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AFML-TR-68-268

AN INVESTIGATION OF THE GENERATION AND UTILIZATION OF ENGINEERING DATA ON WELDMENTS

D. W. Hood
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The Boeing Company

TECHNICAL REPORT AFML-TR-68-268
OCTOBER 1968

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Air Force Materials Laboratory
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

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FOREWORD

This report was prepared by The Boeing Company, Space Division, Materials and Processes, Seattle, Washington, under USAF Contract #F33(615)-67-C-1680, BPSN: 67(687381-738106-62405514). The contract was initiated under Project No. 7381, *Materials Application*, Task No. 738106, *Engineering and Design Data*. The program was administered under the direction of the Air Force Materials Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, with Mr. Marvin Knight (MAAE), Project Engineer.

This report includes work conducted between 1 May, 1967, and 15 August, 1968.

The work was conducted under the direction of E. E. Bauer, program manager, D. T. Lovell, technical leader, and D. W. Hood, principal investigator. Review of test properties and design strength analyses were conducted by T. W. Eichenberger of the Structural Allowables Unit, Missile and Information Systems Division. O. T. Ritchie of the Structural Allowables Unit provided technical direction and consultation. L. Albertin (Materials and Processes) and W. P. Haese (Structural Development) of the Space Division also provided support in the areas of welding and structural design considerations, respectively. The companies listed in Appendix B provided valuable support during the industrial survey portion of the program.

This report was released by the authors in October, 1968. The contractor's report number is D2-114287-1.

This technical report has been reviewed and is approved.

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ABSTRACT

Present industry methods of obtaining engineering data on weldments were reviewed through literature and industrial surveys. Serious lack of uniformity was found within the aerospace industry in the development and use of engineering design data. Difficulties in defining weldment characterization, primarily due to the absence of adequate government or industry-wide welding process specifications, were the major factors limiting industry-wide generation and the use of weldment design data. The determination of weldment design strengths from coupon-derived data, structural data, and other factors has resulted in many differences in design values. It was concluded from the literature and industrial surveys that properly characterized coupon-derived weldment design data was the most meaningful approach in establishing and presenting data that would have industry-wide usefulness. It was also evident that in using coupon-derived weldment design data, a correlation factor must be established for each specific structural component. Guidelines for the generation and presentation of weldment design data were developed. These guidelines were used in a model test program in which design data on 6061 aluminum and Ti-6Al-4V titanium alloy weldments were obtained. Coupon-derived data was statistically treated to determine the minimum weld strength for the two alloys. Significant welding variables and conditions were identified. Manual repair welding was the most significant variable which affected the weldment design strength. The correlation between coupon data and structure was demonstrated by testing welded tubes and pressure vessels. The test program effectively demonstrated the validity of the guidelines.

Based on the surveys and the weldment data obtained in this program, recommendations are made to include the guidelines for the generation and utilization of engineering data on weldments in *Mil-Hdbk-5---Guidelines for Presentation of Data,* AFML-TR-66-386, February, 1967.

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SECTION I

INTRODUCTION

The major objective of this program was to recommend standardized procedures for the generation and presentation of engineering data on weldments. This objective was accomplished in two phases: (1) a review and analysis of present industry techniques resulting in recommended procedures; and (2) a verification of these recommended procedures by weldment evaluation.

Within the aircraft and aerospace industry, the present status of engineering data on weldments is surprisingly behind the comparable technology for general metallic materials and mechanically fastened joints. Considering the many applications of welding in aircraft, missile, booster, and spacecraft hardware, this lack of industry data is not consistent with the quantity of development and production being conducted. The specific reasons for the scarcity of engineering data are numerous but can be largely attributed to nonstandardized practices in welding procedures, weldment evaluation, data treatment and presentation, and ultimate use of data.

Mil-Hdbk-5 is an example of this lack of data on weldments. In Section 8.2 on welded joints, only two pages are devoted to the subject which present limited data on low alloy steels. Very few other handbook-type publications present data on weldments; if presented at all, it is generally referred to as "typical" and is not readily interpreted or directly useful in design.

With the increasing need for lighter efficient structures joined by welding, it is highly desirable to have industry-standardized weldment evaluation procedures. The benefits to be derived from standardization are manyfold; however, progress towards this goal has historically met with differences of opinion and lack of agreement. It was the intent of this program to examine the many facets of this problem and to recommend guidelines to increase the usefulness of weldment design data beyond the originator.

The program approach involved an initial review of the literature in conjunction with an industrial questionnaire and trip to obtain information on present and past practices used in the generation, treatment, and presentation of engineering data on weldments. This necessarily required consideration of welding technology, material and process specifications, inspection methods, acceptance criteria, testing techniques, data analyses, design strength determination, and design use of data. After compilation and analysis of the material, preliminary recommended guidelines were developed for the procedures necessary to obtain standardized weldment design data. As a final program phase a model testing program, based upon the guidelines, was conducted to determine design data for representative alloys and process conditions. Results of this testing program were used to update the preliminary guidelines.

The order of presentation in this report is as follows:

- Aerospace Industry Welding
- Literature Survey
- Industrial Survey
- Considerations in the Development of Weldment Design Data
- Recommended Guidelines
- Verification Testing Program
- Conclusions
- Recommendations

SECTION II

AEROSPACE INDUSTRY WELDING

For the purposes of background and continuity in this report, the following discussion of welding within the aerospace industry is presented.

The weight and reliability aspects of the aerospace industry influence weldment utilization by requiring refined techniques. These techniques apply to welding development, process specifications, inspection methods, design data generation, use of design data, and ultimately production welding. Throughout these various aspects of welding implementation the most refined methods are utilized in order to arrive at an optimum weight structure of known reliability. This is readily observed by comparing the stringent and detailed welding process specifications used in the aerospace industry with those of other industries. Therefore, it is not surprising that the methods of engineering data generation and utilization are relatively complex and involve many detailed considerations.

In the design of general aerospace structures, data of the type presented in Mil-Hdbk-5 [1] is normally used. To be consistent with this established policy, it is necessary to develop a similar approach to the generation of weldment data.

As a result of the initial efforts on the program, it was apparent that a rational approach to generation and utilization of weldment data hinges on a clear definition of weldment design strength. In many if not most cases, various considerations relating to welded structure, i.e., residual and discontinuity stresses, biaxiality, and undetected flaws, are incorporated in the weldment design strength. This is a major source of discrepancy and disagreement among various organizations and their respective design strengths for particular alloys and welding processes.

To establish a firm understanding of weldment design strength generation, the overall sequence of events from welding development to structural design must be reviewed. A sequence of events similar to that shown in Figure 1 is followed to various degrees in developing design data for welding applications. These major events involve welding development, specification establishment, weldment evaluation, data analysis, design strength determination, and design usage.

It is assumed that a given population of weldments will be produced as a result of adherence to specific procedures and controls established in the pertinent specification and design procedures. The next step then is determination of engineering property data for the weldments produced. Reference to Figure 1 shows that both coupon and structure-type testing may be involved in determining the weldment design strength. This intermixing of coupon and structural test results to determine proper design strength is a practice used within the industry to various degrees. It is also seen as the crux of the problem in developing a rational approach to weldment design. In the many other fields of structural design involving castings, forgings, mechanically fastened joints, and fatigue-critical structure, a definite distinction is made between

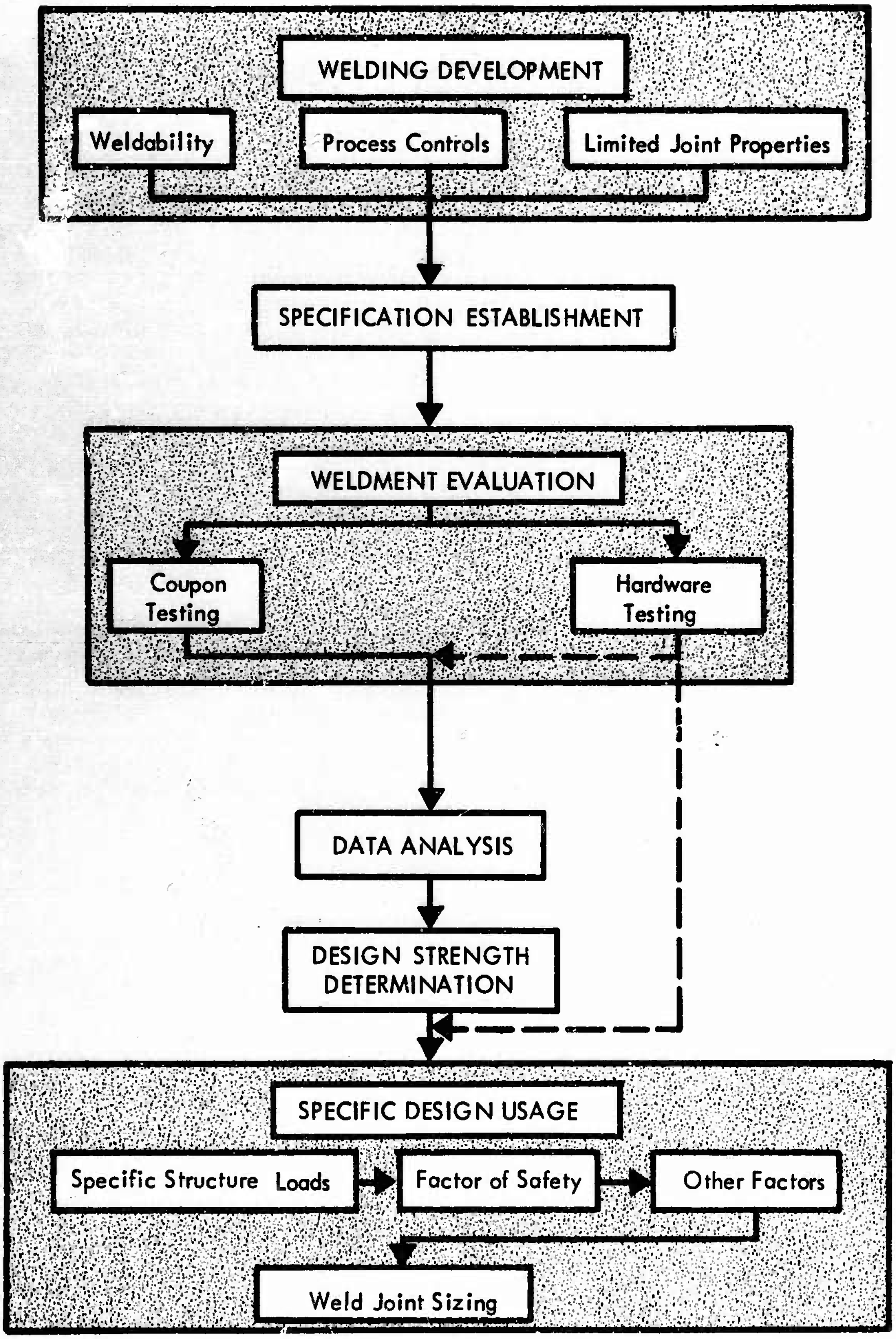


Figure 1: SEQUENCE OF WELDMENT DESIGN CONSIDERATIONS

design strength based on coupon results and the additional factors that must be considered in translation of these coupon results into structural design. This is evidenced by the design strengths published in Mil-Hdbk-5, which are based on test coupon results.

Taking this approach in weldment evaluation overcomes the primary difficulty in developing a rational technique for establishing design strengths. Weldments may be evaluated by standard coupon testing techniques and the resultant data treated statistically to arrive at design strengths of known reliability. These results can then be translated, by applying the required factors or considerations, into structural design for the particular application and state of stress involved. Although this basic approach contains many assumptions, as has been described, the program goal was to verify the applicability of this philosophy to the development and utilization of engineering data on weldments.

SECTION III

LITERATURE SURVEY

The purpose of the literature survey was to obtain information on the methods used by industry to derive fusion weld design information. Included were types of tests utilized, test coupon configurations, data analysis methods, and methods of presenting engineering data on weldments.

The literature survey consisted of computerized searches of NASA and DDC files as well as manual searching of pertinent reports, periodicals, and indexes. Abstracts were written for all pertinent articles. A listing of the sources searched and abstracts obtained is included in Appendix A.

Very little published information is available which deals directly with the topic of design data determination for weldments. The data generally presented in the literature is not intended for design use, but rather is in association with a specific investigation of welding variables or conditions. In order for published data on weldments to be quantitatively useful as design data, each aspect of data generation must be fully delineated. This would include processing and welding variables, inspection and acceptance criteria, testing methods, and data analysis methods. Since industry-accepted standards governing each of these aspects have not been established, it is cumbersome and beyond the scope of this investigation to provide all the necessary associated information. Therefore, the literature survey summary discussed herein is an interpretive analysis of the general factors which have limited the publishing of such data.

In the light of present knowledge and of recent investigative trends, the review pointed up several factors judged as limiting progress toward adoption of standardized procedures for accurately determining weldment design properties. Most of these factors also were encountered in the discussions during the later industry surveys.

The major factors are considered to be:

1) The problem is extremely complex, and the many affected organizations have seemingly differing requirements.

