0.17
Carbon	--	0.07
Nitrogen	0.01	0.03 (300 ppm)
Hydrogen	--	0.01 (100 ppm)
Yttrium	--	0.005
Residual elements, each (3.1.2)	--	0.10
Residual elements, total (3.1.2)	--	0.40
Titanium	remainder	

3.1.1 Vendor may also test for any elements not listed in Table 1 and include this analysis in the report of 4.5. Limits of acceptability may be specified by purchaser (see 8.2.2).

3.1.2 Check Analysis: Composition variations shall meet the requirements of AMS 2249; no variation over the maximum will be permitted for yttrium.

3.2 Melt Practice:

Castings shall be poured at vendor's facility from a master heat.

3.2.1 Alloy shall be multiple melted; the final melting cycle shall be under vacuum. The first melt shall be made by consumable electrode, nonconsumable electrode, electron beam, or plasma arc melting practice. The subsequent melt or melts shall be made using consumable electrode practice with no alloy additions permitted in the last consumable electrode melt.

3.2.2 The metal for castings and specimens shall be melted and poured under vacuum without loss of vacuum between melting and pouring.

3.2.3 Portions of two or more qualified master heats (see 3.4.1) may be melted together and poured into castings using a procedure authorized by purchaser. The two or more qualified master heats, when melted together and poured, shall be requalified and shall have a different master heat number.

3.2.4 Vendor shall have a written procedure acceptable to purchaser which defines the controls, tests, and traceability criteria for castings. Control factors of 4.4.2.2 shall apply. The written procedure shall be only one used for the purchaser for a designated part once it is established and approved. Changes to the written procedure shall be made only when permitted by the purchaser.

3.3 Condition:

Hot isostatically pressed

3.4 Test Specimens:

Specimens shall be machined from castings.

3.4.1 Each master heat shall be qualified by evaluation of chemical and tensile property specimens unless otherwise specified (see 8.2.4) by purchaser.

3.4.2 Chemical Analysis Specimens: Shall be of any convenient size and shape.

3.4.3 Tensile Specimens: Shall be of standard proportions in accordance with ASTM publications referenced in 3.6.

3.5 Heat Treatment:

Castings and representative tensile specimens shall be hot isostatically pressed in accordance with 3.5.1, and heat treated as specified in 3.5.2. Pyrometry shall be in accordance with AMS 2750.

3.5.1 Hot Isostatic Pressing: Castings and specimens shall be hot isostatically pressed at 15 ksi±0.5 ksi (100 MPa ± 3 MPa) at a temperature of 1650°F±25°F (899°C±14°C) for 2 hours and cooled in the autoclave to below 800°F (427°C).

3.5.2 Anneal: Heat to 1550°F±25°F (843°C±14°C) for 2 hours in a vacuum.

3.6 Properties:

Conformance shall be based upon testing of specimens machined from casting.

3.6.1 Room Temperature Tensile Properties: Castings one inch and less in thickness shall be as specified in Table 2 determined in accordance with ASTM E 8 with the rate of strain maintained at 0.003-0.007 inch/inch/minute through the yield strength and then increased so as to produce failure in approximately one additional minute.

TABLE 2 - Minimum Tensile Properties, Specimens Machined from Casting

Property	Value
Tensile Strength	125 ksi (868 MPa)
Yield Strength at 0.2% offset	120 ksi (834 MPa)
Elongation	5.5%

3.7 Surface Contamination: Castings shall be free of any oxygen-rich layer such as alpha case, any carbon rich layer, or other surface contamination determined by metallographic examination at 100X minimum magnification.

3.8 Quality: Castings, as received by purchaser, shall be uniform in quality and condition, sound and free from foreign materials and imperfections detrimental to usage of the castings.

3.8.1.1 Castings shall be free of cracks, laps, hot tears, and cold shuts.

3.8.1.2 Castings shall not be exposed to chlorinated solvents.

3.8.1.3 Castings may be exposed to organic halogen-bearing compounds if promptly and completely removed by subsequent cleaning using procedures acceptable to purchaser.

3.8.2 Acceptance standards for radiographic, fluorescent penetrant, visual, and other inspection methods shall be as agreed upon by purchaser and vendor.

3.8.2.1 Unless otherwise specified, MIL-STD-2175 may be used to specify frequency of inspection (casting class).

3.8.2.2 Unless otherwise specified, ASTM E 1320 may be used to specify radiographic standards (casting grade).

3.8.2.3 When acceptance standards are not specified, grade C of MIL-STD-2175 shall apply. In designated areas, Grade B is required.

3.8.3 Castings shall be produced under radiographic control. This control shall consist of radiographic examination of each casting part number until foundry manufacturing controls in accordance with 4.4.2 have been established. Additional radiography shall be conducted in accordance with the frequency of inspection specified by purchaser, or as necessary to ensure continued maintenance of internal quality.

3.8.3.1 Unless otherwise specified, radiographic inspection shall be conducted in accordance with MIL-STD-453 or other process method specified by purchaser.

3.8.4 Fluorescent penetrant inspection in accordance with MIL-STD-6866 or other process method specified by purchaser.

3.8.5 Castings shall not be peened, plugged, impregnated, or welded unless authorized by purchaser.

3.8.5.1 Purchaser shall define critical or no weld zones.

3.8.5.2 If in-process welding of castings that have been hot isostatically pressed is authorized by purchaser, castings shall be annealed in accordance with 4.6.3 after welding.

4.0 QUALITY ASSURANCE PROVISIONS:

4.1 Responsibility for Inspection:

The vendor of castings shall supply all samples for vendor's tests and shall be responsible for performing all required tests. Purchaser reserves the right to sample and perform any confirmatory testing deemed necessary to ensure that the castings conform to the requirements of this specification.

4.2 Classification of Tests:

4.2.1 Except as specified in 4.2.2, tests for composition (3.1), tensile properties (3.6.1), surface contamination (3.7), and quality requirements (3.8) are acceptance tests and shall be performed as specified in 4.3.

4.2.2 Periodic Tests: Tests for radiographic soundness (3.8.3) are periodic tests and shall be performed at a frequency selected by vendor unless a frequency of testing is specified by purchaser.

4.2.3 Pre-production Tests: Tests for conformance to all technical requirements of this specification are pre-production tests and shall be performed on the first-article control casting (4.3.2), when change in control factors (4.4.2.2) occurs, or when purchaser deems confirmatory testing to be required.

4.3 Sampling and Testing

The minimum testing performed by vendor shall be in accordance with the following:

4.3.1 One chemical analysis specimen or a casting from each master heat shall be tested for conformance with Table 1. Hydrogen, nitrogen, and oxygen determinations shall be obtained on a lot basis after all thermal and chemical processing are completed.

4.3.2 One pre-production casting in accordance with 4.4 shall e tested to the requirements of the casting drawing and to all technical requirements of this specification.

4.3.2.1 First article dimensional inspection sample quantity shall be as specified by purchaser.

4.3.3 Tensile tests shall be conducted to determine conformance with 3.6.1. Sampling and test frequency is dependent upon the type and origin of specimens specified by purchaser.

4.3.3.1 At least one casting of the lowest radiographic quality shall be selected from each lot (see 8.2.6) and tested after hot isostatic pressing and annealing at each location shown on the engineering drawing for conformance with 3.6.1.

4.3.3.1.1 When size and location of specimens are not shown, at least three test specimens shall be tested, including one from the thickest section and one from the thinnest section. Once established under 4.4.2.2, test locations may be changed only as agreed upon by purchaser and vendor.

4.3.3.2 When casting size, section thickness, gating method, or other factors do not permit conformance to 4.3.3.1, sampling and testing shall be as agreed upon by purchaser and vendor.

4.3.4 Castings shall be inspected in accordance with 3.8.2.1 to the methods, frequency, and acceptance standards specified by purchaser and vendor.

4.4 Approval:

4.4.1 Sample casting(s) from new or reworked master patterns produced under the casting procedure of 4.4.2 shall be approved by purchaser before castings for production use are supplied.

4.4.2 For each casting part number, vendor shall establish parameters for process control factors that will consistently produce castings and test specimens meeting the requirements of the casting drawing and this specification. These parameters shall constitute the approved casting procedure and shall be used for the production of subsequent castings. If it is necessary to make any change to these parameters, vendor shall submit a statement of the proposed change for purchaser re-approval. When requested, vendor shall also submit test specimens, sample castings, etc. to purchaser for re-approval.

4.4.2.1 Production castings produced prior to receipt of purchaser's approval shall be at the vendor's risk.

4.4.2.2 Control factors for producing castings include, but are not limited to, the factors of Table 3. Supplier's procedures shall identify tolerances, ranges, and/or control limits.

TABLE 3 - Control Factors

a. Composition of ceramic cores, if used
b. Arrangement and number of patterns used in the mold
c. Size, shape, and location of gates and risers
d. Mold refractory formulation
e. Grain refinement methods
f. Mold back-up material (weight, thickness, or number of dips)
g. Type of furnace, and charge for melting
h. Mold preheat and metal pouring temperatures
i. Solidification and cooling procedures
j. Cleaning operations (mechanical and chemical)
k. Heat treatment
l. Hot isostatic pressing
m. Straightening
n. Final inspection methods
o. Location of specimens machined from casting

4.4.2.2.1 Any of the control factors of Table 3 for which parameters are considered proprietary by vendor may be assigned a code designation. Each variation in such parameters shall be assigned a modified code designation.

4.4.2.2.1.1 Purchaser shall be entitled to review proprietary control factor details and coding at vendor's facility.

4.5 Reports:

The vendor of castings shall furnish with each shipment a report showing the results of acceptance tests to determine conformance to the technical requirements of this specification. This report shall include the purchase order number, master heat identification, heat treat/HIP/lot identification, AMS-49XXY, part number, quantity, and source of property specimens (see 4.3.3.1.1).

4.6 Resampling and Retesting:

If the results of a valid test fail to meet the requirements, two additional specimens in accordance with 4.3 from the same master heat or lot, as applicable, shall be tested for each nonconforming characteristic. The results of each additional test, and the average of the results of all tests (original and retests) shall meet the specified requirements; otherwise, the master heat or lot shall be rejected. Results of all tests shall be reported, including data that does not meet the specified requirements.

4.6.1 A test may be declared invalid if failure is due to specimen mispreparation, test equipment malfunction, or improper test procedure.

4.6.2 In addition to 4.6.1, a tensile may be declared invalid if failure is due to random process defects such as inclusions or gas holes.

5. PREPARATION FOR DELIVERY:

5.1 Identification:

Individual castings shall be identified in accordance with AMS 2804.

5.1.1 Traceability: Individual castings shall be traceable to their conditions of manufacture and inspection up to and including the point of acceptance by the purchaser.

5.2 Packaging:

Castings shall be prepared for shipment in accordance with commercial practice and in compliance with applicable rules and regulations pertaining to the handling, packaging, and transportation of the castings to ensure carrier acceptance and safe delivery.

5.2.1 For direct U.S. Military procurement, packaging shall be in accordance with MIL-STD-2073-1, Commercial level, unless Level A is specified in the request for procurement.

6. ACKNOWLEDGEMENT:

A vendor shall mention this specification number and its revision letter in all quotations and when acknowledging purchase orders.

7. REJECTIONS:

Castings not conforming to this specification, or to modifications authorized by purchaser, will be subject to rejection.

8. NOTES:

8.1 Marginal Indicia:

New issue. Not used.

8.2 Definitions:

8.2.1 "Acceptable to purchaser": Does not require prior written approval from purchaser, but allows vendor to make a decision and purchaser the right to disapprove the decision.

8.2.2 "Purchaser": The cognizant engineering organization responsible for casting design and fitness for use, or the designee of this engineering organization.

8.2.3 "Authorized by purchaser": Requires prior written approval from the purchaser.

8.2.4 "Specified": Requires documented instruction from purchaser through casting drawing, purchase order, specification, or other engineering documentation.

8.2.5 "Agreed upon by purchaser and vendor": Requires concurrence of both purchaser and vendor. Such concurrence is typically documented by way of the casting drawing, purchase order, or other engineering documentation.

8.2.6 "Lot": For hydrogen testing, and for room temperature tensile testing, a lot shall consist of all castings of the same part number, poured from a single master heat in one or more consecutive melts (see 8.2.7) through a single furnace campaign of not longer than twelve hours and processed through each hot isostatic pressing and anneal in the same furnace loads. For visual and nondestructive testing, a lot shall consist of castings of the same part number, manufactured under the same process control parameters of 4.4.2.2.

8.2.7 "Melt": All castings poured from a single furnace charge. Also referred to as remelt, submelt, heat, or subheat.

8.3 Dimensions and properties in inch/pound units and the Fahrenheit temperatures are primary; dimensions and properties in SI units, and the Celsius temperatures are shown as the approximate equivalents of the primary units and are presented only for information.

8.4 Purchase documents, including those for direct U.S. Military procurement, should specify not less than the following:

Title, number, and date of this specification
Part number or pattern number of castings desired
Quantity of castings desired
Size and location of specimens for room temperature, elevated temperature tensile and creep rupture testing are specified (see 3.4.4.2 and 3.6)
Inspection methods and acceptance standards (see 3.8.2)
Level A packaging, if required (see 5.2.1)

Key words: Aerospace Quality, Castings, Investment Castings, Precision Castings, Titanium Alloy, Ti-6Al-4V.

PREPARED UNDER THE JURISDICTION OF AMS COMMITTEE G.