2) Few industry-wide standards, specifications, or codes on welding exist that are not out of date. They are seldom applicable to the current requirement for creating highly efficient designs.

3) Industry has not always agreed on identification of weldment properties that are most significant to a basic performance criterion and relatable to diverse design problems.

4) There is yet inadequate understanding of size and geometric effects necessary to scale up from coupon tests to subsize assemblies and to full-size components.

5) No overall criteria have had general industry acceptance for effectively establishing and identifying design strengths as determined from welded coupon tests.

In presenting design data for weldments it has been difficult and cumbersome to provide the associated information which describes the population of weldments the data represents. This includes a definitive description of welding conditions and range of variables, weldment quality and means of assessing quality, testing procedures, and data analysis methods.

The present status of industry-wide standards and specifications applicable to aerospace welding is far behind industry technology. Weldments are most frequently produced utilizing corporate specifications that are significantly more detailed and stringent than military specifications. Because no military or industry-wide specifications are available, meaningful definition of welding conditions and weldment quality for design data presentation is very difficult.

The type of design data required by industry has not been well identified. This in turn has complicated establishment of quality-level and acceptance criteria for weldments. That presently existing acceptance criteria are largely arbitrary is apparent: most are invariant with respect to design service requirements. For example, it is fairly obvious that the effect of surface porosity will vary widely depending on whether static yielding or high cycle fatigue cracking is the failure criterion. The influence of a sharper discontinuity will also vary with the state of stress. Yet acceptance standards have seldom been derived or selected on the basis of specific service requirements.

Since a uniform practice concerning design data for weldments has not been established, very little progress has been made in establishing procedures for using coupon test results in the design of welded structures. In most cases structural testing of weldments to demonstrate and confirm design practices has been a necessity.

Coupon testing methods, such as the generally accepted transverse uniaxial welded tensile coupons, appear to have reasonable industry agreement for most typical applications. However, agreement on what should be the preferred method to process and identify coupon-generated design strength data has been a major deficiency within industry, as witnessed by the inability of the Mil-Hdbk-5 committee to include 6061 welded design strengths in the handbook in 1961.

The more recent literature is revealing increasing awareness and attention to many of these problems. Design analyses are being refined, statistical methods are being applied more frequently in test planning and data analysis, nondestructive tests are being applied to the special problems of weld inspection and correlated with test results, and fracture mechanics principles and fatigue studies are being employed to quantitatively evaluate the effects of flaws in establishing realistic acceptance criteria. All of these are creating an increasing capability to develop improved weld design allowables.

SECTION IV

INDUSTRIAL SURVEY

The objective of the industrial surveys was to determine the practices concerning weldments which are currently used within the industry. This involved both industrial tour and questionnaire approaches.

INDUSTRIAL TOURS

A total of 16 organizations was visited during the industrial tours as summarized in Appendix B. These were selected as a representative cross section of the aircraft and aerospace industry.

In conducting the survey tours, each organization was initially contacted by telephone, followed by a letter describing the intent and purpose of the survey. In all cases the survey was well received and willingness to cooperate in the survey was evident.

It was obvious that all aspects of the program could not be discussed in detail during the industrial tours. This would have required a prohibitive amount of preparation on the part of each organization visited, as well as considerably more time for discussion. In addition, detailed data for specific weldment applications were considered proprietary in many cases. For these reasons, tour discussions were directed toward establishing the overall approach to weldment evaluation and utilization.

During the discussions considerable latitude in emphasis and sequence of topics was allowed, depending upon those present and the nature of the welding applications involved. However, the following items were reviewed in each case:

1) Summary of the contract objectives and approach;

2) Approach to weldments used at the organization visited;

3) Approaches applicable to the program;

4) Specific or typical applications.

Each of the above items was discussed with regard to the general approach, welding development, welding process, process control, engineering properties of weldments, test methods, design strength determination, design data presentation, and design use of weldment data. A summary of the industrial tours is given in the following sections for each of the above topics.

General Approach

The following statements summarize the opinions of industry in regard to their general approaches to welding application:

1) Welding is avoided in basic design if at all possible.

2) When welding is used, as conservative an approach as possible is taken.

3) A "standard" approach to weldment utilization is usually not used. Each application is treated specifically using slightly different approaches depending on the circumstances involved.

4) Verification hardware or testing of simulated structures is usually involved in each application.

The approach taken in evaluating and using weldments is necessarily linked to the degree of sophistication dictated by the design requirements. Many applications discussed were not weight-critical and could be readily designed using a very conservative approach with typical or literature-supplied design properties. In contrast, the more critical structure required a refined approach, which included consideration of all of the known variables and their effect on design properties. Discussion was directed toward these latter approaches for application to this program.

Welding Development

In all cases involving new materials, welding processes, or designs, welding development was required in order to gain experience and familiarity with the particular application being considered. During this initial stage, optimized procedures are developed, and the process variables of concern are established. This is accomplished by welding experimentation and evaluation of the resulting weldment properties. Test methods include both weldability and engineering property determination for the ranges of variables selected.

Although the object of the majority of welding development studies was not the generation of design strength properties, considerable data was obtained concerning weldability and sensitivity of weldment properties to a wide range of process and weldment character variations. This information was used during later weldment design to aid in selection of appropriate degrees of conservatism or weldment design factors. These test data for properties such as cracking tendency and bend ductility are not used or presented as design properties, but to influence eventual design in a qualitative or experience factor fashion.

Welding Process

The majority of welding is accomplished with the gas tungsten arc (GTA) process. This is attributed to the preponderance of thin-gage weldments and high-quality requirements of the industry. Gas metal arc (GMA) welding is the second most common process and is used for heavier-gage welding where deposition rates become more important. Of the newer processes, electron beam welding (EBW) is finding increased acceptance and will be more frequently used as industry experience is gained.

Process Control

Corporate, rather than military, specifications are normally used for process control. This is necessary due to the laxity of process requirements, absence of specific weldment discontinuity levels, and inadequate stipulation of inspection methods in current military specifications.

It was unanimously agreed that adequate specifications common to industry were required prior to the development of industry-wide engineering data. The other alternative to this requirement would be presentation of the pertinent processing and weldment quality information in association with the engineering data. Although this is a major obstacle to establishing industry-wide design properties for weldments, it was not the intent of this survey to resolve it but rather to recognize it, briefly discuss it, and then assume that adequate specifications could be provided.

Engineering Properties of Weldments

The two types of engineering properties of weldments are those concerned with weldability and those generally termed design properties. Throughout industry, various types of weldability testing are conducted and a significant quantity of data obtained. However, this type of testing and the use of the resulting data is qualitative. For this reason the major concern of the survey was with the more definitive design properties.

The primary design property used for weldments was transverse uniaxial tensile ultimate strength. Even in situations where other properties dictated final design, ultimate strength was used in initial sizing or stress checking. The many other properties such as longitudinal uniaxial tensile, shear, fatigue behavior, tensile yield strength, notched tensile strength, and fracture toughness were less frequently used.

Test Methods

The test methods used for weldments generally follow those applied to base metal. The testing procedures are usually those of Federal Test Method 151 or ASTM. Specimen configurations are not, however, clearly established within the industry. In the case of static tensile specimens, rigid requirements for thickness-to-width ratios are not followed. In the case of butt welds in sheet material, the most frequently used specimen width minimum was 0.5 inch. However, in several instances a minimum of 0.75 inch was preferred. As material gage increases, this problem becomes more difficult, and less agreement was found.

In regard to the overall objectives of this program, it was felt by many of the organizations contacted that test coupon configuration and test methods were the two facets of welding that could be most readily and most desirably standardized within the industry.

Design Strength Determination

It was generally agreed that the most desirable method of test data treatment was the statistical approach. However, in actual practice there was not generally sufficient data available for a comprehensive analysis of variables and determination of extensive design data. This limitation of available data is a major factor in the use of "experience factors" in establishing design strengths.

The approaches used for determining tensile ultimate design strengths of a typical butt weld included the following:

1) Annealed strength of base metal;

2) Application of factors ranging from 0.5 to 1.0 to mean, minimum or statistically derived minimum results;

3) Statistical determination, usually 99% probability and 95% confidence.

It should be reemphasized that the type of application and availability of data were major contributors to the diversity of approaches used in the treatment of data.

Design Data Presentation

The method of presenting design data was not uniform within industry. In cases where extensive welding was used, data was presented in graphic form, usually showing effect-of-temperature curves for mean or typical and statistical minimum or minimum design strength. In instances where data was obtained for specific applications, design strengths were presented in tabular form. In all instances the design data was presented with references to particular processing specifications and other pertinent limiting variables.

Design Use of Weldment Data

The design use of data on weldments concerns the generally proprietary aspect of the survey, and for this reason only limited information was obtained. This topic was discussed in general rather than specific corporate examples.

From the designer's standpoint, weldments were treated as conservatively as possible. This results in the application of additional factors of experience, which may or may not have been considered in derivation of the design strength.

The use of tensile yield strength in design was not agreed upon. Although design requirements are established for the yielding behavior of structure, these requirements are usually overlooked or erroneously treated in the case of weldments. Despite their somewhat arbitrary usage, yield strengths of weldments measured over a 2-inch gage length are commonly obtained in conjunction with ultimate tensile strength determinations.

Fracture toughness data and its use as a design property for weldments is not well advanced in industry. Most, if not all, organizations are presently obtaining fracture toughness data for weldments and expect this property to find increasing usage. However, these data are not currently termed or used as design properties.

In summary, the industrial tours definitely indicated that a serious lack of uniformity exists within the industry with regard to development and utilization of engineering data on weldments.

INDUSTRIAL SURVEY QUESTIONNAIRE

To obtain additional detailed information on the practices currently used within the aerospace industry, an industrial survey was made.

Surveying Method

Fifty-four organizations concerned with aircraft and aerospace welding were selected and polled. These organizations included aircraft and aerospace manufacturers, government agencies, material producers, research organizations, universities, and welding equipment manufacturers. Organizations responding to the questionnaire are listed in Appendix B.

The industrial survey questionnaire used is included in Appendix B. The questionnaire covered five areas of interest: (1) tensile coupon configuration for design strength determinations, (2) tensile testing methods, (3) determination of fracture toughness parameters for design purposes, (4) specification of welding variables in data generation, and (5) establishment of design allowables. The response to the survey is summarized below.

		Response Summary		
Type of Organization	Polled	No Reply	Acknowledgment*	Reply**
Aircraft and Aerospace	27	6	4	17
Government Agencies	10	4	3	3
Material Producers	9	1	-	8
Research Organizations	3	2	1	-
Universities	3	3	-	-
Welding Equipment Mfgs	2	-	-	-
Totals	54	16	8	30

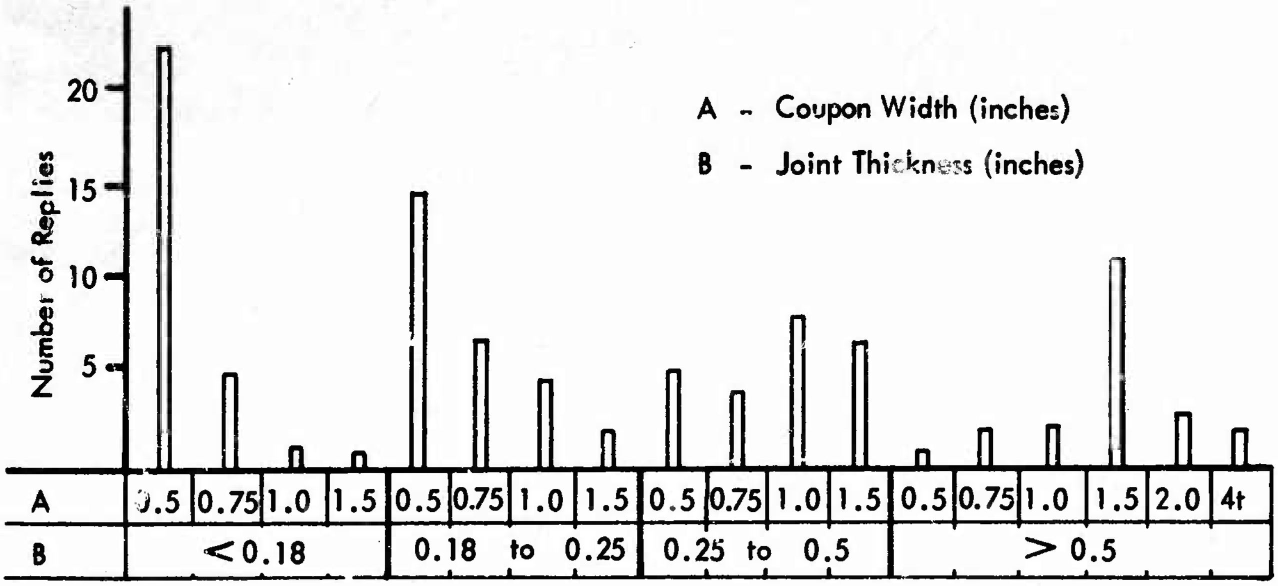
* Questionnaire received, but unable to provide meaningful answers.
** Full and partial replies are shown.

Replies useful to the survey were obtained from 55% of the organizations polled. Generally, a good response was obtained on Questionnaire Parts 1 and II, which dealt with tensile coupon configuration and tensile testing methods. Other sections received partial attention in some instances because the questions did not apply to the work of the organization polled. It was evident from the replies that welding data for design strengths was not generated by government agencies or material producers and was restricted to the aircraft and aerospace manufacturers. Materials producers and welding equipment manufacturers were involved in welding development programs. However, the data generated was of typical nature and is generally not used in the determination of design strengths. Several government agencies conduct welding activities, but in practically all cases the activities are not connected with the design and fabrication of end items. Other government agencies conduct their welding development work under contract and hence assume that the contracting organizations would respond to the questionnaire independently. The response to Questionnaire Part V, "Design Allowables Establishment," was rather limited and consisted exclusively of aircraft and aerospace industry organizations. An interest in the program results was indicated by all survey participants. The results of each survey part are presented below.

Results of the Questionnaire Survey

Questionnaire Item I: Tensile Coupon Configuration---Three tensile coupon configurations were recommended for standardization as a result of the Aerospace Research and Testing Committee Survey (ARTC Project 28-58). These tensile coupons were the transverse tensile, longitudinal tensile, and all-weld-metal tensile coupons. In the survey under this contract, the same coupon configurations were presented for review by the organizations polled in order to obtain information on: (1) the most used weld joint thickness/ test section width combination for various weld joint thicknesses, (2) the minimum ratio between test section width and length normally used in design allowables testing of flat transverse weld coupons, and (3) the weld joint thickness above which transverse round rather than flat coupons are used. In addition, the use of longitudinal weld tensile coupons and all-weld-metal tensile coupons in design strength determination were explored.

I.A Width and Thickness Recommendations---Questionnaire results on the tensile coupon width and thickness recommendations are summarized below.



The graph shows the predominant use of the following weld joint thickness/ test section width combinations:

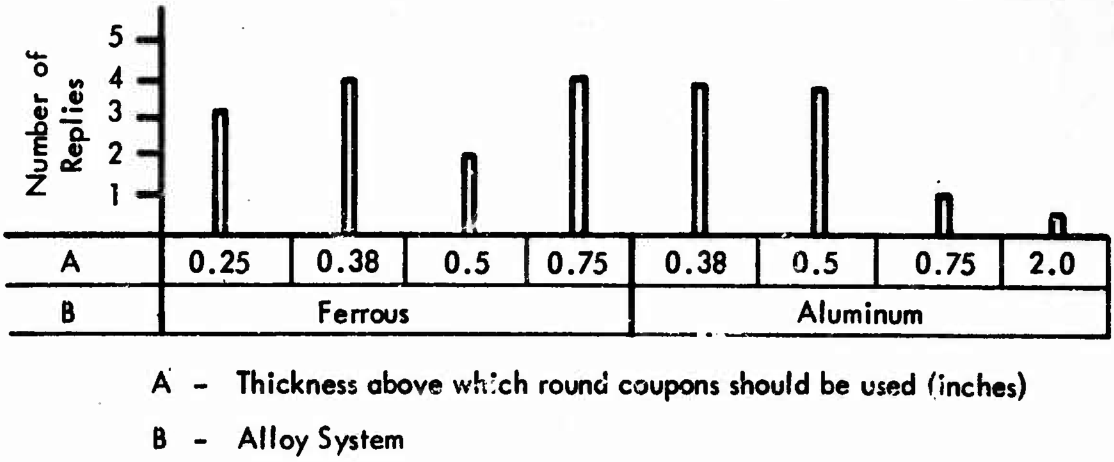
Weld Joint Thickness (inches)	Test Section Width (inches)
<0.18	0.5
0.18 to 0.25	0.5
0.25 to 0.50	1.0
>0.5	1.5

As joint thicknesses increase, less agreement is shown for a single coupon width. It should be noted that five replies indicated that the transverse flat coupon is not used for joints over 0.5 inch in thickness. For joints 0.18-inch thick and less, the 0.5-inch-wide coupon is definitely favored. Above this thickness the results are less uniform. The four-times-thickness minimum coupon width, which is recommended for base metal, is apparently not uniformly used for weldments. A two-times-thickness minimum is closer to the survey results as indicated by the replies to the 0.18- to 0.25- and 0.25- to 0.5-inch-thickness ranges.

I.B Test Section Width-to-Length Ratio---The ratio of coupon test section width to length was 1 to 4 in seventeen replies compared to ten that used other or no specific ratio. This is in agreement with base metal practices in which a recommended ratio of 1 to 4 is used.

I.C Determination of Longitudinal Design Strengths---Longitudinal design strengths were not determined by 64% of the organizations replying to this question. However, when this coupon was used, 75% of the organizations indicated that the ARTC-recommended coupon was satisfactory.

I.D Use of Round Transverse-Weld Coupon---Response to the transverse round rather than flat coupon question indicated a general lack of heavy-gage welding in the aerospace industry due to the limited number of replies. Thirteen organizations answered this question. The results given below show little agreement concerning the joint thickness above which round, rather than flat, coupons are used for aluminum and ferrous alloys.

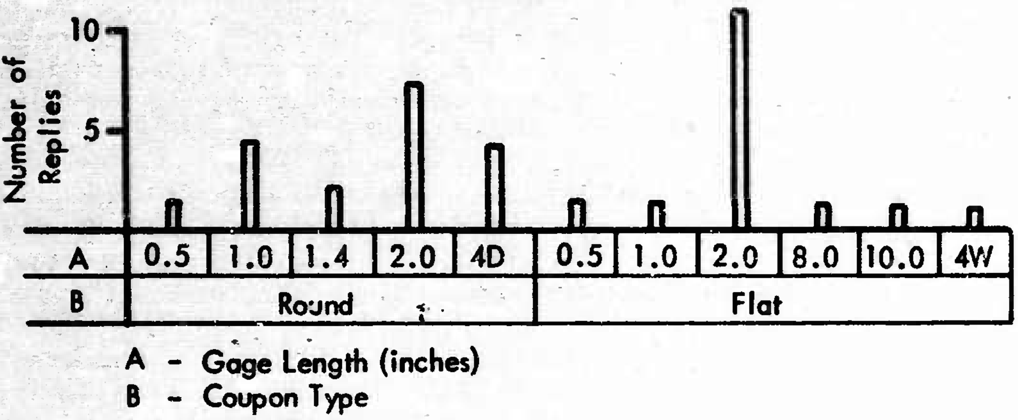


I.E Use of Round All-Weld-Metal Coupon---Round coupons for all-weld-metal evaluations were most frequently used in the 0.252- and 0.505-inch diameters. The ARTC-recommended coupon was acceptable to 88% of the organizations responding.

I.F Round Transverse-Weld Coupon Configuration---The transverse round coupon was acceptable to 80% of the organizations which used this type of specimen for design strength determinations. However, 50% of the organizations that responsed to the poll did not use the transverse round weld specimen in design strength determinations.

Questionnaire Item II: Tensile Testing Methods---Over 90% of the organizations responding utilized Federal Test Method 151 for tensile testing. The ASTM procedures were also shown in some instances.

Design strengths for transverse yield of butt joints were determined by 56% of the organizations that responded to this question. The number of respondents was 24. When this property is determined for 0.2% offset, the gage lengths used are shown below for round and flat coupons.



The results above indicate that the most frequently used gage length for determining the 0.2% offset yield strength is 2 inches for round and flat coupons.

Questionnaire Item III: Fracture Toughness---Replies to this survey question were received from 28 organizations. Fracture toughness (K_{Ic}) properties of weldments were determined by 50% of the organizations. When determined, the ASTM-recommended procedures were followed in 85% of the cases. However, only 14% of the organizations determined K_{Ic} properties or weldments for design use.

Questionnaire Item IV: Welding Variables---The question concerning welding variables was difficult in that a "specified" or "not specified" answer was required for each of the listed potential variables. Six of the 26 respondents indicated that all variables were specified. Although this would be the case in welding development or evaluations of a specific weldment, some of these variables would not normally be specified or controlled when welding is being conducted for general-application design strength determinations.

In essentially all replies, the base material variables of alloy, form, heat-treat condition, and thickness were specified. In addition, the following were also specified in more than 80% of the replies: welding process, welding method, joint preparation, filler material, postweld heat treatment, internal and external quality, weld reinforcement, visual and radiographic inspection methods, and minimum strength requirements. Among the variables not specified in more than 80% of the replies were welding sequence, heat input, restraint, and thermal control tooling.

A less clear distinction between specified and not specified variables was made for preheat, interpass temperature, alignment tooling, weld repair, and ultrasonic and penetrant inspection methods.

Questionnaire Item V: Design Allowable Establishment---The translation of weldment test results into design allowables is generally a difficult task, and the response to this question was naturally selective. Of the 30 questionnaire replies, only 15 organizations made some comment on how ultimate tensile strength weld allowables are derived for various design applications. Statistical test data representing 391 test results of 6061 Al-T4 or T6 weldments with statistical minimums of 99% probability and 95% confidence, 90% probability and 95% confidence, and other design strength choices were given as well as the type of application, which included general aircraft and aerospace structures, weight-critical hardware, and noncritical components. Organizations answering the question on the selection of a weld design allowable almost unanimously chose design values corresponding to 99% probability with 95% confidence. This choice was made not only for general aircraft and aerospace structures and weight-critical applications, but also for noncritical hardware. Two organizations chose the 90% probability 95% confidence minimum value for aerospace structures, and three organizations preferred values representing 85% of the 99% probability 95% confidence level for the same application. Of interest was the fact that no additional reduction factors were generally applied to the above statistical limit values in the design of structures. Only four organizations preferred to apply a reduction factor to the statistical minimum of 99% probability 95% confidence. Two organizations applied a reduction factor ranging from 5 to 20% to compensate for welding conditions not representative of the allowables program. One organization applied a common reduction factor of 15% for all types of applications involving welding, and another organization applied a reduction factor of 10% for all applications to account for the potential difference in welding between test coupons and structures.

Questionnaire Item VI: Design Allowables Establishment for Repair Welds---While there was some reluctance on the part of various organizations to comment on how welding design allowables are being used, there was even more reluctance to discuss how weld repairs are being treated in design. The importance of weld repairs in aerospace structures is evidenced by many service failures originating in repair areas. The mechanical properties are often adversely affected by repair welds, yet only seven organizations answered the weld repair question. Assuming that repair welding was evaluated by an extensive tensile testing program for 6061 aluminum alloy and that the mean ultimate strength of repair welds was 4 ksi lower than that for original weldments for coupons having two repairs, the question asked was: "What design allowable would be selected for general aircraft and aerospace usage?" Three of the seven organizations replying to this question derived the allowable by subtracting 4 ksi from the unrepaired statistical limit of 99% probability 95% confidence (22.9 - 4 = 18.9 ksi). One company applied a 0.85 factor to the unrepaired allowable of 85% of the mean test value (24 x 0.85 = 20.4 ksi). Another organization chose the original weld tensile strength value represented by 85% of the lowest test value, subtracted 4 ksi and multiplied by a factor of 0.85 (18.5 - 4 = 14.5 x 0.85 = 12.3 ksi). The remaining two organizations applied reduction factors of 0.8 and 0.85 to the 99% probability 95% confidence unrepaired statistical limit (22.9 x 0.8 = 18.3 ksi, 22.9 x 0.85 = 19.4 ksi).

The results indicated very little uniformity in handling weld repair allowables for practical design applications.

Conclusions and Recommendations

The industrial survey results illustrate the diversity of opinion expressed in the various detailed aspects of determining engineering properties of weldments. The significant results of the survey questionnaire were as follows, and were considered in the preparation of the guidelines for establishing engineering data on weldments:

1) There is considerable interest in establishing standardized procedures for the evaluation of weldments.

2) The flat transverse weld tensile coupon widths most frequently used for the various joint thicknesses are shown below.

Joint Thickness (inches)	Test Section Width (inches)
<0.18	0.5
0.18 to 0.25	0.5
0.25 to 0.50	1.0

3) The minimum ratio between test section width and length in flat transverse weld specimens should be 1 to 4.

4) Longitudinal tensile properties of weldments are not usually determined for design purposes.

5) There was no clear-cut agreement concerning the joint thickness above which round rather than flat tensile coupons should be used. However, a practical limit could be set at 0.5 inch.

6) Round coupons for all-weld-metal evaluations are most frequently used in diameters of 0.252 and 0.505 inch. The configuration recommended by the ARTC is acceptable for round coupons.

7) Federal Test Method 151 is most widely used in the aerospace industry for tensile testing.

8) Fracture toughness evaluations of weldments are frequently conducted. However, the fracture toughness parameter K_{Ic} is seldom used as a design property. Fracture toughness coupon configurations and procedures for testing are generally those recommended by ASTM.

9) Welding variables generally specified in generating design strength data are: alloy, form, heat-treat condition, material thickness, welding method, joint design, filler material, postweld heat treatment, external and internal quality, weld reinforcement, visual and radiographic inspection methods, and minimum strength requirements.