APPENDIX D

CAST TI-6AL-4V PRODUCTION FIN ANALYSIS
MECHANICAL PROPERTY DATA
MICROSTRUCTURAL NDI DATA
"A" AND "B" ALLOWABLE ANALYSIS

APPENDIX D

CAST TI-6AL-4V PRODUCTION FIN ANALYSIS

This appendix contains the following data discussed previously in Section 5 of this report:

D.1 Tabulated data for the cast Ti-6Al-4V production fins
D.2 Allowables generated using the Boeing software program
D.3 Typical stress-strain curves
D.4 Compression, bearing, and shear data

D.1 MECHANICAL PROPERTY AND MICROSTRUCTURAL DATA FOR CAST TI-6AL-4V FINS

SAMPLE	FTU	FTY	MODULUS	ELONGATION	PBGS	GBA(E-4)	AC(E-3)	APS(E-4)
SUPPLIER Z								
4A-001	133.5	127.7	17.5	9.2	0.040	3.125	3.68	1.56
4A-012	134.1	129.2	17.3	8.4	0.053	3.125	4.06	1.32
4A-013	133.8	128.6	17.3	8.9	0.046	1.950	4.16	1.38
4A-014	134.1	-	-	-	0.050	2.500	4.00	1.25
4A-015	132.2	127.4	17.3	8.1	0.042	3.125	7.08	1.32
4A-021	135.8	130.1	17.2	9.0	0.039	3.125	3.75	1.47
4A-022	133.2	127.2	16.8	9.3	0.047	1.560	3.31	1.00
4A-023	132.1	126.5	17.9	9.9	0.030	4.170	1.88	1.78
4A-024	132.7	127.3	17.1	8.9	0.027	3.125	2.27	1.47
4A-025	131.5	125.8	16.5	9.3	0.027	3.125	3.64	1.25
4G-001	128.7	123.4	16.9	11.2	0.038	2.600	2.71	2.50
4G-012	130.1	124.0	16.8	9.3	0.048	3.520	2.38	1.47
4G-013	129.9	123.6	16.7	8.0	0.055	2.080	3.44	1.47
4G-015	130.1	125.1	16.8	8.6	0.043	2.340	2.75	1.56
4G-021	128.9	123.8	16.7	10.6	0.052	3.125	2.81	1.38
4G-022	129.3	124.1	16.4	11.1	0.040	2.340	2.58	1.78
4G-023	129.6	124.1	16.6	8.7	0.044	3.125	7.50	1.47
4G-024	128.1	123.2	16.8	11.3	0.045	2.030	2.50	1.56
4G-025	129.3	124.3	17.3	9.7	0.060	3.125	6.58	1.67
4H-021	129.5	123.9	16.7	11.8	0.037	2.340	2.92	1.38
4H-022	129.2	123.6	16.9	9.0	0.055	1.560	2.18	1.25
4H-023	127.8	122.5	16.6	10.8	0.057	3.125	3.43	1.04
4H-024	128.1	122.5	16.7	11.3	0.052	3.460	2.03	1.09
4H-025	127.8	123.6	17.1	5.8	0.038	3.580	4.38	1.14
4N-021	132.8	126.9	16.8	8.7	0.033	2.180	3.75	2.08
4N-022	133.1	127.1	17.4	11.1	0.037	3.750	4.27	1.39
4N-023	132.1	126.0	17.2	9.5	0.034	1.880	3.25	1.25
4N-024	132.5	126.6	17.1	9.5	0.042	2.400	3.44	1.09
4N-025	132.9	127.1	17.0	11.5	0.037	3.125	3.75	1.78
4P-011	132.5	126.3	17.1	12.7	0.035	3.125	2.97	1.47
4P-012	132.2	126.4	16.9	11.1	0.040	3.125	3.91	1.14

PBGS = PRIOR BETA GRAIN SIZE
GBA = GRAIN BOUNDARY ALPHA
AC = ALPHA COLONY
APS = ALPHA PLATELET SPACING

SAMPLE	FTU	FTY	MODULUS	ELONGATION	PBGS	GBA(E-4)	AC(E-3)	APS(E-4)	
4P-013	132.4	126.7	17.2	9.6	0.034	3.125	2.81	1.14	
4P-014	132.1	126.6	16.7	10.6	0.037	3.125	3.96	1.39	
4P-015	132.4	126.6	17.0	6.9	0.043	4.680	3.28	1.32	
4P-021	134.6	127.6	17.3	9.3	0.043	2.140	3.59	1.56	
4P-022	133.8	126.8	17.2	8.8	0.034	3.125	4.37	1.25	
4P-023	132.4	126.8	17.1	8.8	0.033	3.125	3.43	1.25	
4P-024	132.6	126.2	17.1	9.7	0.030	2.730	3.59	2.27	
4P-025	133.3	127.9	17.2	10.1	0.033	3.125	2.66	0.96	
4T-011	131.4	125.8	17.3	11.4	N/A	N/A	N/A	N/A	
4T-012	131.6	125.5	17.1	11.9	N/A	N/A	N/A	N/A	
4T-013	131.0	124.7	17.3	10.5	N/A	N/A	N/A	N/A	
4T-014	131.1	125.9	17.1	11.3	N/A	N/A	N/A	N/A	
4T-015	130.4	124.4	17.2	11.5	N/A	N/A	N/A	N/A	
4T-021	131.7	125.9	17.4	10.4	0.023	2.340	5.72	1.25	
4T-022	132.4	126.5	17.3	10.5	0.034	3.125	6.46	1.39	
4T-023	131.8	126.1	17.2	9.0	0.026	1.560	5.47	1.47	
4T-024	131.9	125.8	16.9	8.5	0.035	3.125	7.34	1.66	
4T-025	130.9	125.1	17.1	10.0	0.030	1.560	4.17	1.67	
4AA-011	130.4	124.7	17.2	9.3	0.049	2.340	2.81	1.47	
4AA-012	129.1	125.0	17.2	8.4	0.033	3.125	2.58	1.14	
4AA-013	129.2	124.2	17.4	9.3	0.037	2.600	2.75	1.04	
4AA-014	130.4	123.4	17.1	9.7	0.060	1.870	3.85	1.39	
4AA-021	130.8	125.2	17.2	9.4	0.046	1.560	2.97	1.19	
4AA-022	131.1	124.8	17.0	10.4	0.045	2.600	2.73	1.47	
4AA-023	131.9	126.1	17.5	12.2	0.035	4.690	4.63	1.79	
4AA-024	131.2	125.9	17.2	10.7	0.040	4.170	4.38	1.39	
4AA-025	129.7	124.3	17.1	10.8	0.030	3.125	8.54	1.19	
4AC-011	131.6	125.3	16.5	10.6	0.035	1.880	4.37	1.56	
4AC-012	130.3	124.3	17.0	11.3	0.038	2.730	4.06	1.56	
4AC-013	130.4	124.7	17.4	11.9	0.055	2.920	8.75	2.08	
4AC-014	129.3	123.8	16.8	7.1	0.046	2.560	4.75	1.47	
4AC-015	130.0	124.5	17.3	9.9	0.043	2.600	4.06	1.25	

SAMPLE	FTU	FTY	MODULUS	ELONGATION	PBGS	GBA(E-4)	AC(E-3)	APS(E-4)	
14X-021	131.2	125.9	17.3	10.5	0.032	3.125	3.75	1.19	
14X-022	131.4	125.8	15.8	10.9	0.040	1.560	3.59	1.25	
14X-023	131.1	125.2	17.1	8.7	0.039	2.340	4.69	1.39	
14X-024	132.1	126.2	16.9	11.4	0.033	4.170	7.30	1.32	
14X-025	131.9	127.2	17.1	11.1	0.036	3.125	5.00	1.39	
14X-011	132.5	126.6	16.7	12.0	0.040	1.720	3.75	0.96	
14X-012	132.5	126.2	17.0	10.1	0.027	2.500	5.00	1.25	
14X-013	132.4	126.6	16.7	10.5	0.029	2.340	6.25	1.39	
14X-014	132.5	127.4	17.1	11.0	0.037	2.730	4.38	1.39	
14X-015	133.1	127.1	16.8	11.6	0.036	3.125	4.25	0.96	
14Y-011	133.0	127.4	16.8	8.9	0.044	4.170	3.19	1.79	
14Y-012	133.3	127.4	16.9	11.6	0.038	2.810	5.50	1.32	
14Y-013	132.3	126.3	16.8	11.8	0.045	3.830	4.53	1.47	
14Y-014	132.5	126.3	16.9	10.0	0.040	4.230	3.73	1.67	
14Y-015	132.4	126.3	16.6	10.1	0.036	4.750	3.25	0.78	
14Y-021	130.8	124.5	17.1	11.4	N/A	N/A	N/A	N/A	
14Y-022	130.1	123.7	16.8	11.7	N/A	N/A	N/A	N/A	
14Y-023	130.5	124.9	16.7	12.7	N/A	N/A	N/A	N/A	
14Y-024	129.7	124.3	16.9	11.6	N/A	N/A	N/A	N/A	
14Y-025	130.1	124.0	16.9	11.6	N/A	N/A	N/A	N/A	
SUPPLIER 3									
63-1	130.1	123.7	16.2	5.8	N/A	N/A	N/A	N/A	
63-2	132.8	120.3	15.6	8.2	N/A	N/A	N/A	N/A	
63-3	132.3	118.9	15.8	8.2	N/A	N/A	N/A	N/A	
6C-1	138.3	129.0	16.3	9.7	N/A	N/A	N/A	N/A	
6C-2	135.4	126.8	16.3	7.4	N/A	N/A	N/A	N/A	
6C-3	133.9	126.6	16.0	7.7	N/A	N/A	N/A	N/A	
6C-4	137.9	127.4	16.6	7.9	N/A	N/A	N/A	N/A	
SUPPLIER 1									
A1	128.6	121.9	16.3	10.7	0.043	3.125	5.31	1.32	
A2	127.8	121.9	16.4	9.3	0.035	4.160	6.56	1.39	
A3	128.5	122.5	16.3	9.4	0.048	3.125	4.37	1.38	

SAMPLE	FTU	FTY	MODULUS	ELONGATION	PBGS	GBA(E-4)	AC(E-3)	APS(E-4)
A4	127.8	121.5	16.6	10.1	0.035	3.125	7.00	1.92
A5	127.7	121.5	16.3	9.7	0.045	3.125	8.13	1.14
B1	129.1	122.6	16.6	9.8	0.050	2.730	4.68	1.47
B2	128.1	122.2	16.6	[illegible]	0.040	5.470	4.29	1.39
B3	127.8	121.5	16.6	10.4	0.055	2.730	4.38	2.50
B4	127.5	120.7	16.4	9.2	0.045	4.060	4.29	1.39
B5	127.4	121.6	16.6	9.4	0.050	-	3.91	1.47

D.2 "A" AND "B" ALLOWABLES GENERATED USING BOEING SOFTWARE

ALL FTU DATA
SUPPLIERS 1, 2, AND 3

Sample Size = 125 Error Return Code IER = 0

ALLOWABLES
3p-Weibull Allowables
A = 125.112 B = 127.834

Normal Allowables
A = 125.593 B = 127.965

Nonparametric Allowables
A = ******** B = 127.800

Weibull Parameter Estimates (3p-Weibull)
Threshold = 125.595 Scale = 6.144 Shape = 2.832

Normal estimates of 1- and 10-percentiles
x(.01) = 126.247 x(.10) = 128.413

3p-Weibull estimates of 1- and 10-percentiles
x(.01) = 126.806 x(.10) = 128.371

Other Sample Statistics
Mean = 131.070 Stand. Deviation = 2.073
Skewness = .481 Kurtosis = .782
Coeff. of Variation = .016

Test for Normality
AD = .627 P-value = .105518 IEX = 0

A P-value less than .05 is significant evidence against the hypothesis of normality according to MIL-HDBK 5

Test for the 3p-Weibull Distribution
AD = .637 P-value = .093499 IEX = 0

A P-value less than .05 is significant evidence against the hypothesis of 3p-Weibullness according to MIL-HDBK 5

The 13 smallest data values are

126.800	127.400	127.500	127.700	127.800	127.800	127.800	127.800
127.800	128.100	128.100	128.100	128.200			

The 13 largest data values are

133.300	133.400	133.500	133.500	133.800	133.900	134.100	134.100
134.600	135.400	135.800	137.900	138.300			

FTU

SUPPLIERS 2 AND 3

Sample Size = 115   Error Return Code IER = 0

ALLOWABLES

3p-Weibull Allowables

A = 124.970   B = 128.113

Normal Allowables

A = 126.175   B = 128.406

Nonparametric Allowables

A = ********   B = 128.200

Weibull Parameter Estimates (3p-Weibull)

Threshold = 125.686   Scale = 6.305   Shape = 3.075

Normal estimates of 1- and 10-percentiles

x(.01) = 126.817   x(.10) = 128.846

3p-Weibull estimates of 1- and 10-percentiles

x(.01) = 127.098   x(.10) = 128.719

Other Sample Statistics

Mean = 131.335   Stand. Deviation = 1.942

Skewness = .590   Kurtosis = 1.297

Coeff. of Variation = .015

Test for Normality

AD = .668   P-value = .083832   IEX = 0

A P-value less than .05 is significant evidence against the hypothesis of normality according to MIL-HDBK 5

Test for the 3p-Weibull Distribution

AD = .828   P-value = .030332   IEX = 0

A P-value less than .05 is significant evidence against the hypothesis of 3p-Weibullness according to MIL-HDBK 5

The 12 smallest data values are

126.800	127.800	127.800	128.100	128.100	128.200	128.600	128.700
128.700	128.900	128.900	129.100				

The 12 largest data values are

133.400	133.500	133.500	133.800	133.900	134.100	134.100	134.600
135.400	135.800	137.900	138.300				

FTU
SUPPLIER 2

Sample Size = 108 Error Return Code IER = 0

ALLOWABLES

3p-Weibull Allowables
A = 126.190 B = 128.522

Normal Allowables
A = 126.621 B = 128.570

Nonparametric Allowables
A = ******** B = 128.200

Weibull Parameter Estimates (3p-Weibull)
Threshold = 126.075 Scale = 5.639 Shape = 3.346

Normal estimates of 1- and 10-percentiles
x(.01) = 127.201 x(.10) = 128.968

3p-Weibull estimates of 1- and 10-percentiles
x(.01) = 127.501 x(.10) = 128.953

Other Sample Statistics
Mean = 131.137 Stand. Deviation = 1.692
Skewness = -.065 Kurtosis = -.386
Coeff. of Variation = .013