10) Welding variables normally not specified include: welding sequence, heat input, restraint, and thermal control cooling.

11) Derivation of design strengths by statistical methods resulting in known probability and confidence levels is the preferred method of establishing coupon-derived design strengths.

12) The 99% probability 95% confidence level is preferred as a design strength value.

13) Empirical reduction factors are not normally applied to the statistically derived weld-strength allowable.

14) When reduction factors are used in the design of weldments based on statistical design strength values, they account for: (1) potential differences in welding between test panels and structure; and (2) the welding conditions in the allowables program may not have been totally representative.

SECTION V

CONSIDERATIONS IN THE DEVELOPMENT OF WELDMENT DESIGN DATA

The analysis of the literature and industrial surveys revealed specific considerations that must be given to the development of weldment design data. An analysis of these considerations is given in this section. The major topics are: properties of weldments, population definition, data generation, data treatment, data presentation, and use of weldment data.

PROPERTIES OF WELDMENTS

Various mechanical tests are performed on welded engineering materials in order to obtain weld property data for design. Prior to discussing those weldment properties considered in design of aerospace hardware, it is advisable to briefly review the more important design approaches that have been employed.

Design Approaches to Aircraft and Aerospace Structures

An extensive review of various design approaches to engineering materials is given by Wessel, et al. [2] and will not be repeated here. The most frequently used design approach is that of stress analysis. In structural applications the stresses acting on a component are often not simple stresses, but are combined stresses acting in more than one direction. Therefore, it is important to determine the strength of materials in more than one direction and under environmental conditions expected in service. The stress analysis approach requires that the strength of the structural component be known or that a reasonable estimate of this strength can be made.

A structural member may fail for various reasons. This failure may occur by fracture of the member. In this case, the ultimate strength is used as a measure of the resistance to this type of failure. However, failure may also be considered to occur when permanent deformation exceeds a specified amount. In simple tension, these two modes of failure can be defined by an ultimate and yield stress that are found experimentally. In a similar manner, other useful design criteria such as fatigue, creep, and fracture toughness properties can be obtained experimentally. If the component contains notches or sharp flaws, the stress analysis must take this into account. Many properties are thus important in applying the stress analysis approach. These include tensile ultimate and yield strengths, shear strength, fatigue behavior, and behavior in the presence of various stress concentrations. A recent extension of the stress analysis approach is linear elastic fracture mechanics which becomes an important tool in design and material selection for the prevention of catastrophic fracture in the presence of stress concentrations and crack-like flaws.

The usefulness of fracture mechanics in design is well illustrated by the activities and publications of the ASTM Special Committee E24 on Fracture Testing of Metallic Materials [3]. The use of fracture toughness data and fracture mechanics analysis in predicting critical flaw sizes, evaluating subcritical flaw growth, and estimating structural life have been discussed in some detail in the fifth report of the ASTM Committee and in its book, *Fracture Toughness Testing and Its Application* [4]. Other recent descriptions of the application of fracture mechanics to design are contained in References 5 and 6. A brief description of the basis of the approach and its capabilities follow.

The fracture toughness of a material in the presence of a sharp flaw can be expressed as a material parameter. This parameter is usually described in terms of K_{Ic} (critical stress intensity factor, psi $\sqrt{in.}$), which is determined experimentally. Once properly determined, the fracture toughness parameters can be used to quantitatively evaluate the effects of specific discontinuities in specific situations. The possibility of flaws occurring in weldments makes this an important property for determination.

A second approach utilizes the fact that certain structural materials have a characteristic temperature below which they are susceptible to low stress brittle fracture in the presence of sharp defects and above which brittle fracture does not occur. Many tests are utilized to measure this transition temperature. Usually the particular technique or test employed to measure transition temperature is based in large part on the application of concern. Some of the more common tests used are the Charpy V-notch impact test, the "drop-weight" nil-ductility transition temperature test (NDT), and the explosion bulge test. Other more recently developed crack starter tests are the drop-weight tear and explosion tear tests.

This transition temperature approach is used quite extensively for comparing materials or material conditions. Its use in the aerospace and aircraft industry is limited because the approach lacks the basic quantitative nature that is required to solve specific problems. A preferred solution to the problem of fracture in the presence of defects is offered by the linear elastic fracture mechanics approach previously discussed.

Specific Properties of Weldments

Many properties of weldments are utilized in design within the aerospace industry. Transverse tensile ultimate strength is the most widely used and therefore most frequently determined in a routine manner. For this reason, particular emphasis has been placed on this property.

A description of: butt weld tensile strength, fillet weld shear strength, butt weld shear strength, fracture toughness, creep and stress rupture, and compression properties of weldments is presented below. Included in the description of each of these properties is a discussion of: test methods, data treatment, data presentation, and use of design data.

Other properties obtained from weldment testing including bend, impact, and cracking tendency have not been included due to their limited usefulness in design.

Butt Weld Tensile Strength

Test Methods---The uniaxial tension test is universally used to obtain a measure of the resistance of materials to tensile deformation and failure. The transverse weld flat sheet coupon is the most frequently used for weldment evaluation. Longitudinal-weld flat sheet coupons, round transverse-weld coupons, and round all-weld-metal coupons are used to a lesser degree. The choice of coupon type is related to the behavior exhibited by the particular weld being evaluated and the property of interest.

The transverse-weld coupon is used to determine overall joint strengths. The coupon fails in the zone having the lowest strength, and the properties determined are indicative of the joint efficiency. In the longitudinal-weld coupon, all zones in the joint are strained equally, and the results are used to evaluate the influence of weld-metal ductility on fracture initiation. All-weld-metal coupons are used to evaluate weld-metal strengths.

The availability of accepted test techniques for base-metal testing has resulted in their general application to weldment testing. Tensile tests of weld coupons are conducted per the requirements of established procedures as given in ASTM and federal test method standards. These standards control test equipment, data accuracy, and loading rates. The most used standards are those of Federal Test Method 151 and ASTM E8. While these standards are satisfactory for specifying test procedures, no equivalent standards are available for coupon configuration requirements for weldments. Considerable variation exists within the industry in definition of coupon dimensions.

Tensile properties which are a function of deformation such as yield strength and elongation may be strongly influenced by coupon configuration [7,8,9]. It is desirable to standarize coupon sizes and configurations to provide the basis for more legitimate data comparisons and development of uniform design properties. The definition of suitable weld coupon configurations is complicated by the widely varying properties that may exist across a weld joint.

Testing conducted using a fixed configuration permits measurement of average behavior over the defined gage section. This is most significant for weldments exhibiting largely differing properties from the base material. As a consequence of a study conducted by ARTC [10], recommended configurations were prepared for sheet-type transverse-weld, longitudinal-weld, and round all-weld-metal coupons. Several questions posed in the industrial survey questionnaire circulated during the current program dealt with the suitability of these configurations.

The replies indicated that test section width is generally increased for increased thickness of flat specimens, although few replies indicated a requirement for a minimum width-to-thickness (w/t) ratio. It was also determined that round transverse-weld coupons were used for thick joints, but the thickness at which this transition is made was inconsistent.

The effect of coupon w/t ratio is illustrated in Figure 2 for as-welded 2219-T87 alloy. Coupons of various widths were machined from full-thickness panels with weld beads removed. The three weld processes illustrate the effect of weld deposit zone width with the electron beam weld representing a very narrow fusion zone and the six-pass GTA weld representing a wide fusion zone. The ultimate strength and elongation increase with increasing width to a fairly constant value above w/t = 2. The trend of yield strength with coupon width is not as consistent, suggesting an interaction due to fusion zone width and gage length. Transverse-weld round coupons were included for comparison. The properties measured using the round coupons agreed most closely with those of the narrow flat coupons with nearly the same cross-sectional area.

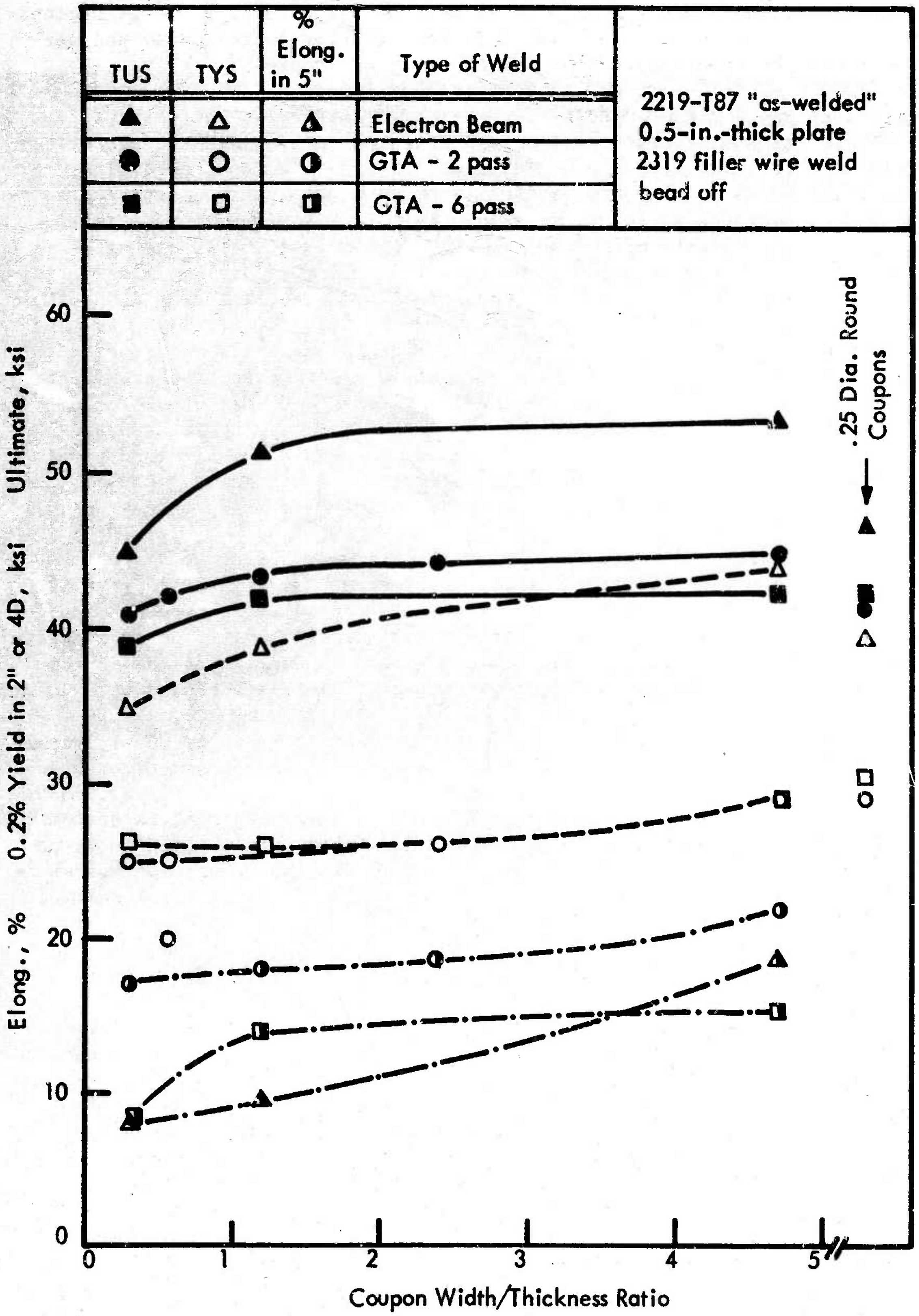


Figure 2: TENSILE COUPON CONFIGURATION EFFECTS

The configurations recommended for use are similar to those recommended by ARTC [10] with additional minimum width requirements for the flat coupons. Round specimens are recommended for use for joints over 0.5-inch thick. This is based on the need for a standardized transition thickness and the apparent acceptability as indicated from the industrial questionnaire. Sketches of these configurations are included in the guidelines.

Data Treatment---The data usually obtained from the uniaxial tension test includes the tensile ultimate strength, tensile yield strength, and percent elongation. These values, when obtained from a weldment test must be treated in a manner that will provide the necessary information in a form requiring a minimum amount of interpretation. The basic property directly obtained from the transverse-weld test is the ultimate failure stress which defines the property of the weakest zone in the weldment. Yield strength and elongation, determined using a defined gage length, represent an average behavior over this length. This is particularly important when the deformation characteristics differ significantly for the various weldment zones. For a fixed gage length, the proportion of weld-metal, heat-affected zone, and the unaffected base metal included within the test section may be altered significantly depending on weld process, joint design, material thickness, or heat input. Deformation can be concentrated in the local area of the weld deposit, and the apparent deformation as measured over a fixed gage length may be very low even though the weld metal itself is deforming drastically. This type of action is illustrated in Figure 3 for a 2219-T87 as-welded coupon, which was instrumented with strain gages to examine the local deformation characteristics. The large differences between the 0.2% offset yield strength for the 2-inch gage length, heat-affected zone, and weld metal are quite evident. A study by Alcoa Research Laboratories [11] shows a difference of up to 30% in the indicated yield strength of as-welded 0.25-inch-thick 6061-T6 when measured over gage lengths from 0.25 to 10 inches.