Test for Normality
AD = .570 P-value = .139710 IEX = 0

A P-value less than .05 is significant evidence against the hypothesis of normality according to MIL-HDBK 5

Test for the 3p-Weibull Distribution
AD = .513 P-value = .192532 IEX = 0

A P-value less than .05 is significant evidence against the hypothesis of 3p-Weibullness according to MIL-HDBK 5

The 12 smallest data values are

126.800	127.800	127.800	128.100	128.100	128.200	128.600	128.700
128.700	128.900	128.900	129.100				

The 12 largest data values are

133.100	133.200	133.300	133.300	133.400	133.500	133.500	133.800
134.100	134.100	134.600	135.800				

ALL FTY DATA
SUPPLIERS 1, 2, AND 3

Sample Size = 124   Error Return Code IER = 0

ALLOWABLES
3p-Weibull Allowables
A = 116.963   B = 121.720

Normal Allowables
A = 120.079   B = 122.277

Nonparametric Allowables
A = ********   B = 121.600

Weibull Parameter Estimates (3p-Weibull)
Threshold = 111.922   Scale = 14.039   Shape = 7.950

Normal estimates of 1- and 10-percentiles
x(.01) = 120.688   x(.10) = 122.695

3p-Weibull estimates of 1- and 10-percentiles
x(.01) = 119.793   x(.10) = 122.500

Other Sample Statistics
Mean = 125.156   Stand. Deviation = 1.921
Skewness = -.431   Kurtosis = .396
Coeff. of Variation = .015

Test for Normality
AD = .729   P-value = .060571   IEX = 0

A P-value less than .05 is significant evidence against the hypothesis of normality according to MIL-HDBK 5

Test for the 3p-Weibull Distribution
AD = .377   P-value = .379999   IEX = 1

A P-value less than .05 is significant evidence against the hypothesis of 3p-Weibullness according to MIL-HDBK 5

The 13 smallest data values are

118.900	120.300	120.700	121.500	121.500	121.500	121.600	121.900
121.900	122.200	122.500	122.500	122.500			

The 13 largest data values are

127.400	127.400	127.400	127.400	127.400	127.600	127.700	127.900
128.200	128.600	129.000	129.200	130.100			

FTY

SUPPLIERS 2 AND 3

Sample Size = 114 Error Return Code IER = 0

ALLOWABLES

3p-Weibull Allowables

A = 119.932 B = 122.662

Normal Allowables

A = 120.925 B = 122.880

Nonparametric Allowables

A = ******** B = 122.500

Weibull Parameter Estimates (3p-Weibull)

Threshold = 118.020 Scale = 8.069 Shape = 4.903

Normal estimates of 1- and 10-percentiles

x(.01) = 121.490 x(.10) = 123.269

3p-Weibull estimates of 1- and 10-percentiles

x(.01) = 121.178 x(.10) = 123.120

Other Sample Statistics

Mean = 125.452 Stand. Deviation = 1.703

Skewness = -.462 Kurtosis = 1.550

Coeff. of Variation = .014

Test for Normality

AD = .578 P-value = .135037 IEX = 0

A P-value less than .05 is significant evidence against the hypothesis of normality according to MIL-HDBK 5

Test for the 3p-Weibull Distribution

AD = .658 P-value = .082438 IEX = 0

A P-value less than .05 is significant evidence against the hypothesis of 3p-Weibullness according to MIL-HDBK 5

The 12 smallest data values are

118.900 120.300 122.500 122.500 122.500 122.500 123.000 123.200
123.400 123.400 123.600 123.600

The 12 largest data values are

127.400 127.400 127.400 127.400 127.600 127.700 127.900 128.200
128.600 129.000 129.200 130.100

FTY
SUPPLIER 2

Sample Size = 107   Error Return Code IER = 0

ALLOWABLES
3p-Weibull Allowables
A = 121.854   B = 123.296

Normal Allowables
A = 121.522   B = 123.241

Nonparametric Allowables
A = ********   B = 123.200

Weibull Parameter Estimates (3p-Weibull)
Threshold = 121.925   Scale = 4.023   Shape = 2.583

Normal estimates of 1- and 10-percentiles
x(.01) = 122.036   x(.10) = 123.593

3p-Weibull estimates of 1- and 10-percentiles
x(.01) = 122.603   x(.10) = 123.608

Other Sample Statistics
Mean = 125.503   Stand. Deviation = 1.490
Skewness = .213   Kurtosis = -.037
Coeff. of Variation = .012

Test for Normality
AD = .400   P-value = .310509   IEX = 1

A P-value less than .05 is significant evidence against the hypothesis of normality according to MIL-HDBK 5

Test for the 3p-Weibull Distribution
AD = .468   P-value = .246515   IEX = 0

A P-value less than .05 is significant evidence against the hypothesis of 3p-Weibullness according to MIL-HDBK 5

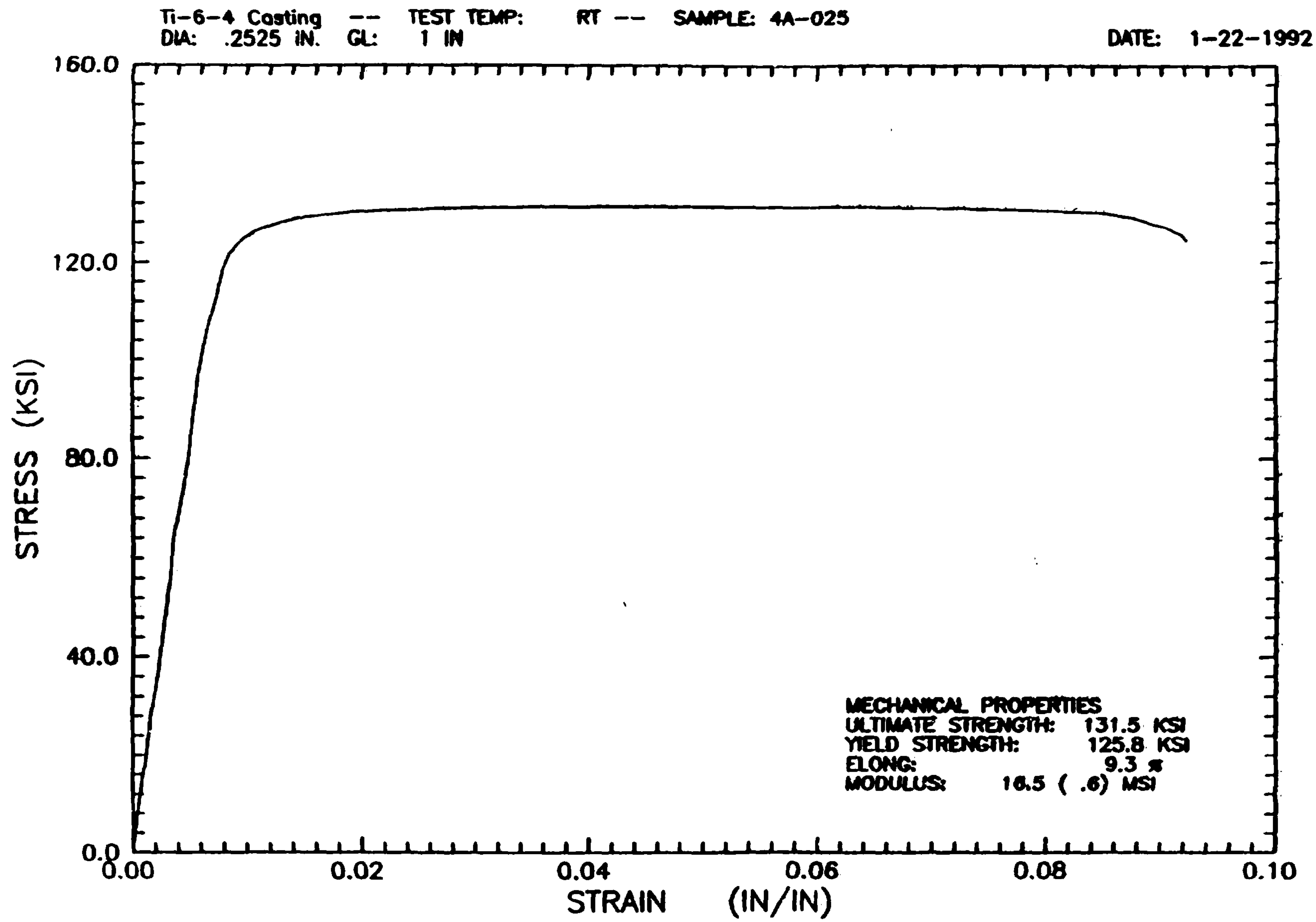
The 11 smallest data values are

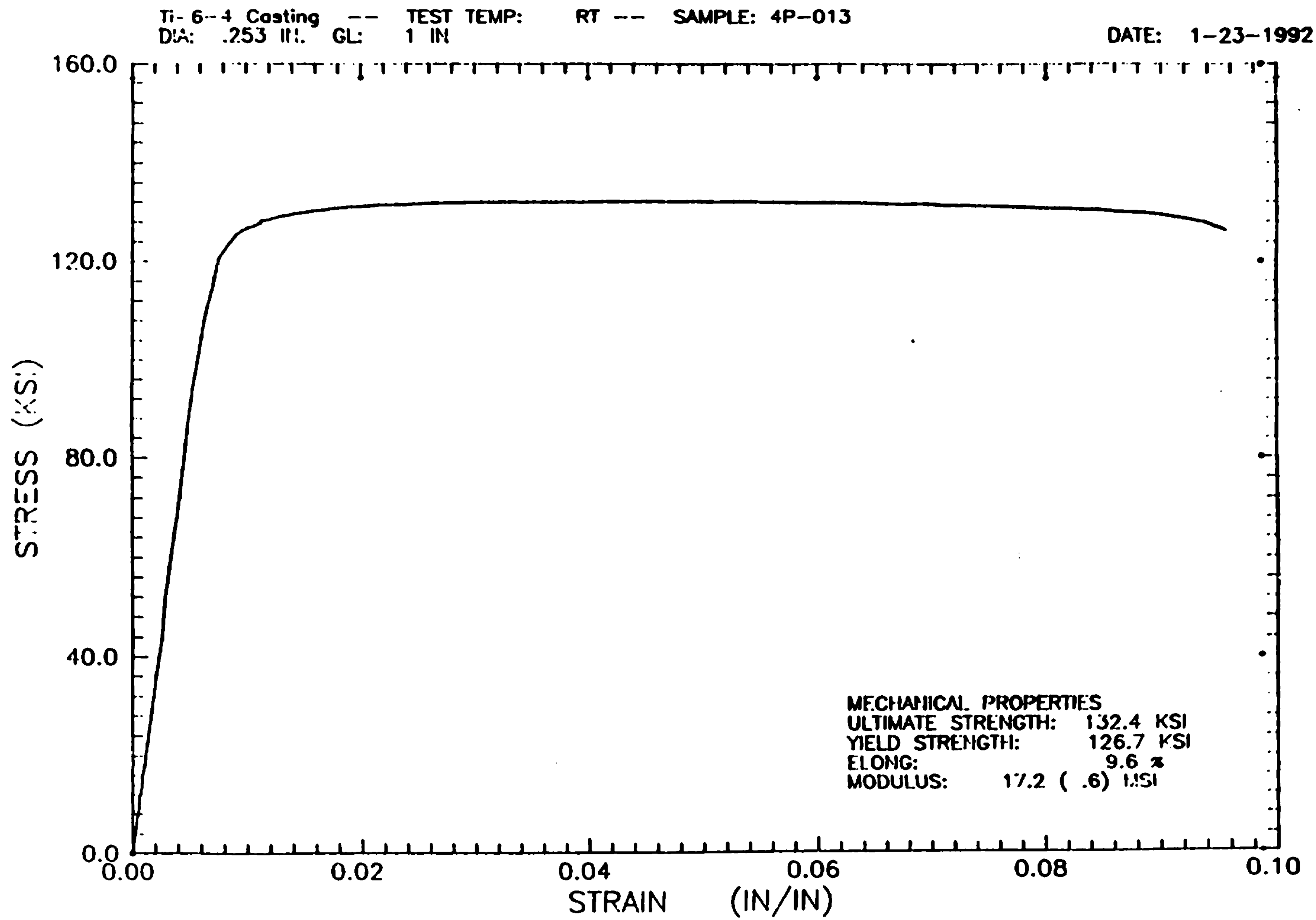
122.500	122.500	122.500	122.500	123.000	123.200	123.400	123.400
123.600	123.600	123.600					

The 11 largest data values are

127.400	127.400	127.400	127.400	127.600	127.700	127.900	128.200
128.600	129.200	130.100					

D.3 TYPICAL STRESS-STRAIN CURVES


Ti-6-4 Casting -- TEST TEMP: RT -- SAMPLE: 4A-025
DIA: .2525 IN. GL: 1 IN
DATE: 1-22-1992
STRESS (KSI)
160.0
120.0
80.0
40.0
0.0
0.00
0.02
0.04
0.06
0.08
0.10
STRAIN (IN/IN)
MECHANICAL PROPERTIES
ULTIMATE STRENGTH: 131.5 KSI
YIELD STRENGTH: 125.8 KSI
ELONG: 9.3 %
MODULUS: 16.5 (.6) MSI


Ti- 6--4 Casting -- TEST TEMP: RT -- SAMPLE: 4P-013
DIA: .253 IN. GL: 1 IN
DATE: 1-23-1992
160.0
120.0
80.0
40.0
0.0
STRESS (KSI)
0.00
0.02
0.04
0.06
0.08
0.10
STRAIN (IN/IN)
MECHANICAL PROPERTIES
ULTIMATE STRENGTH: 132.4 KSI
YIELD STRENGTH: 126.7 KSI
ELONG: 9.6 %
MODULUS: 17.2 (.6) MSI

D.4 COMPRESSION, BEARING, AND SHEAR DATA

BACKGROUND

Nine samples of cast titanium alloy fins were submitted to our laboratory for mechanical testing. The titanium alloy was identified as Ti-6Al-4V. We were requested to perform compression, pin bearing, and shear testing on these samples. The machining and testing was to be performed in accordance with TCP-92-015.