The treatment of transverse-weld tensile data is usually concentrated on the tensile ultimate strength. Nearly half of the organizations polled during this program do not consider yield strength as a design property. The analysis of transverse-weld tensile data should be conducted on data grouped so as to recognize the significant parameters acting. Development of design strength values should include analysis sufficient to define these parameters and their limits.

The longitudinal-weld tensile test was not used for development of design strengths by the majority of those replying to the industrial survey. The results from this type of test are an average behavior, which is dependent on the proportion of the coupon width comprised of the various weld zones. The data, therefore, must be treated accordingly. Data groupings and analysis of values should be aimed toward isolation of significant parameters and their definition.

The all-weld-metal tension test is used primarily for evaluation of actual weld-metal strengths. The data usually represent metal deposited under closely controlled conditions. The all-weld-metal specimen permits accurate evaluation of weld-metal strength and ductility. However, the closely controlled conditions under which the specimens are prepared usually minimize the amount of base-metal dilution. The treatment of all-weld-metal data should take into account these conditions and should be examined with respect to significant processing parameters and their influence.

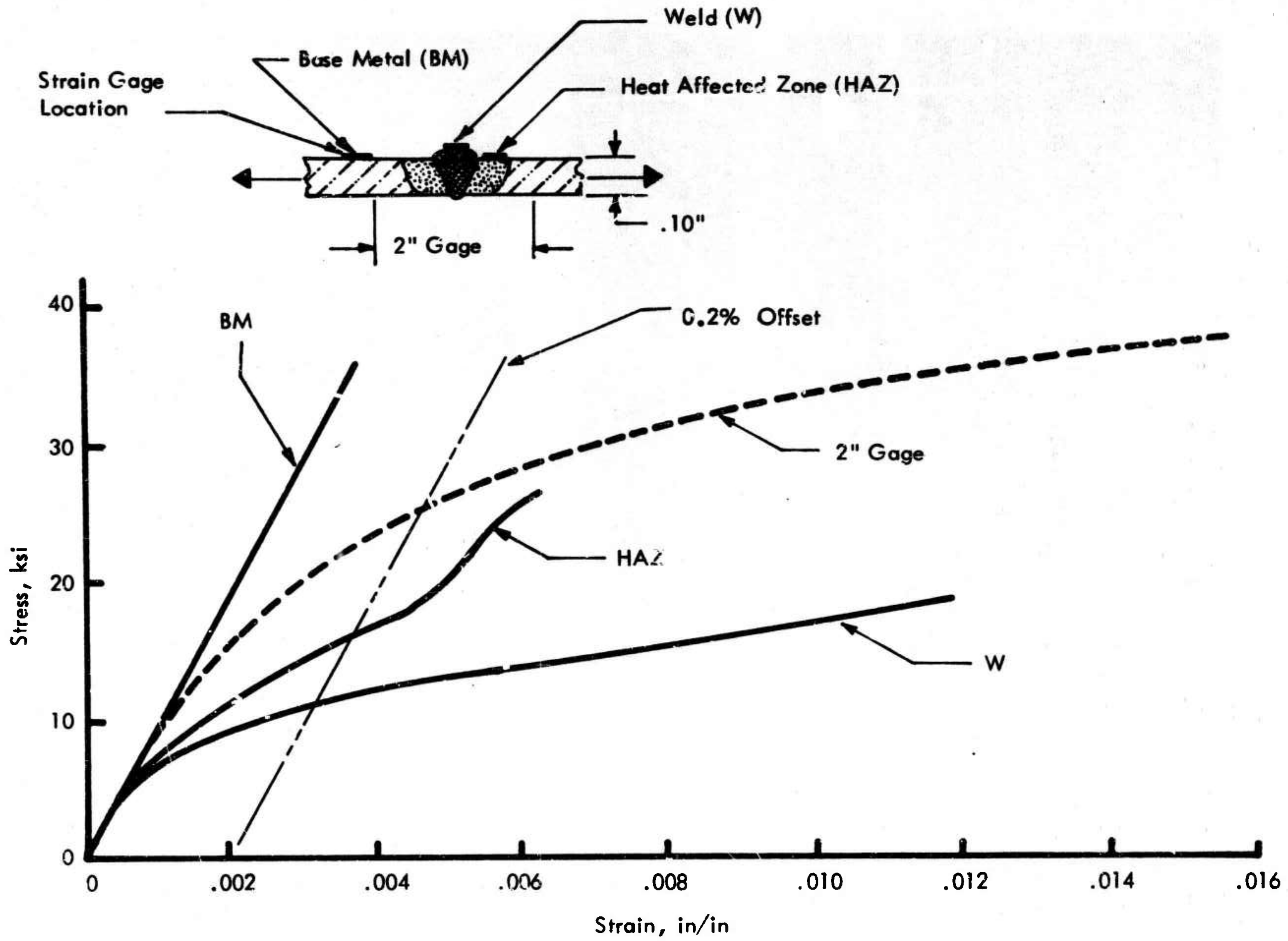


Figure 3: STRESS-STRAIN CHARACTERISTICS OF 2219-T87 AS-WELDED JOINTS

Uniform data analysis techniques should be used for the treatment of weld tensile data. The development of design values should be accomplished using statistical techniques to arrive at values of known reliability. Significant material and processing parameters should be recognized during analysis, and data should be grouped for treatment accordingly.

Data Presentation---The presentation of butt weld tension data should include a description of the pertinent welding conditions to be associated with the mechanical property values. It is recognized that this may be cumbersome in many cases due to the lack of adequate specification coverage. It is required, however, to provide meaningful and useful design data.

As pointed out in the previous discussion, many of the properties of interest may be specifically related to the test configurations. This is especially true for longitudinal-weld properties and yield strength and ductility values for transverse-weld tests. Presentation of these values should include reference to the specific test configurations from which they were determined and the method of measurement.

Data presented in as complete and concise manner as possible will minimize the amount of arbitrary interpretation required for its application. The presentation of data should include, as a minimum, the basis on which the values were derived (statistical limits, etc.), significant welding conditions, materials used, and any postweld treatments.

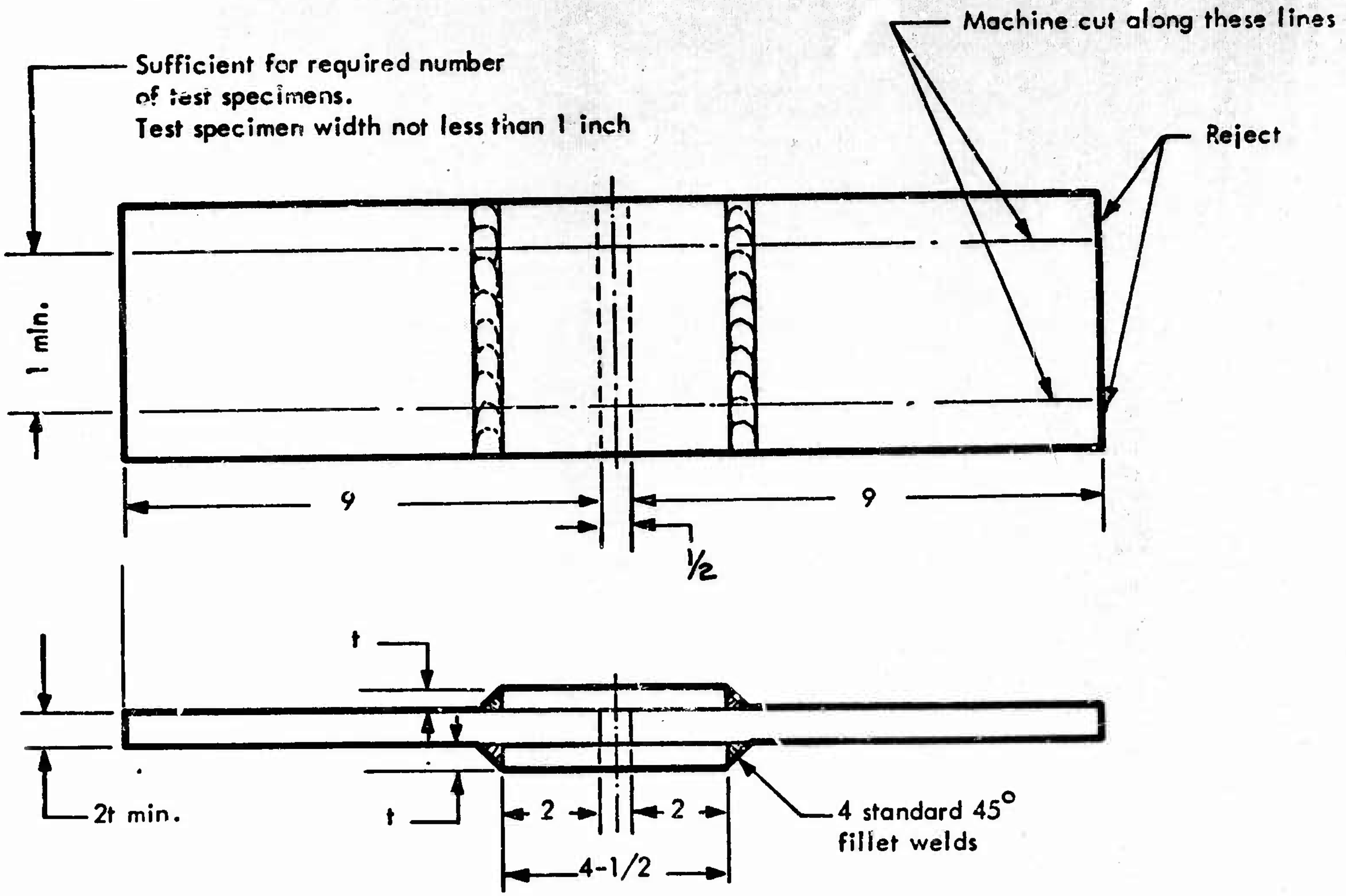
Use of Design Data---The presentation of design data is based on coupon-derived properties. The application of these properties in design must recognize the possibility that the behavior of a structure may be significantly different. The rational application of coupon-derived strengths to structural design requires the development of correlations between coupon and structural behavior.

A study correlated the burst stresses for as-welded 2219-T87 pressure vessels with coupon strengths derived from round transverse-weld coupon tests [12]. It was concluded that pressure vessel design strength should be based on the application of a correlation factor of 0.82 to the statistically derived minimum coupon test values.

The above case illustrates the necessity for rational application of coupon-derived strength values. The development of uniform test methods and analysis techniques in conjunction with correlation with structural experience is necessary to provide the basis for rational use of coupon test results for design.

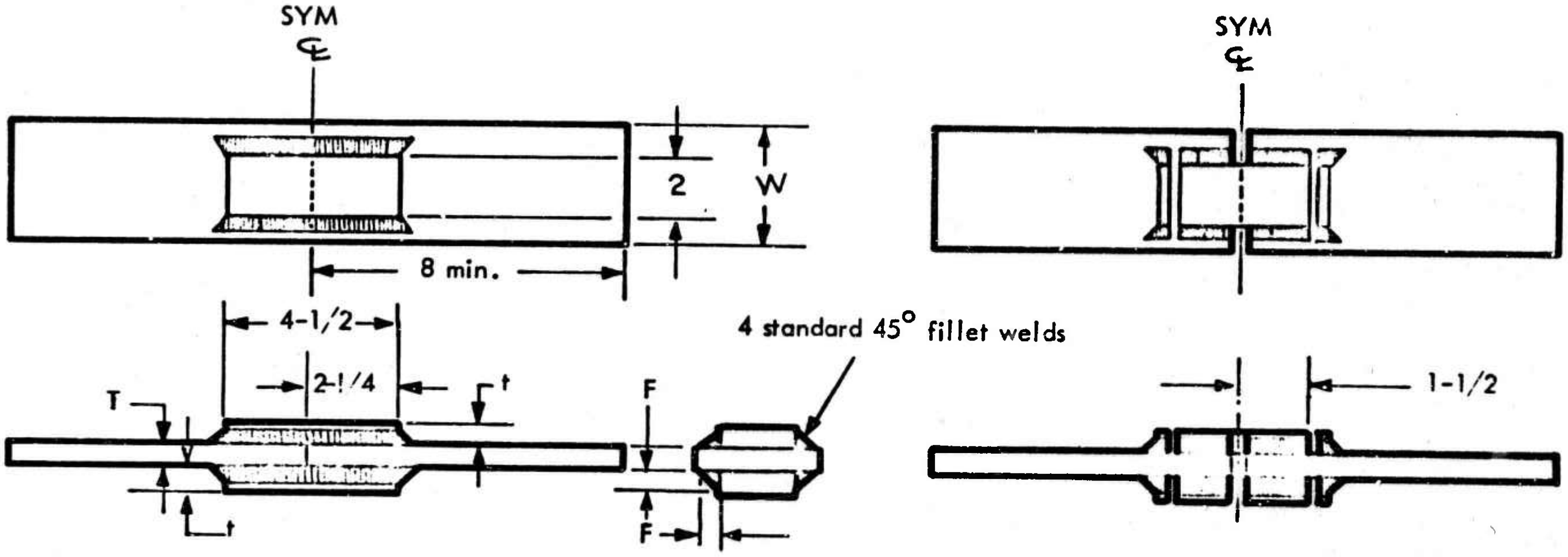
Fillet-Weld Shear Strength

Test Methods---Evaluation of the strength of fillet welds is usually accomplished using both longitudinal and transverse fillet-weld-shearing coupons. The test coupon configurations most generally used are shown in Figures 4 and 5. The dimensions shown are those of MIL-STD-418 and the AWS welding handbook. Other configurations have been used [13], but most are objectionable due to unsymmetrical loading or are applicable only to a narrow range of fillet sizes.