TEST RESULTS

Compression Testing

Three of the submitted fins were machined to obtain 3/8" diameter by 1" long specimens for compressive yield strength testing. The specimens were machined and tested in accordance with ASTM E9. The results of these tests are shown below.

Fin Identification	Compressive Yield Strength, psi (0.2% offset)
4A-01	133,000
4G-01	125,000
4G-02	125,000

Pin Bearing Tests

Pin bearing test specimens were cut and machined from three of the submitted fin samples. The specimens were machined with a 1/4" diameter hole. The edge distance ratio was 1.5. Each specimen was machined and tested in accordance with ASTM E238. The results of these tests are shown in the table below.

Fin Identification	Thickness, in.	Pin Bearing Yield Strength, psi	Pin Bearing Ultimate Strength, psi
4T-01	.0934	187,000	218,000
4P-01	.1232	207,000	228,000
4AA-02	.1248	205,000	235,000

Shear Testing

The remaining three fins were cut to obtain specimens for shear testing. The specimens were machined to the greatest thickness possible to be obtained from each fin. The shear specimens were machined and tested in accordance with MIL-STD-1312, test #20 with reference to ASTM Proceedings, Volume 58, Evaluation of Single-Shear Specimen for Sheet Material. The results of these tests are shown in the table below.

Fin Identification	Length of Shear Path, in.	Thickness, in.	Shear Strength, psi
4H-02	.2437	.1486	88,300
4M-02	.2470	.1506	92,300
4T-02	.2481	.1486	88,400

Respectfully submitted,

TAUSSIG ASSOCIATES, INC.

Mark A. Hineman

Mark A. Hineman, P.E.
Senior Metallurgical Engineer

MAH/nb

APPENDIX E

FRACTURE MECHANICS DATA

APPENDIX E

FRACTURE MECHANICS DATA

This appendix contains the results of testing compact tension specimens and bend specimens excised from the cast Ti-6Al-4V fins. Data from constant-amplitude fatigue tests is also contained in this section.

BACKGROUND

Six samples of titanium castings were submitted to our laboratory for mechanical testing. The testing was performed in accordance with "Engineering Work Statement for Fracture Mechanics Testing for Use of Titanium Castings Without a Casting Factor", WS-MAT-7165. The mechanical tests were to include fatigue crack growth testing of three specimens per ASTM E647, and plane-strain toughness testing of three specimens per ASTM E992 and E399, and R-curve determination per E561.

TEST RESULTS

Fatigue Crack Growth Testing

Three fatigue crack growth test specimens were machined from the submitted castings in accordance with ASTM E647-88. The specimens were 0.50-C(T) specimens were precracked at room temperature using an R-ratio of 0.1. Each specimen was tested under a constant load with increasing K conditions at room temperature and with an R-ratio of 0.1. Graphs of crack length vs. the number of cycles were developed using a clip gage to measure the crack opening. These results are for all three specimens in Figure No. 2, and are individually presented in Figure Nos. 4, 6, and 8.

At specific cycle intervals, static load and COD measurements were determined to verify compliance of the specimens. The compliance measurements were converted to physical crack extension using Hudak and Saxena equations as follows:

$$A/W = 1.0010 - 4.6695\, U_x + 18.46\, U_x^2 - 236.82\, U_x^3$$

$$+ 1214.9\, U_x^4 - 2.43.6\, U_x^5$$

$$\text{Where } U_x = (\{EBV/P\}^{1/2} + 1)^{-1}$$

Graphs of da/dn vs. Delta K were developed for each specimen. These graphs are compiled in Figure No. 1. and are individually presented as Figure Nos. 3, 5, and 7. Tables of the data obtained during each test are presented in Tables 1 through 6.

Fracture Toughness per E399

Three 0.400-C(T) compact fracture toughness specimens were cut and machined from the submitted titanium castings. The specimens were precracked and tested at +75°F. The specimens were tested and the results were evaluated in accordance with ASTM E399-90. The specific test results are presented in Tables 7, 8, and 9, and a summary is shown on page 2.

Sample	Kq KSI $(in)^{1/2}$	Valid/Invalid	No. of Invalids
4AA-01	70.6	Invalid	3
4AC-01	66.8	Invalid	3
4G-02	70.0	Invalid	3

R-Curve Determination

The test results of the three fracture toughness specimens were evaluated per ASTM E561-86. The results of each specimen are presented in Tables 10 through 12 and a summary is shown below.

Sample	$K_{[illegible]}$ KSI $(in)^{1/2}$	$K_{[illegible]}$ KSI $(in)^{1/2}$	Valid/Invalid
4AA-01	122.7	140.9	Invalid
4AC-01		112.7	Invalid
4G-02	118.6	125.0	Invalid

Fracture Toughness Per E992

The test results of the three fracture toughness specimens were also evaluated per ASTM E992-84. The results of these evaluations are shown in the table below.

Sample	K-ER, KSI $(in)^{1/2}$
4AA-01	147.1
4AC-01	117.9
4G-02	131.6

Respectfully submitted,

TAUSSIG ASSOCIATES, INC.

Mark A. Hineman

Mark A. Hineman
Senior Metallurgical Engineer

MAH/nb

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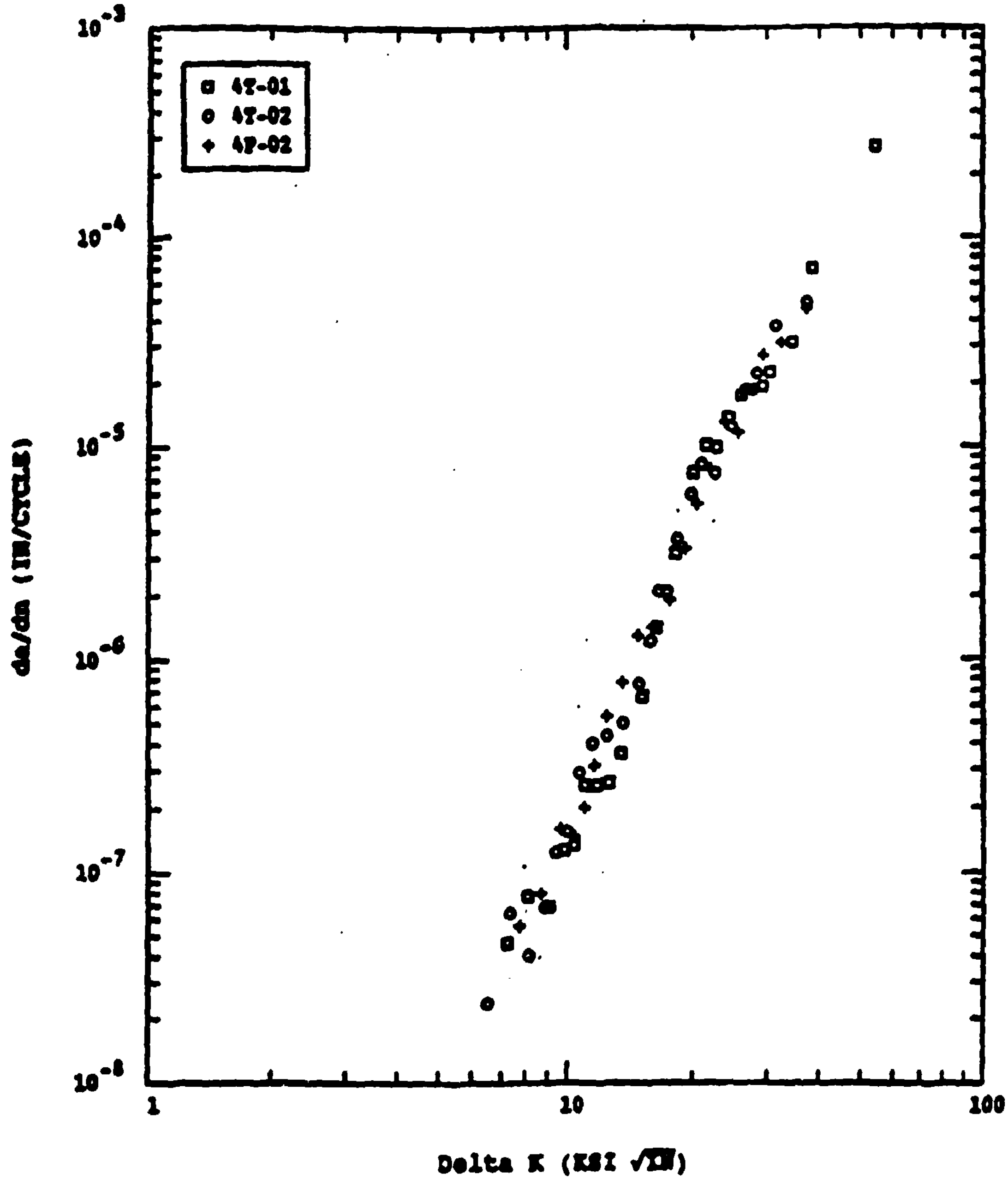
Figure No. 1



da/dn vs Delta K Graph for all three specimens.

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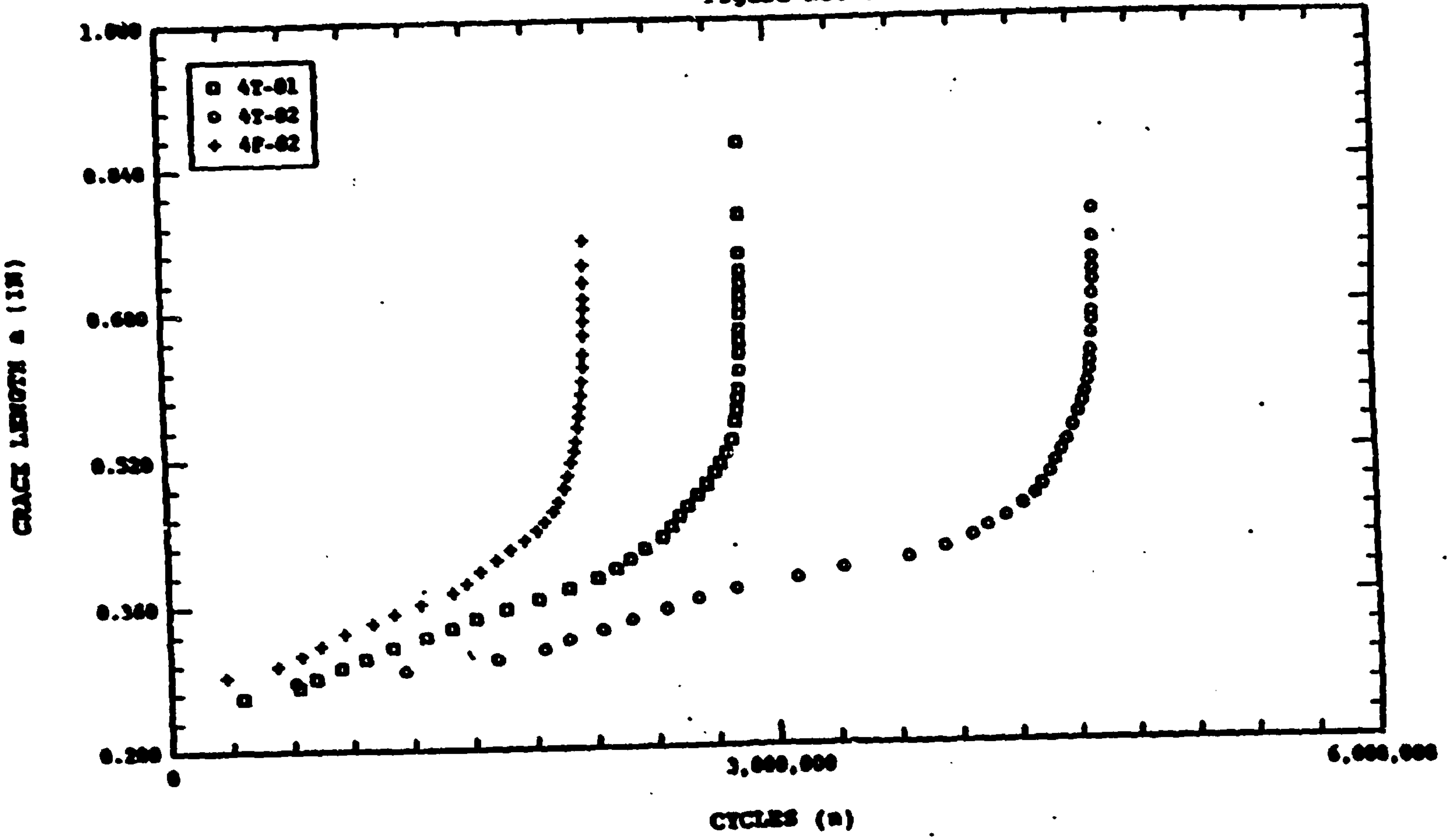
Figure No. 2



a vs n Graph for all three specimens.

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Table 1: Test Data for Sample 4T-01

FATIGUE CRACK GROWTH TEST REPORT

PRELIMINARY INFORMATION:

SAMPLE NUMBER: 4T-01
YIELD STRENGTH: 60.0 KSI
ENVIRONMENT: Air
CRACK PLANE ORIENTATION: ---

TEST DATE: 07-09-1992
MODULUS: 16.5 MSI
HUMIDITY: 45%

SPECIMEN MEASUREMENTS:

THICKNESS (B) = 0.100 IN.
WIDTH (W) = 0.999 IN.
NOTCH (An) = 0.196 IN.

SIDE 1 (A1) = 0.271 IN.
SIDE 2 (A2) = 0.265 IN.

PRECRACKING SUMMARY:

STRESS INTENSITY FACTOR RANGE = 7.090 KSI(SQRT.IN.)
STRESS RATIO = .1

TEST PARAMETERS:

MAXIMUM LOAD = 150 LBS.
LOAD RANGE = 135 LBS.
STRESS RATIO = .1

MINIMUM LOAD = 15 LBS.
FREQUENCY = .1-20 Hertz
WAVEFORM = SINE

CRACK CURVATURE CORRECTION:

PRECRACK FRONT: NONE REQUIRED
TERMINAL FATIGUE CRACK: NONE REQUIRED

VALIDITY CHECKS PER ASTM E647-86:

1. DIFFERENCE BETWEEN A1 AND A2 MUST BE < 0.25 * B — VALID
   DIFFERENCE = 0.006 IN. 0.25 * B = .025

2. THE CRACK MUST NOT DEVIATE MORE THAN 5% FROM THE PLANE OF SYMMETRY — VALID

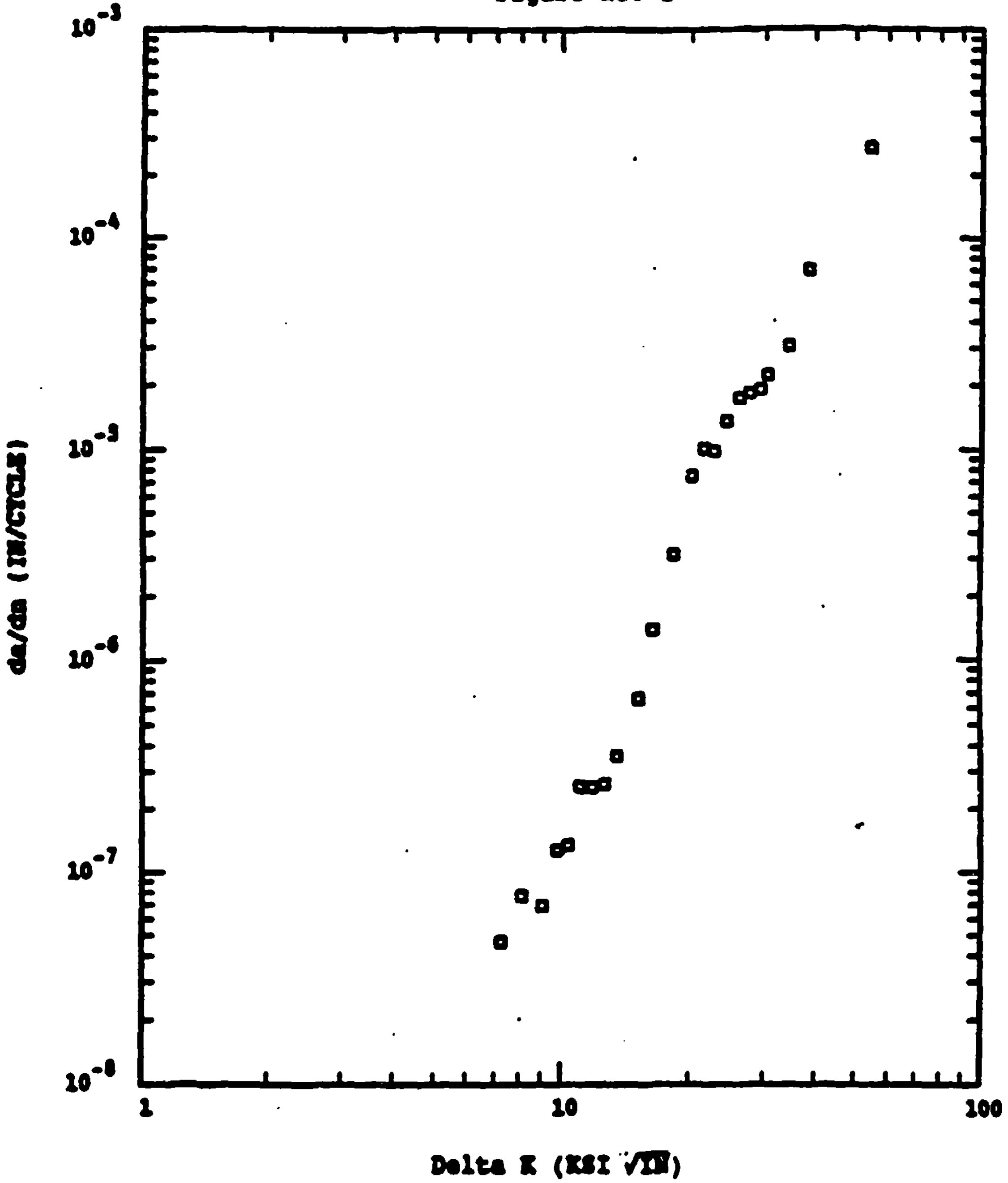
ALL VALIDITY CHECKS ARE VALID.

Table 2: Fatigue Crack Growth Test Results for Sample R5-01

Pmax (LBS)	EB(V/P)	a (IN)	N	da (IN)	dN	da/dN (IN/CYCLE)	delta K (KSI √IN)	Ick
		0.2992	951011					
150	25.07	0.3013	961013	0.0449	960505	4.6739E-08	7.25	0
150	29.29	0.3440	1511002	0.0427	549989	7.7614E-08	8.12	0
150	34.30	0.3858	2111006	0.0418	600004	6.9615E-08	9.05	0
150	37.15	0.4063	2271004	0.0206	159998	1.2850E-07	9.81	0
150	40.72	0.4294	2441003	0.0230	169999	1.3541E-07	10.40	0
150	44.78	0.4526	2531000	0.0232	89997	2.5791E-07	11.07	0
150	49.36	0.4757	2621002	0.0231	90002	2.5658E-07	11.83	0
150	54.75	0.4994	2711009	0.0237	90007	2.6378E-07	12.66	0
149	60.37	0.5210	2771010	0.0216	60001	3.6018E-07	13.81	0
151	70.66	0.5542	2821003	0.0332	49993	6.6314E-07	15.19	0
150	79.96	0.5788	2838502	0.0246	17499	1.4078E-06	16.42	0
150	94.60	0.6103	2848505	0.0315	10003	3.1482E-06	18.23	0
150	105.28	0.6291	2851004	0.0189	2499	7.5469E-06	20.14	0
150	113.40	0.6417	2852250	0.0126	1246	1.0088E-05	21.83	0
150	122.30	0.6541	2853501	0.0124	1251	9.8734E-06	22.79	0
150	136.35	0.6711	2854755	0.0170	1254	1.3587E-05	24.38	0
150	146.48	0.6819	2855377	0.0108	622	1.7294E-05	26.07	0
150	158.54	0.6933	2856002	0.0115	625	1.8349E-05	27.89	1
150	172.73	0.7053	2856628	0.0120	626	1.9091E-05	29.29	1
152	191.73	0.7192	2857252	0.0139	624	2.2282E-05	30.48	1
150	223.55	0.7384	2857878	0.0192	626	3.0739E-05	34.40	1
144	331.60	0.7819	2858501	0.0434	623	6.9719E-05	38.59	1
136	905.33	0.8624	2858800	0.0805	299	2.6931E-04	54.25	1

An Ick value of 1 indicates that the data violates the specimen size requirments (w-a >= (4/pi)((kmax/ys)^2)

Figure No. 3



da/dn vs Delta K Graph for sample 4T-01.

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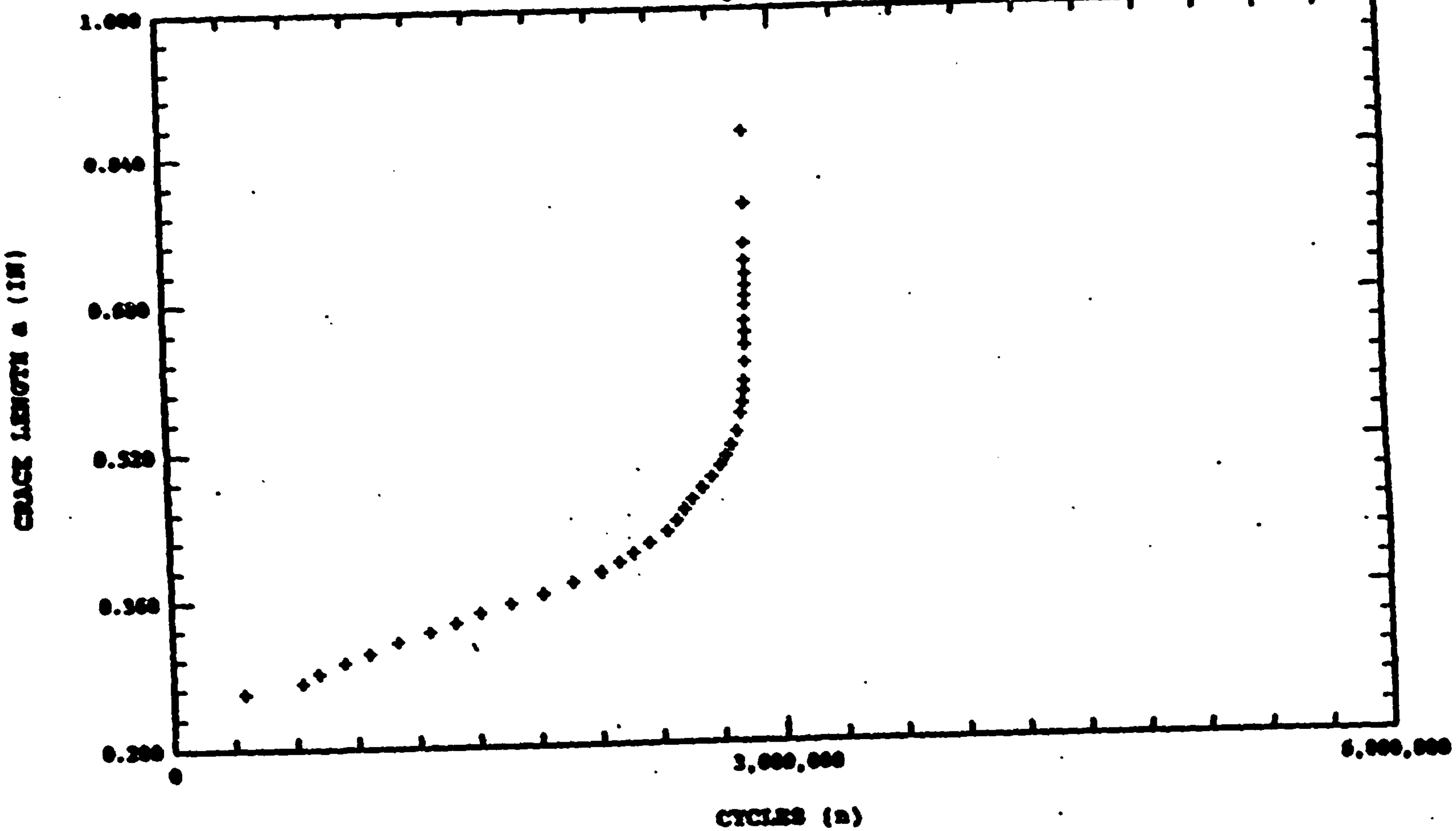
Figure No. 4



a vs n Graph for sample 4T-01.

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Table 3: Test Data for Sample 4T-02.

FATIGUE CRACK GROWTH TEST REPORT

PRELIMINARY INFORMATION:

SAMPLE NUMBER: 4T-02
YIELD STRENGTH: 60.0 KSI
ENVIRONMENT: Air
CRACK PLANE ORIENTATION: ---

TEST DATE: 07-09-1992
MODULUS: 16.5 MSI
HUMIDITY: 45%

SPECIMEN MEASUREMENTS:

THICKNESS (B) = 0.100 IN.
WIDTH (W) = 0.999 IN.
NOTCH (An) = 0.191 IN.

SIDE 1 (A1) = 0.261 IN.
SIDE 2 (A2) = 0.263 IN.

PRECRACKING SUMMARY:

STRESS INTENSITY FACTOR RANGE = 5.959 KSI(SQRT.IN.)
STRESS RATIO = .1

TEST PARAMETERS:

MAXIMUM LOAD = 130 LBS.
LOAD RANGE = 117 LBS.
STRESS RATIO = .1

MINIMUM LOAD = 13 LBS.
FREQUENCY = .1-20 Hertz
WAVEFORM = SINE

CRACK CURVATURE CORRECTION:

PRECRACK FRONT: NONE REQUIRED
TERMINAL FATIGUE CRACK: NONE REQUIRED

VALIDITY CHECKS PER ASTM E647-86:

1. DIFFERENCE BETWEEN A1 AND A2 MUST BE < 0.25 * B — VALID

   DIFFERENCE = 0.002 IN. 0.25 * B = .025

2. THE CRACK MUST NOT DEVIATE MORE THAN 5% FROM THE PLANE OF SYMMETRY — VALID

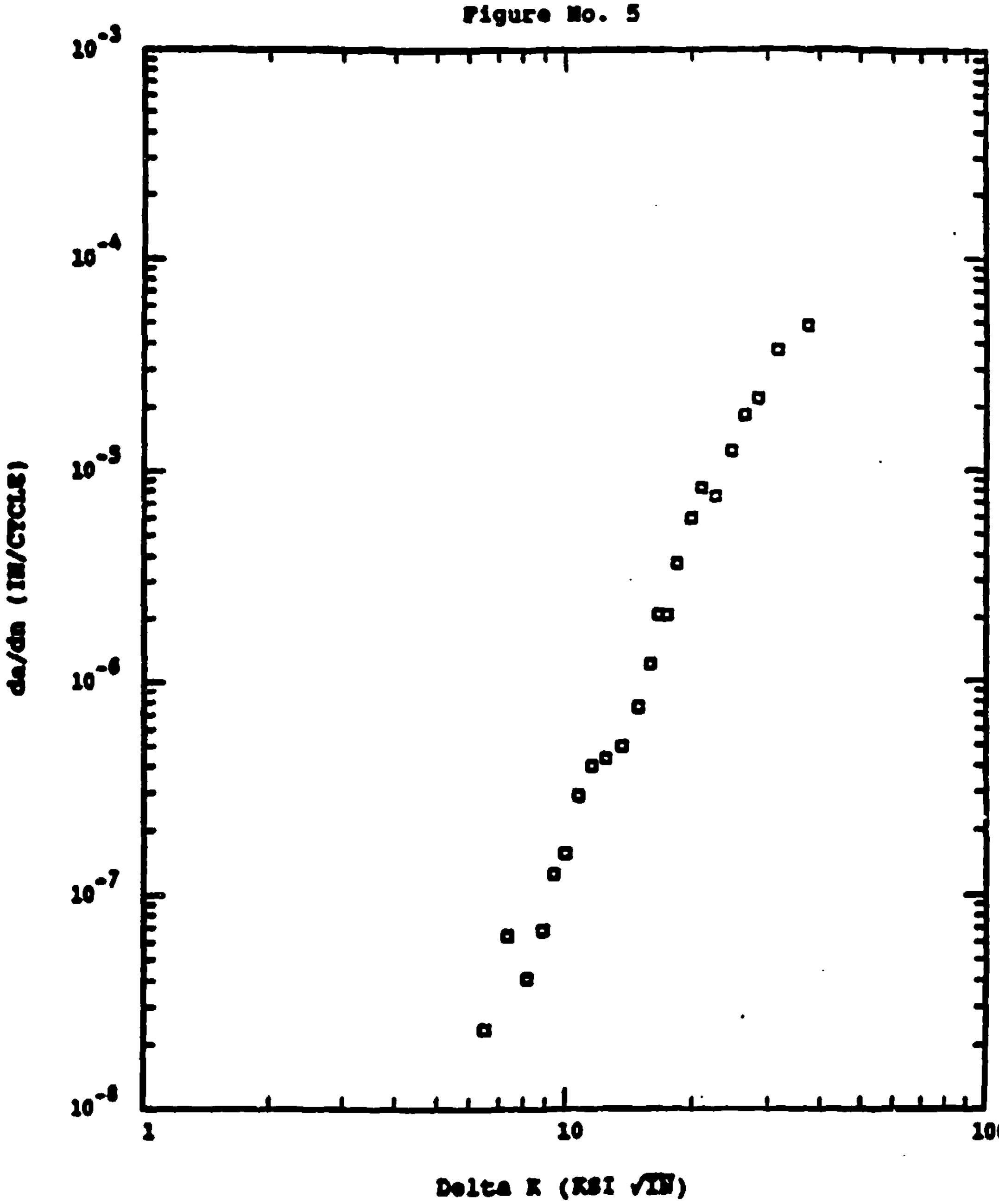
ALL VALIDITY CHECKS ARE VALID.

Table 4: Fatigue Crack Growth Test Results for Sample 4T-02.

Pmax (LBS)	EB(V/P)	a (IN)	N	da (IN)	dN	da/dN (IN/CYCLE)	delta K (KSI √IN)	Ick
		0.3166	1951012					
131	26.76	0.3194	1961019	0.0465	1960514	2.3736E-08	6.52	0
131	31.23	0.3612	2611012	0.0417	649993	6.4220E-08	7.32	0
130	36.76	0.4036	3651005	0.0424	1039993	4.0812E-08	8.15	0
130	40.10	0.4255	3971007	0.0219	320002	6.8430E-08	8.87	0
130	43.73	0.4468	4141002	0.0213	169995	1.2552E-07	9.40	0
130	48.27	0.4704	4291003	0.0235	150001	1.5696E-07	10.00	0
130	53.41	0.4938	4371012	0.0234	80009	2.9223E-07	10.71	0
130	59.53	0.5180	4431005	0.0242	59993	4.0309E-07	11.57	0
129	67.34	0.5442	4491001	0.0263	59996	4.3809E-07	12.50	0
129	76.16	0.5693	4541010	0.0250	50009	5.0026E-07	13.65	0
129	85.76	0.5922	4571007	0.0229	29997	7.6468E-07	14.91	0
129	91.52	0.6043	4581002	0.0121	9995	1.2074E-06	15.80	0
129	96.95	0.6147	4586008	0.0104	5006	2.0837E-06	16.62	0
129	102.84	0.6251	4591008	0.0104	5000	2.0793E-06	17.39	0
128	114.58	0.6434	4596000	0.0183	4992	3.6731E-06	18.36	0
129	125.68	0.6584	4598507	0.0150	2507	5.9799E-06	19.80	0
128	134.25	0.6687	4599752	0.0103	1245	8.2741E-06	21.03	0
129	152.22	0.6875	4602255	0.0188	2503	7.4967E-06	22.60	0
130	169.86	0.7030	4603507	0.0155	1252	1.2378E-05	24.60	0
130	184.70	0.7143	4604130	0.0113	623	1.8142E-05	26.46	1
130	205.30	0.7279	4604751	0.0136	621	2.1966E-05	28.41	1
129	246.65	0.7510	4605376	0.0230	625	3.6852E-05	31.56	1
130	328.85	0.7810	4606002	0.0300	626	4.7934E-05	37.35	1

An Ick value of 1 indicates that the data violates the specimen size requirements (w-a >= (4/pi)((kmax/ys)^2)

Figure No. 5



da/dn vs Delta K Graph for sample 4T-02.

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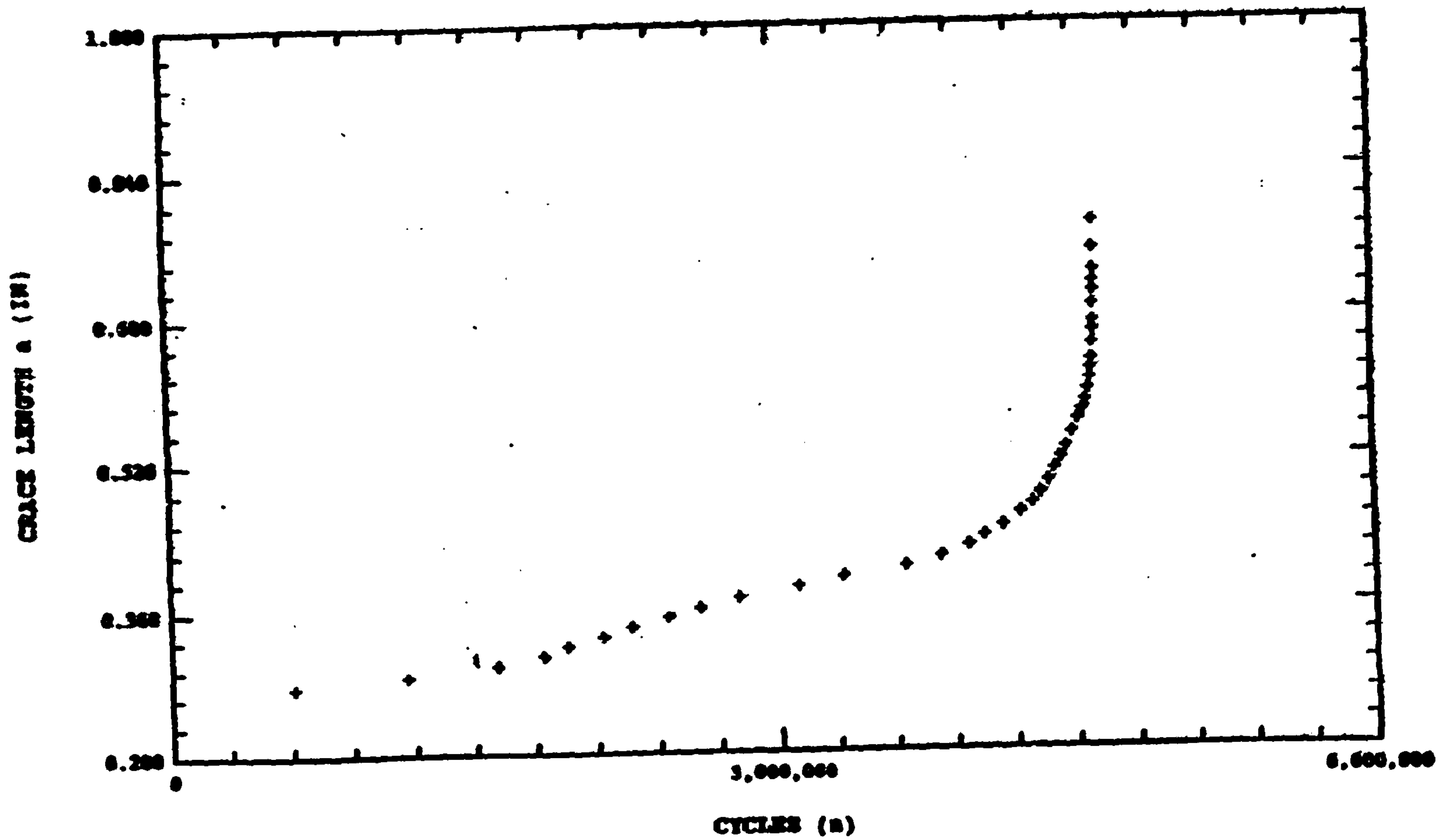
Figure No. 6



a vs n Graph for sample 4T-02

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Table 5: Test Data for Sample 4P-02

FATIGUE CRACK GROWTH TEST REPORT

PRELIMINARY INFORMATION:

SAMPLE NUMBER: 4P-02
YIELD STRENGTH: 60.0 KSI
ENVIRONMENT: Air
CRACK PLANE ORIENTATION: ---

TEST DATE: 07-10-1992
MODULUS: 16.5 MSI
HUMIDITY: 45%

SPECIMEN MEASUREMENTS:

THICKNESS (B) = 0.100 IN.
WIDTH (W) = 1.000 IN.
NOTCH (An) = 0.193 IN.

SIDE 1 (A1) = 0.271 IN.
SIDE 2 (A2) = 0.265 IN.

PRECRACKING SUMMARY:

STRESS INTENSITY FACTOR RANGE = 7.081 KSI(SQRT.IN.)
STRESS RATIO = .1

TEST PARAMETERS:

MAXIMUM LOAD = 150 LBS.
LOAD RANGE = 135 LBS.
STRESS RATIO = .1

MINIMUM LOAD = 15 LBS.
FREQUENCY = .1-20 Hertz
WAVEFORM = SINE

CRACK CURVATURE CORRECTION:

PRECRACK FRONT: NONE REQUIRED
TERMINAL FATIGUE CRACK: NONE REQUIRED

VALIDITY CHECKS PER ASTM E647-86:

1. DIFFERENCE BETWEEN A1 AND A2 MUST BE < 0.25 * B — VALID
   DIFFERENCE = 0.006 IN. 0.25 * B = .025
2. THE CRACK MUST NOT DEVIATE MORE THAN 5% FROM THE PLANE OF SYMMETRY — VALID

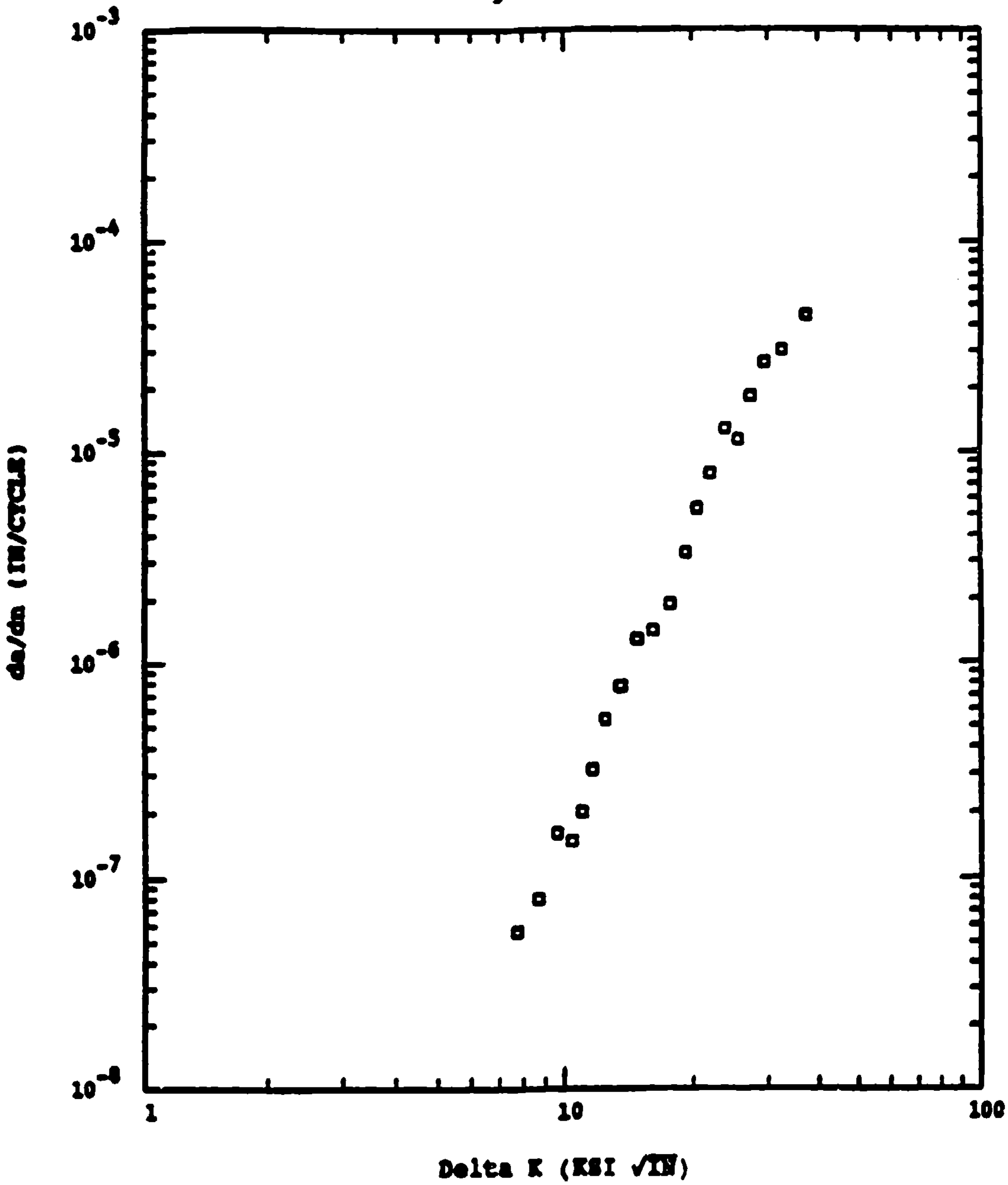
ALL VALIDITY CHECKS ARE VALID.