t = specified size of fillet weld + 1/8

Figure 4: TRANSVERSE FILLET WELD SHEARING COUPON



Specimen after machining

Specimen after machining

Dimensions

Size of weld, F, in.	1/8	1/4	3/8	1/2
Thickness t, in. (min.)	3/8	1/2	3/4	1
Thickness T, in. (min.)	3/8	3/4	1	1-1/4
Width W, in.	3	3	3	3-1/2

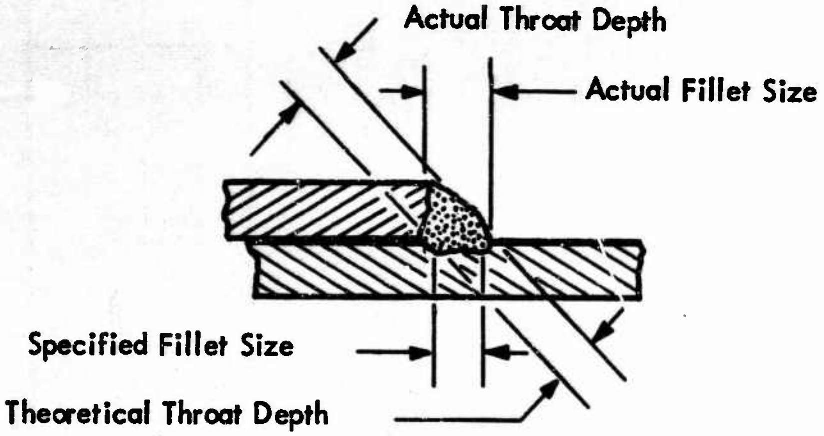
Figure 5: LONGITUDINAL FILLET WELD SHEARING COUPONS

Fillet welds are sensitive to weld and fusion zone defects such as weld undercut and root penetration. The stress concentration effect at the root of a fillet weld can be magnified if separation between the lapped plates occurs or if loading methods result in significant bending in this region. Thus fabrication of the coupons should result in representative weldments, and any unusual factors should be noted.

The test coupons are ruptured under tensile loading and the maximum load is determined. Standard testing procedures have not been detailed specifically for the fillet-weld test, but loading should conform to the general requirements for a tension test with respect to test machine accuracies, loading rates, and eccentricity of loading as given in Federal Test Method 151 or appropriate ASTM standards. In general, the loading rate will be less than one-quarter of the breaking load per minute.

Data Treatment---The raw test data obtained from the fillet-weld-shearing test is the maximum load and the appropriate dimensions of the coupon including the length of weld fractured and the fillet-weld size.

An area of inconsistency evident in a review of fillet-weld data is the method used for accounting for fillet size. The specified fillet size is usually the minimum leg dimension allowed, and actual welds may exceed this size by a significant amount. The fillet-weld size has also been stated based on other criteria as shown in the following sketch.



Fillet-weld strength data has been treated using two approaches. One method determines the strength based on the load per lineal inch of weld for a stated fillet size. The other method determines the strength based on an apparent shearing stress in pounds per square inch of throat area. The use of specified fillet size or theoretical throat depth does not recognize the variation that may exist in actual weld size. Therefore, use of actual weldment dimensions is preferred in analysis of test data.

The treatment of data in terms of pounds per inch of weld results in different strength values for each size of weld. Analysis of data covering a range of fillet sizes can result in a curve showing shearing strength as a function of fillet size. Figures 6 and 7 illustrate data for some aluminum fillet welds developed in this manner.

Treatment of data in terms of apparent shearing stress permits a more comprehensive evaluation of fillet-weld strengths. The shearing stress determined by dividing the test load by the fillet-weld throat area results in a value that may be relatively constant over a range of fillet-weld sizes. This is apparent from Figures 6 and 7 where the increase in shearing load is nearly linear with increasing size. Minimum shear strengths were determined statistically [14] for the data of Figures 6 and 7 in terms of nominal throat area stresses. These values are shown below.

Parent Metal	Filler Metal	Postweld Treatment	Transverse Shear Strength (ksi)	Longitudinal Shear Strength (ksi)
6061	4043	Naturally aged 2 to 3 months	15	11.5
2219	2319	Heat treated and aged	29	22

Shear strength based on throat area stress.

Welded by manual GMA process.

Fillet size 0.75 inch.

Note: Statistical minimums calculated on the basis of 75% confidence that at least 99% of the population would lie above the stated values. Log-normal distribution is assumed. Values are taken from Reference 14.

Consistent data treatment is desirable to provide a common bases for comparison of data. The use of data in terms of shearing stress is preferred over the use of shearing strength in pounds per inch for several reasons:

1) The use of actual throat area in calculating stress values minimizes the variability in the data due to weld contour.

2) Data may be combined for several fillet sizes and thus reduce the amount of testing required or give added confidence in the evaluation of a given sample size.

3) Welding specifications are not consistent in providing requirements for fillet-weld sizes and contours, and data comparisons are more meaningful in terms of stress.

Uniform data analysis techniques should be used for the treatment of the data to arrive at suitable strength values for presentation. Fillet-weld shear data lends itself to the statistical analysis techniques described in the guidelines. A statistical analysis should be used for the generation of design data.

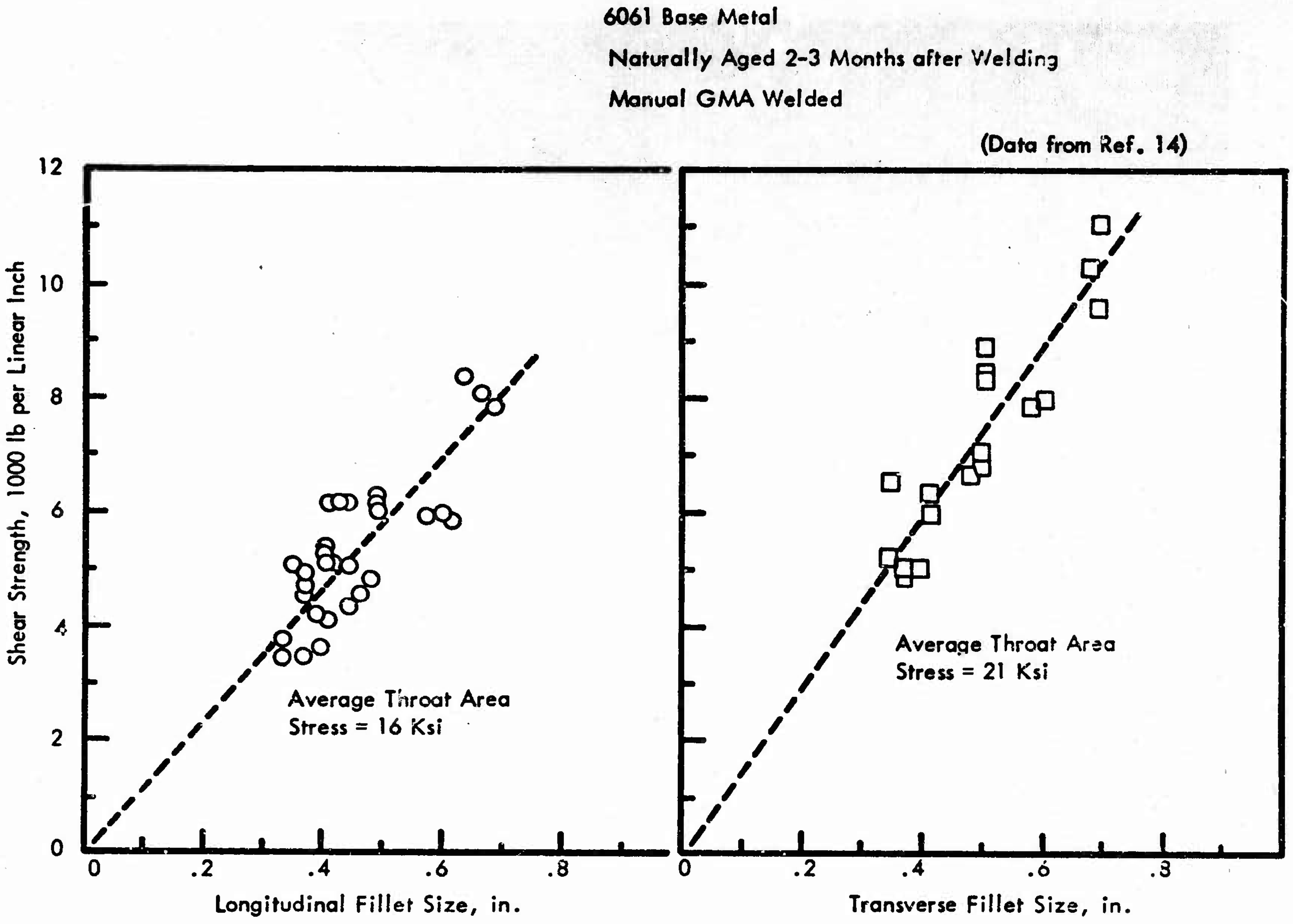


Figure 6: SHEAR STRENGTHS OF FILLET WELDS MADE WITH 4043 FILLER METAL

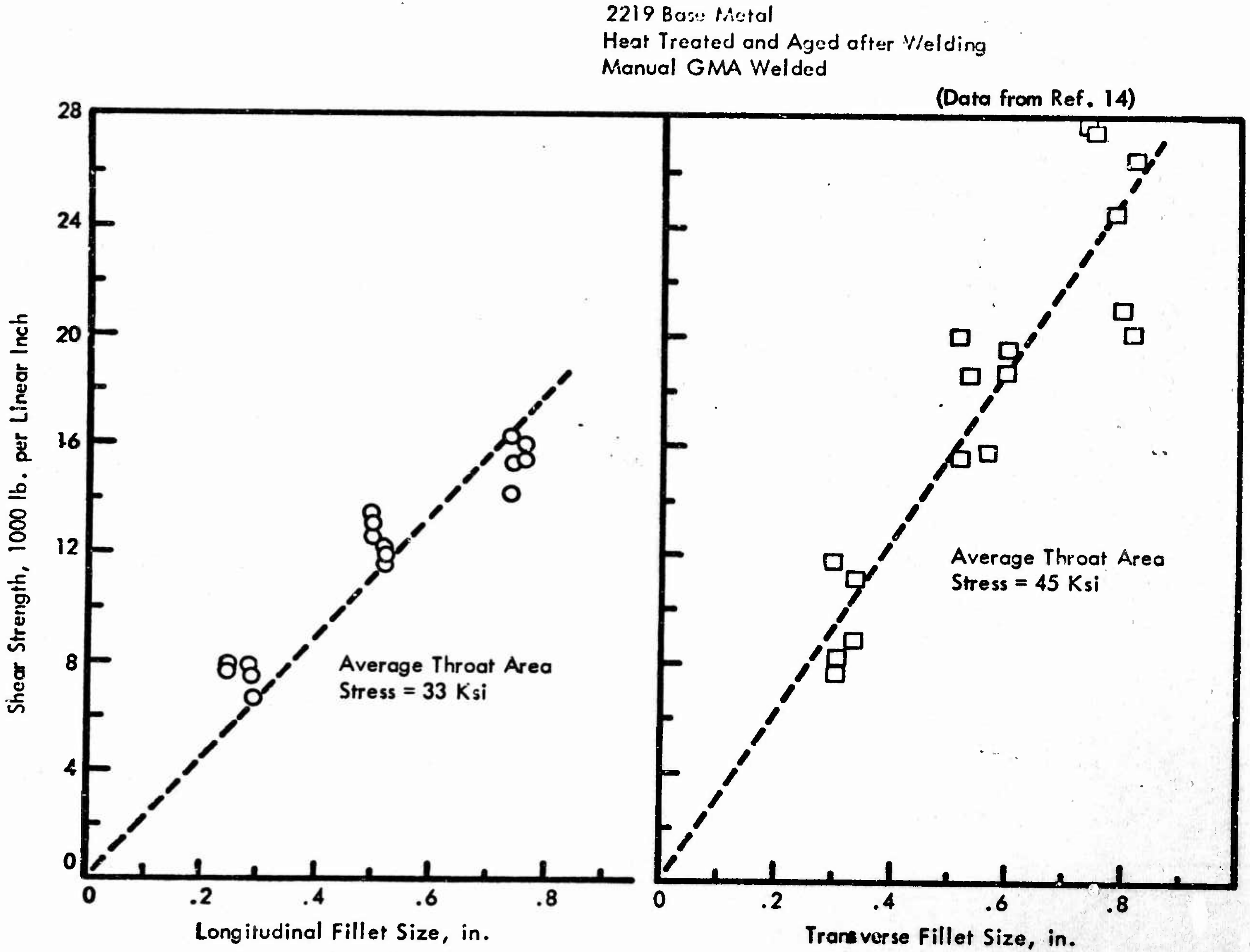


Figure 7: SHEAR STRENGTHS OF FILLET WELDS MADE WITH 2319 FILLER METAL

Data Presentation---The presentation of fillet-weld data should be consistent with the basis on which it was generated. The actual data may be presented in a form similar to the tabulation above. In addition to strength value presentation, however, a description of material and processing parameters also should be given to aid in their interpretation. These should include a description of base-metal alloy and heat-treat condition, welding process, filler metal, postweld treatment, joint thicknesses and types, and any other factors deemed significant. If design data is presented, precautionary notes regarding its use may also be required.