Table 6: Fatigue Crack Growth Test Results for Sample 4P-02

Pmax (LBS)	EB(V/P)	a (IN)	N	da (IN)	dN	da/dN (IN/CYCLE)	delta K (KSI √IN)	Ick
		0.3259	851003					
151	27.71	0.3293	861007	0.0482	860337	5.6020E-08	7.74	0
151	32.55	0.3725	1401003	0.0432	539996	8.0009E-08	8.69	0
150	37.36	0.4081	1621009	0.0356	220006	1.6184E-07	9.63	0
150	40.57	0.4289	1761001	0.0208	139992	1.4830E-07	10.42	0
150	44.05	0.4490	1861011	0.0202	100010	2.0168E-07	11.00	0
150	48.35	0.4713	1931000	0.0222	69989	3.1743E-07	11.67	0
149	54.34	0.4982	1981015	0.0269	50015	5.3879E-07	12.51	0
150	61.44	0.5253	2016010	0.0271	34995	7.7528E-07	13.61	0
149	69.44	0.5511	2036006	0.0258	19996	1.2903E-06	14.84	0
149	77.20	0.5725	2051003	0.0213	14997	1.4234E-06	16.09	0
149	89.68	0.6011	2066001	0.0286	14998	1.9093E-06	17.62	0
149	98.25	0.6177	2071010	0.0165	5009	3.3033E-06	19.24	0
149	106.03	0.6310	2073500	0.0133	2490	5.3478E-06	20.58	0
149	119.31	0.6507	2076005	0.0197	2505	7.8763E-06	22.04	0
145	132.05	0.6668	2077256	0.0161	1251	1.2881E-05	23.88	0
149	145.08	0.6811	2078501	0.0143	1245	1.1475E-05	25.62	0
149	157.03	0.6927	2079127	0.0115	626	1.8423E-05	27.36	1
149	177.20	0.7095	2079755	0.0168	628	2.6758E-05	29.46	1
150	205.07	0.7285	2080378	0.0191	623	3.0589E-05	32.44	1
150	259.53	0.7566	2081005	0.0281	627	4.4762E-05	37.22	1

An Ick value of 1 indicates that the data violates the specimen size requirments (w-a >= (4/pi)((kmax/ys)^2)

Figure No. 7



da/dn vs Delta K Graph for Sample 4P-02

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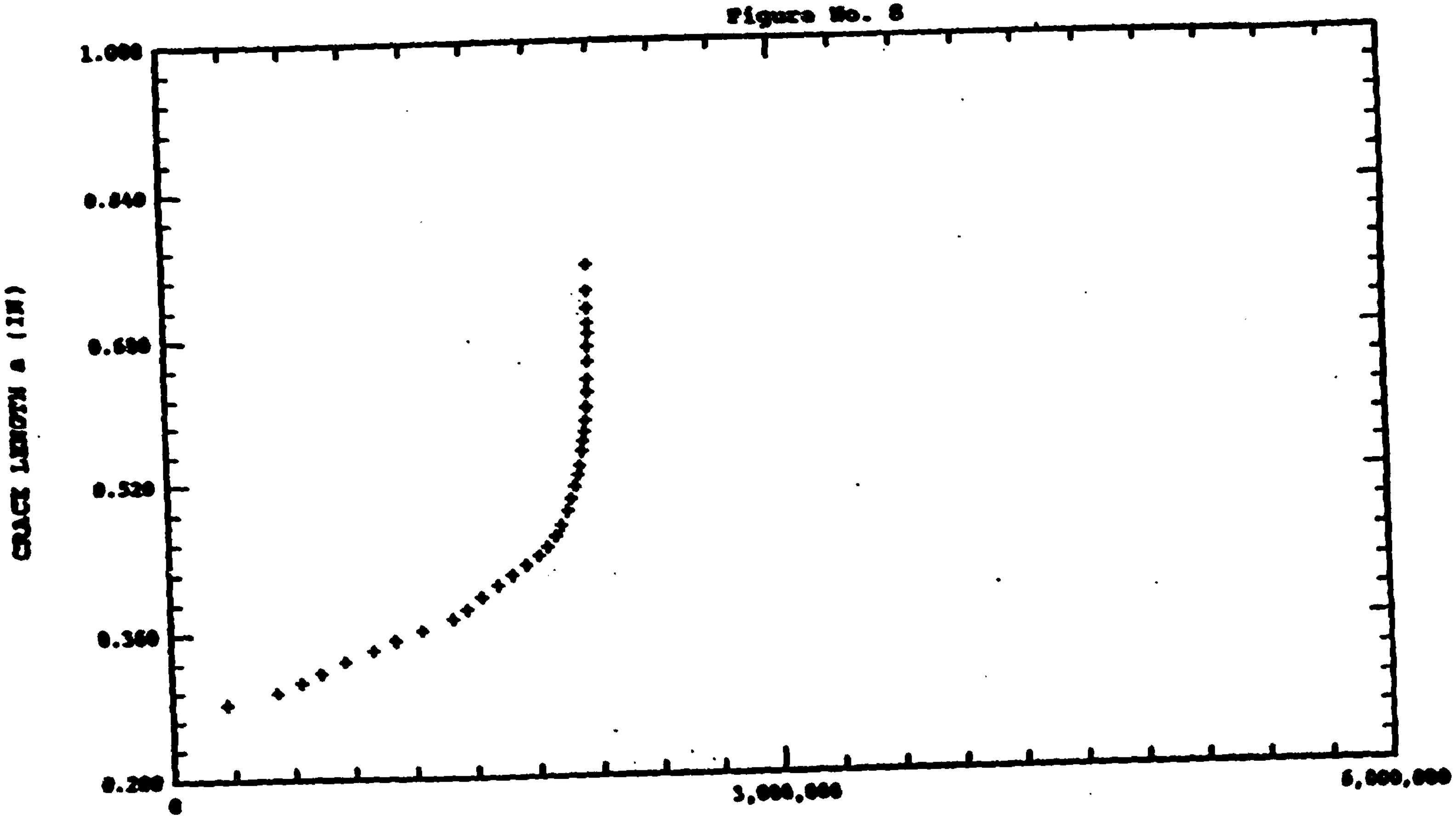
Figure No. 8



a vs n Graph for Sample 4P-02.

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Table 7: Fracture Toughness Per E399, Sample 4AA-01

FRACTURE TOUGHNESS TEST REPORT

PRELIMINARY INFORMATION:

SAMPLE: 4AA-01

ALLOY & TEMPER: TI 64
PRODUCT THICKNESS: 0.000
TEST TYPE & ORIENT: 0.400-C(T) N/A
TEST DATE: 920630
YIELD STR.(YS): 125.0 KSI

MATERIAL SPEC.: NONE

PRODUCT: NONE
LAB: 103983
TEST PLANE: T/2
TEST TEMP(°F): 75
MODULUS: 16.0 MSI

SPECIMEN MEASUREMENTS:

THICKNESS (B) = 0.226 IN.
WIDTH (W) = 0.799 IN.
AVE. CRACK LENGTH (A) = 0.386 IN.
FRACTURE APPEARANCE = 47% FRACTION OBLIQUE
HEIGHT (2H) = 0.960 IN.
TOTAL WIDTH (W1) = 1.030 IN.
NOTCH TO HOLE (H1) = 0.220 IN.

CRACK LENGTHS

SIDE 1 (A1) = 0.368 IN.
QUARTER POINT 1 (A2) = 0.383 IN.
CENTER POINT (A3) = 0.393 IN.
QUARTER POINT (A4) = 0.381 IN.
SIDE 2 (A5) = 0.377 IN.

FATIGUE PRECRACKING SUMMARY:

MAXIMUM FATIGUE LOAD = 300 LBS
KF (MAX) = 13.6 KSI(SQRT.IN.)

LOAD RATIO = +0.1
CYCLES = 133080

TEST RESULTS:

CANDIDATE LOAD (PQ) = 1555 LBS
KQ = 70.6 KSI(SQRT.IN.)
SPECIMEN STRENGTH RATIO = 1.928

MAXIMUM LOAD (PMAX) = 2345 LBS
K-RATE = 43.2 KSI (SQRT.IN)/MIN

VALIDITY CHECKS PER ASTM E399

1. B MUST BE > OR = R=2.5*(KQ/YS)**2 — INVALID
   B = 0.226 R = 0.797
2. A MUST BE > OR = R=2.5*(KQ/YS)**2 — INVALID
   A = 0.386 R = 0.797
3. PMAX/PQ MUST BE < OR = 1.10 — INVALID
   PMAX/PQ = 1.51
4. A/W MUST BE BETWEEN 0.45 AND 0.55 — VALID
   A/W = 0.48
5. DIFFERENCE BETWEEN ANY TWO OF A2,A3,A4 MUST BE < OR = .1*A — VALID
   MAX. DIFF = 0.012 0.10*A = 0.039
6. A1 AND A5 MUST BE BETWEEN 0.328 AND 0.444 — VALID
   A1 = 0.368 , A5 = 0.377
7. DIFFERENCE BETWEEN A1 AND A5 MUST BE < OR = .1*A — VALID
   DIFFERENCE = 0.009 0.10*A = 0.039
8. 0.60*KQ MUST BE > OR = KF(MAX) — VALID
   KF(MAX) = 13.6 KSI(SQRT.IN.) 0.6*KQ = 42.3 KSI(SQRT.IN.)
9. KF(MAX)/E MUST BE < OR = 0.002 — VALID
   KF(MAX)/E = 0.001
10. K-RATE MUST BE BETWEEN 30 AND 150 KSI(SQRT.IN.)/MIN — VALID
    K-RATE = 43 KSI (SQRT.IN.)/MIN
11. PRECRACK LENGTHS MUST BE > OR = 0.025*W OR 0.05 IN. — VALID
    0.025*W OR 0.050 = 0.050 IN. MIN. LENGTH = 0.050 IN.
12. FATIGUE PRECRACK PLANE MUST BE < OR = 10 DEG. — VALID
13. TEST CURVES INITIAL SLOPE MUST BE BETWEEN 0.7 AND 1.5 — VALID
    ACTUAL SLOPE = 1.3

***** TEST IS INVALID PER ASTM-E399 ; KQ = 70.6 KSI(SQRT.IN.) *****

Table 8: Fracture Toughness Per E399, Sample 4AC-01

FRACTURE TOUGHNESS TEST REPORT

PRELIMINARY INFORMATION:

REQ. NO.: NONE
SAMPLE: 4AC-01

ALLOY & TEMPER: TI 64
PRODUCT THICKNESS: 0.000
TEST TYPE & ORIENT: 0.400-C(T) N/A
TEST DATE: 920830
YIELD STR.(YS): 125.0 KSI

S. O. NO.: NONE
MATERIAL SPEC.: NONE

PRODUCT: NONE
LAB: 103983
TEST PLANE: T/2
TEST TEMP(°F): 73
MODULUS: 16.0 MSI

SPECIMEN MEASUREMENTS:

THICKNESS (B)	= 0.220 IN.
WIDTH (W)	= 0.79[illegible] IN.
AVE. CRACK LENGTH (A)	= 0.382 IN.
FRACTURE APPEARANCE	= 30% FRACTION OBLIQUE
HEIGHT (2H)	= 0.960 IN.
TOTAL WIDTH (W1)	= 1.000 IN.
NOTCH TO HOLE (H1)	= 0.220 IN.

CRACK LENGTHS

SIDE 1 (A1)	= 0.371 IN.
QUARTER POINT 1 (A2)	= 0.374 IN.
CENTER POINT (A3)	= 0.384 IN.
QUARTER POINT (A4)	= 0.399 IN.
SIDE 2 (A5)	= 0.376 IN.

FATIGUE PRECRACKING SUMMARY:

MAXIMUM FATIGUE LOAD	= 300 LBS	LOAD RATIO	= +0.1
KF (MAX)	= 13.8 KSI(SQRT.IN.)	CYCLES	= 276730

TEST RESULTS:

CANDIDATE LOAD (PQ)	= 1450 LBS	MAXIMUM LOAD (PMAX)	= 2060 LBS
KQ	= 66.8 KSI(SQRT.IN.)	K-RATE	= 44.0 KSI (SQRT.IN)/MIN
SPECIMEN STRENGTH RATIO	= 1.709		

VALIDITY CHECKS PER ASTM E399

Check	Result
1. B MUST BE > OR = R=2.5*(KQ/YS)**2 B = 0.220 R = 0.713	INVALID
2. A MUST BE > OR = R=2.5*(KQ/YS)**2 A = 0.382 R = 0.713	INVALID
3. PMAX/PQ MUST BE < OR = 1.10 PMAX/PQ = 1.42	INVALID
4. A/W MUST BE BETWEEN 0.45 AND 0.55 A/W = 0.48	VALID
5. DIFFERENCE BETWEEN ANY TWO OF A2,A3,A4 MUST BE < OR = .1*A MAX. DIFF = 0.025 0.10*A = 0.038	VALID
6. A1 AND A5 MUST BE BETWEEN 0.325 AND 0.439 A1 = 0.371 A5 = 0.376	VALID
7. DIFFERENCE BETWEEN A1 AND A5 MUST BE < OR = .1*A DIFFERENCE = 0.005 0.10*A = 0.038	VALID
8. 0.60*KQ MUST BE > OR = KF(MAX) KF(MAX) = 13.8 KSI(SQRT.IN.) 0.6*KQ = 40.1 KSI(SQRT.IN.)	VALID
9. KF(MAX)/E MUST BE < OR = 0.002 KF(MAX)/E = 0.001	VALID
10. K-RATE MUST BE BETWEEN 30 AND 150 KSI(SQRT.IN.)/MIN K-RATE = 44 KSI (SQRT.IN.)/MIN	VALID
11. PRECRACK LENGTHS MUST BE > OR = 0.025*W OR 0.05 IN. 0.025*W OR 0.050 = 0.050 IN. MIN. LENGTH = 0.053 IN.	VALID
12. FATIGUE PRECRACK PLANE MUST BE < OR = 10 DEG.	VALID
13. TEST CURVES INITIAL SLOPE MUST BE BETWEEN 0.7 AND 1.5 ACTUAL SLOPE = 1.2	VALID

***** TEST IS INVALID PER ASTM-E399 ; KQ = 66.8 KSI(SQRT.IN.) *****

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Table 9: Fracture toughness Per E399, Sample 4G-02

FRACTURE TOUGHNESS TEST REPORT

PRELIMINARY INFORMATION:

REQ. NO.: NONE
SAMPLE: 4G-02

ALLOY & TEMPER: TI 64
PRODUCT THICKNESS: 0.000
TEST TYPE & ORIENT: 0.400-C(T) N/A
TEST DATE: 920630
YIELD STR.(YS): 125.0 KSI

S. O. NO.: NONE
MATERIAL SPEC.: NONE

PRODUCT: NONE
LAB: 103983
TEST PLANE: T/2
TEST TEMP(°F): 73
MODULUS: 16.0 MSI

SPECIMEN MEASUREMENTS:

THICKNESS (B) = 0.246 IN.
WIDTH (W) = 0.799 IN.
AVE. CRACK LENGTH (A) = 0.379 IN.
FRACTURE APPEARANCE = 51% FRACTION OBLIQUE
HEIGHT (2H) = 0.960 IN.
TOTAL WIDTH (W1) = 1.000 IN.
NOTCH TO HOLE (H1) = 0.220 IN.

CRACK LENGTHS

SIDE 1 (A1) = 0.372 IN.
QUARTER POINT 1 (A2) = 0.379 IN.
CENTER POINT (A3) = 0.383 IN.
QUARTER POINT (A4) = 0.376 IN.
SIDE 2 (A5) = 0.372 IN.

FATIGUE PRECRACKING SUMMARY:

MAXIMUM FATIGUE LOAD = 300 LBS
KF (MAX) = 12.2 KSI(SQRT.IN.)

LOAD RATIO = +0.1
CYCLES = 181460

TEST RESULTS:

CANDIDATE LOAD (PQ) = 1720 LBS
KQ = 70.0 KSI(SQRT.IN.)
SPECIMEN STRENGTH RATIO = 1.774

MAXIMUM LOAD (PMAX) = 2430 LBS
K-RATE = 39.1 KSI (SQRT.IN)/MIN

VALIDITY CHECKS PER ASTM E399

1. B MUST BE > OR = R=2.5*(KQ/YS)**2 — **INVALID**
   B = 0.246 R = 0.785
2. A MUST BE > OR = R=2.5*(KQ/YS)**2 — **INVALID**
   A = 0.379 R = 0.785
3. PMAX/PQ MUST BE < OR = 1.10 — **INVALID**
   PMAX/PQ = 1.41
4. A/W MUST BE BETWEEN 0.45 AND 0.55 — VALID
   A/W = 0.47
5. DIFFERENCE BETWEEN ANY TWO OF A2,A3,A4 MUST BE < OR = .1*A — VALID
   MAX. DIFF = 0.007 0.10*A = 0.038
6. A1 AND A5 MUST BE BETWEEN 0.322 AND 0.436 — VALID
   A1 = 0.372 A5 = 0.372
7. DIFFERENCE BETWEEN A1 AND A5 MUST BE < OR = .1*A — VALID
   DIFFERENCE = 0.000 0.10*A = 0.038
8. 0.60*KQ MUST BE > OR = KF(MAX) — VALID
   KF(MAX) = 12.2 KSI(SQRT.IN.) 0.6*KQ = 42.0 KSI(SQRT.IN.)
9. KF(MAX)/E MUST BE < OR = 0.002 — VALID
   KF(MAX)/E = 0.001
10. K-RATE MUST BE BETWEEN 30 AND 150 KSI(SQRT.IN.)/MIN — VALID
    K-RATE = 39 KSI (SQRT.IN.)/MIN
11. PRECRACK LENGTHS MUST BE > OR = 0.025*W OR 0.05 IN. — VALID
    0.025*W OR 0.050 = 0.050 IN. MIN. LENGTH = 0.052 IN.
12. FATIGUE PRECRACK PLANE MUST BE < OR = 10 DEG. — VALID
13. TEST CURVES INITIAL SLOPE MUST BE BETWEEN 0.7 AND 1.5 — VALID
    ACTUAL SLOPE = 1.3

***** TEST IS INVALID PER ASTM-E399 ; KQ = 70.0 KSI(SQRT.IN.) *****

McDonnell Douglas Missile Systems Co.
Report No. 103983

Table 10: R-Curve Determination, Sample 4AA-01

COMPACT TENSION FRACTURE TOUGHNESS TEST REPORT (R-CURVE)

PRODUCT: NONE
MATERIAL SPEC.: NONE
LOT NUMBER: 4AA-01
TEST DATE: 920630
LOADING RATE: 951 LB/MIN.

TEST TYPE: 0.400-C(T)
LAB NO.: 103983
PRODUCT THICKNESS: 0.000
TEST PLANE: T/2
DIRECTION: N/A
43% RELATIVE HUMIDITY
YIELD STRENGTH: 125.0 KSI

ALLOY & TEMPER: TI 64
J.O. NO.: NONE
REC'D FROM: NONE

TESTED AT: +73 F

MODULUS: 16.0 MSI

AI = 0.386 INCH
B = 0.120 INCH
W = 0.799 INCH

VL = 0.0140 INCH
PQL = 1.120 KIPS
ADJUSTED E = 17919.79 KSI
KBCL = 50.7811
P25 = 2.215 KIPS
C25 = 1.6819048-03
AEE25 = 0.3434
FAW25 = 11.0844
BS25 = 11.044 KSI
AC25 = 0.436 INCH

KBCO = 50.7811

V25 = 0.0372 INCH
CEB25 = 60.225

KBC25 = 6.7430782-02

KMAX = 140.9 KSI SQRT. INCH
KR25 = 122.7 KSI SQRT. INCH

N	P	V	A	STRESS	K	DAP	RY	SECANT	ACHK	ICHK
1	1.120	0.014	0.386	5.544	50.616	0.000	0.026	0	0.209	0
2	1.555	0.020	0.394	7.698	73.405	0.008	0.053	5	0.437	1
3	1.830	0.025	0.404	9.059	88.299	0.018	0.075	10	[illegible]	1
4	2.040	0.030	0.414	10.096	103.157	0.028	0.107	15	0.857	1
5	2.205	0.034	0.425	10.915	115.677	0.039	0.136	20	[illegible]	1
6	2.215	0.037	0.436	11.044	122.686	0.050	0.153	25	[illegible]	1
7	2.323	0.041	0.447	11.509	135.910	0.061	0.183	30	1.481	1
8	2.345	0.044	0.456	11.608	140.856	0.071	0.202	34	1.617	1

REMAINING UNCRACKED LIGAMENT LENGTH IS LESS THAN (1.27324*(K/YLDSTR)**2)
LIMITING VALUES ARE K= [illegible] KSI SQRT(IN) LIGAMENT LENGTH = 0.3937 IN.

McDonnell Douglas Missile Systems Co.
Report No. 103983

Table 11: R-Curve Determination, Sample 4AC-01

COMPACT TENSION FRACTURE TOUGHNESS TEST REPORT (R-CURVE)

PRODUCT: NONE
MATERIAL SPEC.: NONE
LOT NUMBER: 4AC-01
TEST DATE: 920430
LOADING RATE: 936 LB/MIN.

TEST TYPE: 0.400-C(T)
LAB NO.: 103983
PRODUCT THICKNESS: 0.000
TEST PLANE: T/2
DIRECTION: N/A
AIR RELATIVE HUMIDITY
YIELD STRENGTH: 125.0 KSI

ALLOY & TEMPER: XX 64
J.O. NO.: NONE
REC'D FROM: NONE
TESTED AT: +75 F
MODULUS: 16.0 MSI

AI = 0.382 INCH
B = 0.380 INCH
W = 0.799 INCH

VL = 0.0150 INCH
PL = 1.055 KIPS
ADJUSTED E = 15974.07 KSI
EBCL = [illegible]
PC = 2.040 KIPS
CC = [illegible]E-05
[illegible] = [illegible]
[illegible] = [illegible]
SN = 10.475 KSI
AC = 0.429 INCH

EBCO = 49.8803

VC = 0.0279 INCH
CHECK = 64.763

EBC = 6.465756E-02

KMAX = 112.7 KSI SQRT. INCH

N	P	V	A	STRESS	K	DAF	KY	SECANT	ACHK	ICHK
1	1.055	0.015	0.382	5.365	48.399	0.000	0.024	0	0.191	0
2	1.430	[illegible]	[illegible]	7.374	[illegible]	[illegible]	0.048	5	[illegible]	0
3	1.720	0.027	0.400	8.747	84.209	0.018	0.072	10	0.578	1
4	[illegible]	0.031	0.410	[illegible]	[illegible]	[illegible]	0.095	15	0.750	1
5	2.020	[illegible]	0.421	10.273	107.157	[illegible]	0.117	20	[illegible]	1
6	2.040	0.036	0.429	10.475	112.743	0.046	0.130	23	1.036	1

1 = REMAINING UNCRACKED LIGAMENT LENGTH IS LESS THAN (1.27324*(K/YLDSTR)**2)
LIMITING VALUES ARE K= 71.09 KSI SQRT(IN) LIGAMENT LENGTH = 0.4118 IN.

Table 12: R-Curve Determination, Sample 4G-02

COMPACT TENSION FRACTURE TOUGHNESS TEST REPORT (R-CURVE)

TEST TYPE: 0.400-C(T)
LAB NO.: [illegible]
PRODUCT THICKNESS: 0.000
TEST PLANE: T/L
DIRECTION: N/A
AIR RELATIVE HUMIDITY
YIELD STRENGTH: 125.0 KSI

ALLOY & TEMPER: TI 64
J.O. NO.: NONE
REC'D FROM: NONE
TESTED AT: +75 F
MODULUS: 16.0 MSI

PRODUCT: NONE
MATERIAL SPEC.: NONE
LOT NUMBER: 4G-02
TEST DATE: 920430
LOADING RATE: 900 LB/MIN.

AI = 0.379 INCH
B = 0.346 INCH
W = 0.799 INCH

VL = 0.0111 INCH
PVL = 0.948 KIPS
ADJUSTED E = 17098.65 KSI
KDCL = 49.0878
P25 = 2.413 KIPS
C25 = 1.[illegible]E-05
AE25 = [illegible]
[illegible] = 10.[illegible]
[illegible] = 10.[illegible] KSI
AC25 = 0.430 INCH

KDCO = 49.0878

V25 = 0.0373 INCH
CHI25 = 60.810

KDC25 = 6.498535E-02

KMAX = 124.9 KSI SQRT. INCH
K25 = 118.6 KSI SQRT. INCH

N	P	V	A	STRESS	K	DAF	KY	SECANT	ACRK	ICRK
1	0.948	0.011	0.379	4.211	38.483	0.000	0.015	0	0.131	0
2	1.730	0.021	0.38[illegible]	7.[illegible]	73.0[illegible]	0.009	0.033	5	0.4[illegible]	1
3	1.943	0.027	0.39[illegible]	[illegible]	[illegible]	0.016	0.0[illegible]	10	0.6[illegible]	1
4	2.270	0.031	0.40[illegible]	10.[illegible]	101.[illegible]	0.02[illegible]	0.10[illegible]	15	0.83[illegible]	1
5	2.373	0.034	0.41[illegible]	10.[illegible]	111.[illegible]	0.0[illegible]	0.13[illegible]	20	1.01[illegible]	1
6	2.413	0.037	0.430	10.[illegible]	11[illegible]	0.050	0.15[illegible]	25	1.147	1
7	2.430	0.040	0.440	11.851	124.851	0.061	0.159	30	1.272	1

1 = REMAINING UNCRACKED LIGAMENT LENGTH IS LESS THAN (1.2732*(K/YLDSTR)**2)
LIMITING VALUES ARE K= 69.96 KSI SQRT(IN)   LIGAMENT LENGTH = 0.3969 IN.

U.S. GOVERNMENT PRINTING OFFICE 750-113

SUPPLEMENTARY

INFORMATION

DEPARTMENT OF THE AIR FORCE

WRIGHT LABORATORY (AFMC)
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

ERRATA - A264414

FROM: WL/MLSE Bldg 652 — 4 June 93
2179 Twelfth St Ste 1
Wright-Patterson AFB OH 45433-7718

SUBJ: Error in Report WL-TR-92-4090 "Use Of Titanium Castings Without a Casting Factor"

TO: Distribution List

1. Please note that an error has been found in the subject report on page 31. The error is in the derived properties; compression, bearing, and shear.

2. Attached is a corrected table to replace the one in error.

3. If you have any questions concerning this, the point of contact is Steven Thompson at (513) 255-5063.

Steven R. Thompson
Engineering and Design Data
Materials Engineering Branch
Systems Support Division

1 Atch
Distribution List

Mechanical & Physical Properties For
TI-64, Investment Cast

Specification			
Form		Investment Cast	
Temper		Annealed, HIP'd	
Thickness, or diameter, in			
Basis	Typical	B	A
Mechanical Properties			
F_{tu}, ksi	131	128	125
F_{ty}, ksi	125	123	120
F_{cy}, ksi			122
F_{su}, ksi			86
F_{bru}, ksi (e/D = 1.5)			212
F_{bry}, ksi (e/D = 1.5)			181
e, percent		5.5	
K_c, ksi•in$^{1/2}$			
E, 10^3 ksi		17	
E_c, 10^3 ksi			
G, 10^3 ksi			
m			
Physical Properties:			
w, lbs/in			
C, Btu/lb•F			
K, Btu/hr•ft•F			
a, 10^{-6}in/in.F			

Data source: Cast fins and step plates
Number of specimens: 115

FIGURE 17. SUMMARY OF ALLOWABLES FOR CAST TI-6AL-4V