Use of Design Data---As in the case for many other weldment properties, the presentation of design data is based on coupon-derived strengths. Except for specific design applications, the fillet-weld shear strength is very difficult to use in hardware design. However, several items should be mentioned which may influence the application of such properties to design.

The symmetrical geometry of the test coupons from which data is derived is not indicative of many design applications. For instance, a single lap joint may have considerably more bending at the critical area near the root of the fillet, and its load-carrying ability may be impaired. Thus, it is necessary to develop correlations between coupon and structural behavior to enable rational application of coupon-derived design strengths.

The stress state in a fillet weld is not one of pure shear. The shearing stress determined from coupon tests is an apparent stress indicative of the load-carrying ability for a particular type of loading. This is illustrated in the tabulation, where the stresses reported for transverse loading differ significantly from those for longitudinal loading of the fillet welds. In some current structural specifications [15] the use of transverse shear values are limited to double fillet welds and single fillet welds in joints designed so as to minimize bending. Otherwise, longitudinal shear values are used.

The rational application of design strength values is dependent on the development of uniform test methods and analysis techniques which can be correlated with structural experience.

Butt Weld Shear Strength

Test Methods---It has been the practice to use base-metal shear-to-tensile ratios to estimate weld shear strength from weld tensile results. Therefore, butt weld shear tests have had limited use. The property generally determined from such tests is the ultimate shear strength of the deposited weld metal. Testing, when conducted, is usually confined to all-weld-metal coupons conforming to the configuration requirements for base-metal tests. Limited use of a butt weld shearing coupon for sheet material was indicated by the replies to a questionnaire circulated by ARTC [16]. Of 28 replies received, only two used this coupon, and the dimensions varied considerably. The base-metal test methods are detailed in ARTC 13-S1.

Data Treatment---The data obtained from the shear test is usually restricted to the ultimate failure stress. These values, when obtained from a weldment test, should be treated in a manner that will provide the information desired in a form requiring a minimum amount of interpretation. The analysis of data should be conducted on data grouped so as to recognize the welding parameters which may be significant. Some of the more important variables to be considered are coupon geometry, weld quality, and base-metal dilution in addition to the basic material and processing parameters.

The treatment of all-weld-metal results can be accomplished using the derived property concept as used for base-metal tests. Results can be correlated with all-weld-metal tensile results to obtain a reduced ratio applicable to tensile design strengths to arrive at shear design strengths.

Data Presentation---The presentation of butt weld shear data should include a description of the pertinent welding conditions associated with the mechanical property values. Due to the use of nonstandard tests, the configurations used to develop the values should also be shown. If data for design use is presented, the basis on which it was determined (direct statistical assurance limits, reduced ratio confidence limits, etc.) should be clearly stated. The actual form for presentation can be very similar to that used for the presentation of tensile strengths.

Use of Design Data---The presentation of design strength data, as discussed previously, may be based on test coupon data or may be proportioned from tension data. The application of these properties to design must recognize the possibility that the behavior of structure may be different.

Fracture Toughness

Test Methods---Evaluation of the fracture toughness properties of weldments is usually accomplished using test methods and procedures recommended by ASTM. Considerable work has been done by ASTM Committee E24 on Fracture Testing of Metals to develop test coupons and testing techniques for determining the fracture characteristics of high-strength metals. The procedures have been developed principally for base-metal evaluation, but their application to weldments has been demonstrated successfully.

The design and testing of fracture toughness coupons for determining plane strain fracture toughness (K_{Ic}) is detailed in ASTM STP 410 [17]. The majority of replies received from the industrial survey questionnaire indicated that the ASTM-recommended procedures were followed.

Techniques for measuring the K_{Ic} properties of weldments are similar to those for testing base metal except for considerations of adequate sampling for studying additional variables not present for base material. These variables include the significance of the welding conditions, weld process, and notch or crack tip orientation with respect to weldment zone.

Data Treatment---Fracture toughness data is usually treated in terms of the plane strain fracture toughness property K_{Ic}. In addition to the material and processing parameters which influence other strength properties of a weldment, K_{Ic} values may also be highly dependent on crack location and orientation with respect to the fusion weldment zones. The analysis and treatment of K_{Ic} data should be accomplished on data grouped so as to identify significant parameters.

The scatter evident from K_{Ic} testing may be considerable. The variation in test values is usually much greater than that expected for conventional tensile tests [18]. Thus the determination of significant welding parameters and their influence is sometimes difficult without the benefit of statistical analysis.

Table I summarizes some test data for welded 18% Ni steel plate [19] and illustrates some of the pertinent considerations in the treatment of weldment toughness values. From the range of test values for K_{Ic} shown, considerable overlap of values for the various welding methods and crack locations was evident. It is most difficult to determine the relative significance of the variables by visual inspection of the data alone. The authors of the reference data used the students "t" test to examine the significance of the variables and were able to show the relative significance between welding methods, specimen orientation, and crack location. They were then able to conclude that:

1) For specimens cut parallel with the rolling direction of the plate, the K_{Ic} value is significantly higher than for those cut in the transverse direction;

2) The values for GTA welds are more consistent and higher than those for GMA and short arc welds;

3) Significant differences exist between crack tip locations, with the lowest K_{Ic} values occurring at the weld center.

Treatment of data in this manner permits the selection of test criteria representing minimum toughness conditions so that an efficient statistical program can be designed to further evaluate the significance of additional variables such as base metal and filler metal lots, welding machines and operators, and environmental factors.

Data Presentation---The requirements for the presentation of fracture toughness data for weldments cannot be reduced to a simple list of pertinent details. It is important that fracture toughness data be presented with sufficient information to adequately describe the material and conditions represented. The presentation of actual K_{Ic} values can be accomplished in a relatively straightforward manner, but the qualification of the values as to the particular material and processing conditions which they represent may be complex.

Room-temperature K_{Ic} values can be presented in tabular form with the effect of temperature or other environmental factors shown graphically. This method of presentation has been suggested for use in a handbook presentation [20] but precautionary notes or reference to additional comments regarding material and processing history and the influence of environmental factors are required.

The presentation of K_{Ic} values for weldments should include a description of the material and processing history, the location or weld zone which the values represent, and the basis (average, range, or minimum) for the values shown.

Table I: SUMMARY OF K_{Ic} TEST DATA ON 18Ni (250) WELDMENTS

(Data summarized from Ref. 19)

Base Plate Heat No. [1]	Kind of Weld	Specimen Orientation [2]	Crack Tip Location [3]	K_{Ic}, KSI $\sqrt{\text{In.}}$			Number of Tests	Coefficient of Variation
				Max.	Min.	Avg.		
X14636	Base Plate	L		91.5	75.4	84.33	24	0.041
		T		93.1	69.5	76.96	26	0.060
	GTA	L	CW	113.8	60.3	83.79	17	0.152
			FZ	109.3	90.0	100.00	7	0.068
			HAZ	104.0	82.3	94.56	8	0.093
		T	CW	82.4	57.2	59.63	18	0.116
			FZ	89.6	76.2	82.08	7	0.057
			HAZ	90.0	59.5	74.69	10	0.139
	GMA	L	CW	105.7	60.4	77.69	12	0.054
			HAZ	105.7	78.4	91.28	9	0.104
X53013		T	CW	87.3	54.4	74.30	19	0.117
			HAZ	102.3	89.8	93.55	6	0.101
	Short Arc	L	CW	89.1	61.5	72.81	19	0.088
			HAZ	120.4	92.6	106.77	18	0.074

[1] 0.75 Thick Plate, Aged 915°F - 4 Hrs.

		Heat X14636	Heat X53013
UTS, KSI	L	272	265
	T	259	275
TYS, KSI	L	263	258
	T	248	268
Elong., %	L	4.0	4.7
	T	4.6	4.0

[2] L = Longitudinal specimen with long transverse notch
T = Long transverse specimen with longitudinal notch

[3] CW = Center of weld
FZ = Fusion zone
HAZ = Heat affected zone

Use of Design Data---The use of fracture toughness data for design is still in the development stage. Correlation between coupon-derived design properties and actual structural behavior is required in order to build confidence in the application of K_{Ic} values to design. Whereas 50% of the organizations replying to the industrial survey questionnaire determined fracture toughness, only 14% determined K_{Ic} properties for design use.

The presentation of fracture toughness values at this time is generally accomplished using typical values. Application of these values requires considerable interpretation regarding the relation of the reported values to the design application. Factors such as data scatter, crack location, and geometry and processing sequence must all be considered.

The use of minimum properties for design has been advocated [17], but sufficient information has not been generated to make this practical at the present time. The adequate reporting of all significant variables when publishing K_{Ic} test values should be emphasized so that a significant statistical sample can be gathered over a period of time to make this goal possible.

Several examples of the application of fracture toughness data to typical engineering problems have been reported [21]. Additional experience needs to be documented in this area so that K_{Ic} values for design use can be defined.

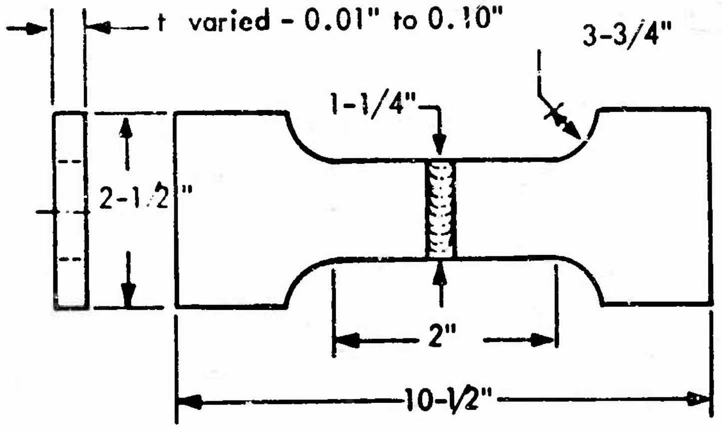
Fatigue Strength

Test Methods---The majority of fatigue testing is conducted using small coupons subjected to simple load spectra. The axial-load-fatigue coupon or the rotating beam bending fatigue coupons are the most used, but much fatigue testing is accomplished using nonstandard coupons.

The coupon configuration study conducted by DMIC/ARTC [13] indicated that the most used fatigue coupons are similar to those shown in Figure 8. In most cases, the use of other coupon geometries is dictated by attempts to simulate actual weldments.

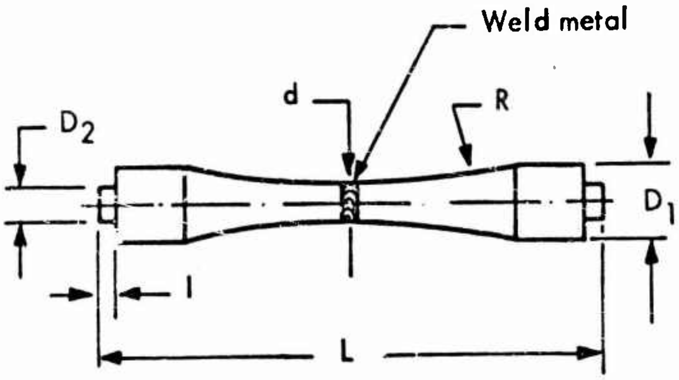
The test requirements and methods for weldment fatigue tests are similar to those used for base metal evaluation. Details have been published and are available in references such as ASTM STP 91 [22]. The inherent characteristics of geometric and metallurgical variables in a welded joint require that care be exercised in preparation of coupons. Surface notches or discontinuities such as undercutting or overlap, root defects, lack of fusion, arc craters, and abrupt convexity in surface passes are especially significant.

Data Treatment---The data obtained from an individual fatigue test is the number of loading cycles to cause failure at a particular condition of alternating stress. This data is usually used to develop S-N curves for specific material and test conditions. The S-N curve is drawn to represent the data obtained on a group of identically prepared specimens, all tested in the same environment with the same type of loading but at several maximum stress levels.



Dimensions varied greatly: tested over wide range of temperature from -100 to +1600F, usually in air: tested with and without weld reinforcement depending on service conditions.

TRANSVERSE-WELD, AXIAL-FATIGUE SPECIMEN - FLAT



Dimensions, inches					
l	L	d	D_1	D_2	R
0.50	10.21	1.00	1.50	0.640	9.00
- -	3-7/16	0.300 ±0.003	0.480	- -	9-7/8

Second set of dimensions are for standard R. R. Moore specimen with drilled and tapped specimen ends; specimens usually tested at room temperature in air.

ROTATING-BEAM, BENDING-FATIGUE SPECIMEN

Figure 8: FATIGUE COUPONS

The S-N curves are usually generated by plotting of the test data using coordinates of maximum stress, S, and the logarithm of the number of cycles to failure, log N. Where few data points are available an average, or mean life, curve is faired through the data points by eye. Where larger amounts of data are available, analytical techniques are available for establishing the curve. A method of establishing a mean curve is shown in ARTC Report W-76 [23]. Statistical techniques can be used if data samples are sufficient. These statistical techniques are described fully in ASTM STP 91A [24].

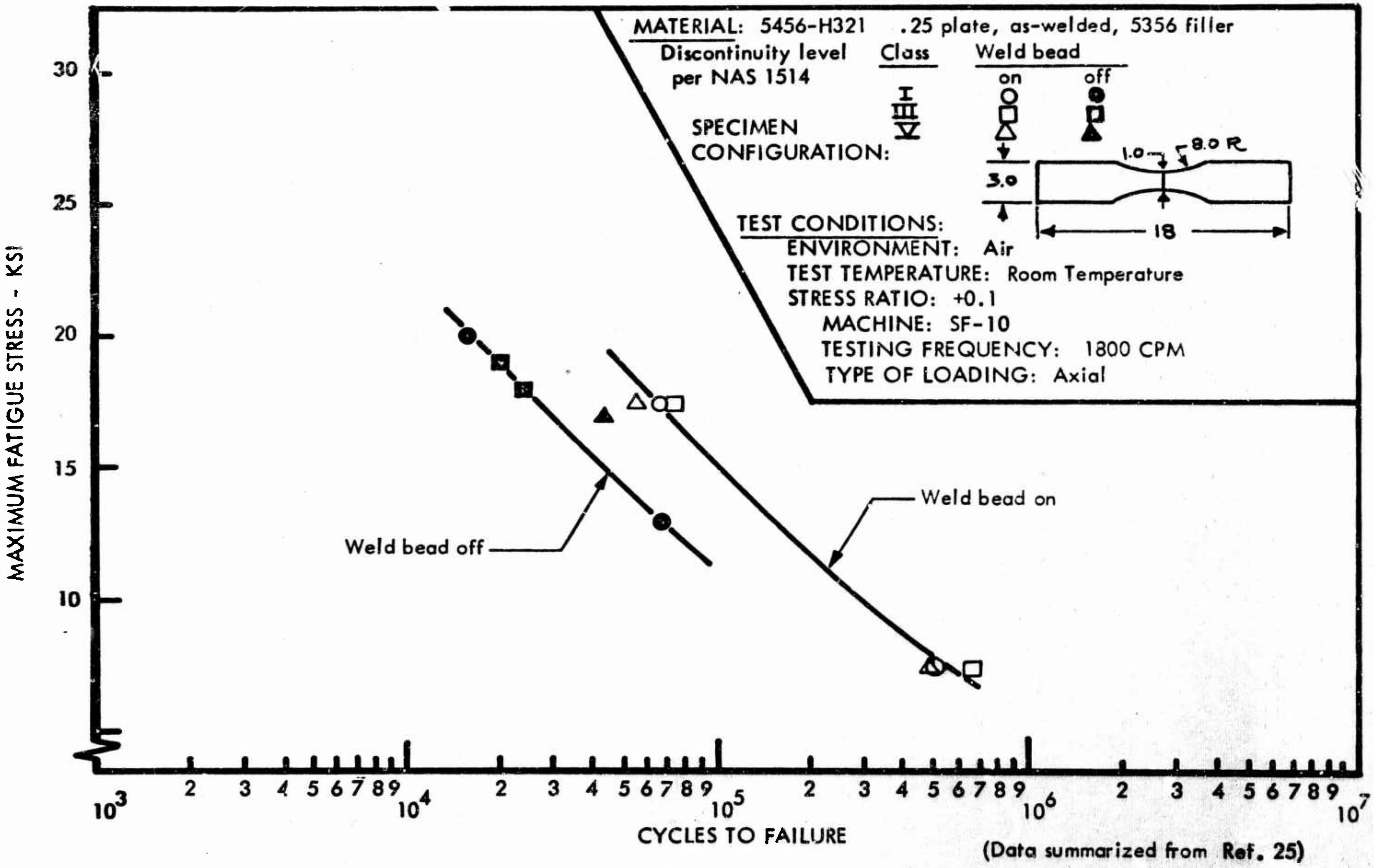
The treatment of test data on weldments should conform to the general practices used for base materials except for consideration of weldment variables such as processing history, weldment quality levels, and joint configurations. In some cases, it is desired to group data for a common test condition representing several weldment variables such as joint thickness or quality levels in order to build a larger data sample. The significance of these variables should be examined prior to combining data to ensure that the sample is truly representative of the stated conditions.

Figure 9 illustrates a mean life comparison made to determine the effect of discontinuities on the fatigue life of some 5456 aluminum welds [25]. Specimens were tested that contained various radiographic discontinuity levels classified per NAS 1514. The computed log mean life for each discontinuity level is compared in Figure 9 for both weld-bead-on and weld-bead-off coupons. It was concluded in this case that the discontinuity levels examined did not significantly influence the mean fatigue life, but there was a significant change between bead-on and bead-off coupons.

The treatment of fatigue data should be aimed toward isolation of significant material and processing parameters. The strong influence of coupon geometry and test conditions should be recognized during the treatment of any fatigue data.

Data Presentation---The majority of fatigue data is presented in the form of S-N curves or constant lifetime diagrams. Data presentation methods have been detailed for both of these diagrams in terms of base metal evaluations [26]. In addition to the material and processing details required for the base metal presentation, additional details regarding welding method, joint configuration, processing details, and quality levels should be presented. Since much of the desired weldment information is not adequately covered by specification requirements, this additional information should be covered by adequate notes or reference to an explanatory description of weldment details.

The published data on fatigue strengths of welded joints show wide variations. Reports accompanying the data many times omit very significant details, possibly because their importance was not recognized. It should be emphasized that all contributing factors known or controlled during fabrication and testing should be supplied with test data so that a reliable interpretation of the data is possible. Weldments generally show a much wider scatter than base materials, and it is advisable to show an indication of the degree of scatter in weldment presentations.



(Data summarized from Ref. 25)

Figure 9: WELDED 5456 ALUMINUM FATIGUE DATA

Use of Data---Fatigue data generated from coupons does not apply directly to the design of structure since it does not include the effect of structural geometry. Design for fatigue is usually based on empirical considerations and is usually in general rather than precise terms. Structure considered critical in fatigue is usually verified by testing components.

One of the difficulties in applying coupon-derived fatigue data to the design of structure is that the simple load spectra generally used for coupon tests are inadequate to account for the fluctuating nature of stresses frequently encounted in service environments. Another obstacle to the accurate prediction of the fatigue life of a welded structure from coupon-derived fatigue data is the influence of residual stresses that may occur as a direct result of the restraints imposed on the cooling weld metal by the unheated portions of the adjacent structure.

The standard coupon test does provide much-needed information on the material and processing variables of significance. The standard fatigue test is an effective method for revealing points of stress concentrations due to geometric and metallurgical factors, which can be very helpful in improving design details.

Creep and Stress Rupture

Test Methods---Creep and stress-rupture tests are used to determine the time-dependent deformation and fracture strengths. These tests are used only to a limited extent for evaluation of weldments. The DMIC/ARTC weld specimen survey [13] indicated that only the transverse-weld stress-rupture specimen was used to any appreciable extent.

Coupon design, testing equipment, and testing procedures are generally identical for creep and stress-rupture testing. The main difference between the two types of tests is the requirement to measure deformation during the creep test. The test methods and procedures used are identical to those for base metals and are detailed in ASTM E139-58T [27].

Test coupons of the size and shape used for tensile testing are generally used for creep and stress-rupture testing. The particular coupon used is subject to the same limitations as for the tension test. The stress-rupture test measures the ultimate load-carrying ability as a function of time and is consequently not as configuration dependent as the creep test. Creep test values associate time-dependent deformation with stress, and the significance of arbitrarily selected gage lengths is similar to those of the tensile test. In most instances, creep specimen gage lengths are made the same as the tensile specimen gage lengths to provide comparative data.

Data Treatment---It is well recognized that creep rates and rupture times from individual tests are sensitive to both material and test variables. The treatment of test data must recognize these variables and care should be exercised so that the influence of test variables can be isolated from the material behavior.

Creep and stress-rupture data for a particular weldment may cover a wide range of times and temperatures. Considerable use is made of parametric analysis methods that permit the evaluation of data representing various times and temperatures. These methods are detailed in the literature [28, 29, 30] and will not be treated here due to their complexity. It should be emphasized that the data treatment method selected should be used with sufficient caution so that the influence of significant welding variables will be recognized.

Data Presentation---Presentation of creep and stress-rupture data on weldments should include a description of the pertinent welding conditions and parameters, the basic materials and processing sequence, and the test configuration. Since adequate specification coverage for weldments is generally not available, much of this information may have to be supplied through reference to explanatory notes. The actual presentation format will depend upon the type of data and the treatment method selected. Presentation formats have been suggested [26, 31] for base metal data, and the use of a similar format for weldment data is recommended. When parametric presentations are utilized, the time-temperature-stress envelope included in the data sample should be specified so that the user of the information will not inadvertently extrapolate data to conditions not verified by testing.

Use of Design Data---Creep, in service environments, is typified by complex conditions of loading and temperature. The number of possible stress-temperature-time profiles is infinite. Creep and stress-rupture data presented for design use are usually obtained using conditions of constant uniaxial load and temperature. The difficulties in extrapolating from the simple to the complex stress-temperature-time conditions have not been fully explored. Thus, it is recognized that it may be necessary to conduct verification tests under actual service conditions if significant creep appears likely to occur.

The correlation of weldment creep data with service behavior is made more complex because of the geometric and metallurgical variations which may exist through the gage length of the test coupons. The data obtained is thus an average value over a selected gage length, and considerable interpretation may be required to relate this to an actual structural joint.

Compression

Test Methods---Compression testing is seldom used for evaluation of weldment strengths. The determination of compressive yield strengths for weldments is subject to the same considerations as discussed for tensile yield strength determinations. All-weld-metal coupons can be tested to evaluate weld metal strengths, but the influence of base metal dilution is not accounted for. Transverse-weldment coupon test results are subject to the proportion of the gage length composed of weld metal, heat-affected base metal, and base metal.

To be consistent with the development of other static mechanical properties, test procedures for compression testing should be conducted per the requirements of established procedures such as those given in ASTM standards [32]. No standards are available for weldment coupon configuration requirements, but the base metal configurations can be used if sufficient detail is supplied with the data so that it can be adequately characterized.

Data Treatment---Compressive yield-strength data represents the behavior for a defined amount of deformation (usually 0.2% offset) over a stated gage length. The treatment of weldment data should use uniform data analysis techniques similar to those used for tensile data analysis. Significant material and processing parameters should be recognized during analysis and data should be grouped for treatment accordingly.

Data Presentation---The presentation of compression yield strength data for weldments must recognize that the property may be dependent on test configuration. The requirement to provide meaningful and useful engineering data dictates that the presentation of data must include reference to the specific test configurations and methods of measurement.

The data presentation format can take the same form as for the presentation of tensile data. Data values can be presented in tabular form with environmental effects shown graphically. Additional descriptive information on material and processing conditions, test configurations, and other significant parameters should be covered by explanatory notes.

Use of Design Data---As with other weldment properties, it is anticipated that design data for compressive strength will be presented on the basis of coupon-derived properties. The application of those properties in design must recognize the possibility that the behavior of a structure may be somewhat different. The rational application of such design data requires the development of correlations between coupon and structural behavior.

Much of the compressive design of weldments is currently accomplished using design values estimated from tensile yield strength tests of weldments or in some cases the compressive yield strength of the annealed base metal. The general attitude of conservatism in weldment design evident from the industrial survey trips is one possible explanation as to why these procedures have been successful. As the use of weldments increases, the determination of actual weldment properties becomes increasingly important, and their efficient application to the design of structure depends upon the development of adequate testing methods and correlations with structural experience.

POPULATION DEFINITION

The importance of population definition cannot be overemphasized with regard to its influence on the orderly establishment of engineering data on weldments. This is demonstrated by considering the general procedures followed in welding typical high-quality aerospace structures.

Figure 10 is a schematic diagram illustrating those procedures. The coupon-derived design strength is obtained by evaluation of weldments produced in accordance with a stated welding specification. This same welding specification must then be used in the fabrication of subsequent structure. In some instances structural considerations will require some deviation from conditions used in the design strength program. These deviations must be included in the final design considerations. For example, the design property of transverse tensile ultimate strength may have been based on weldments with weld reinforcements removed, and the particular design prohibits the

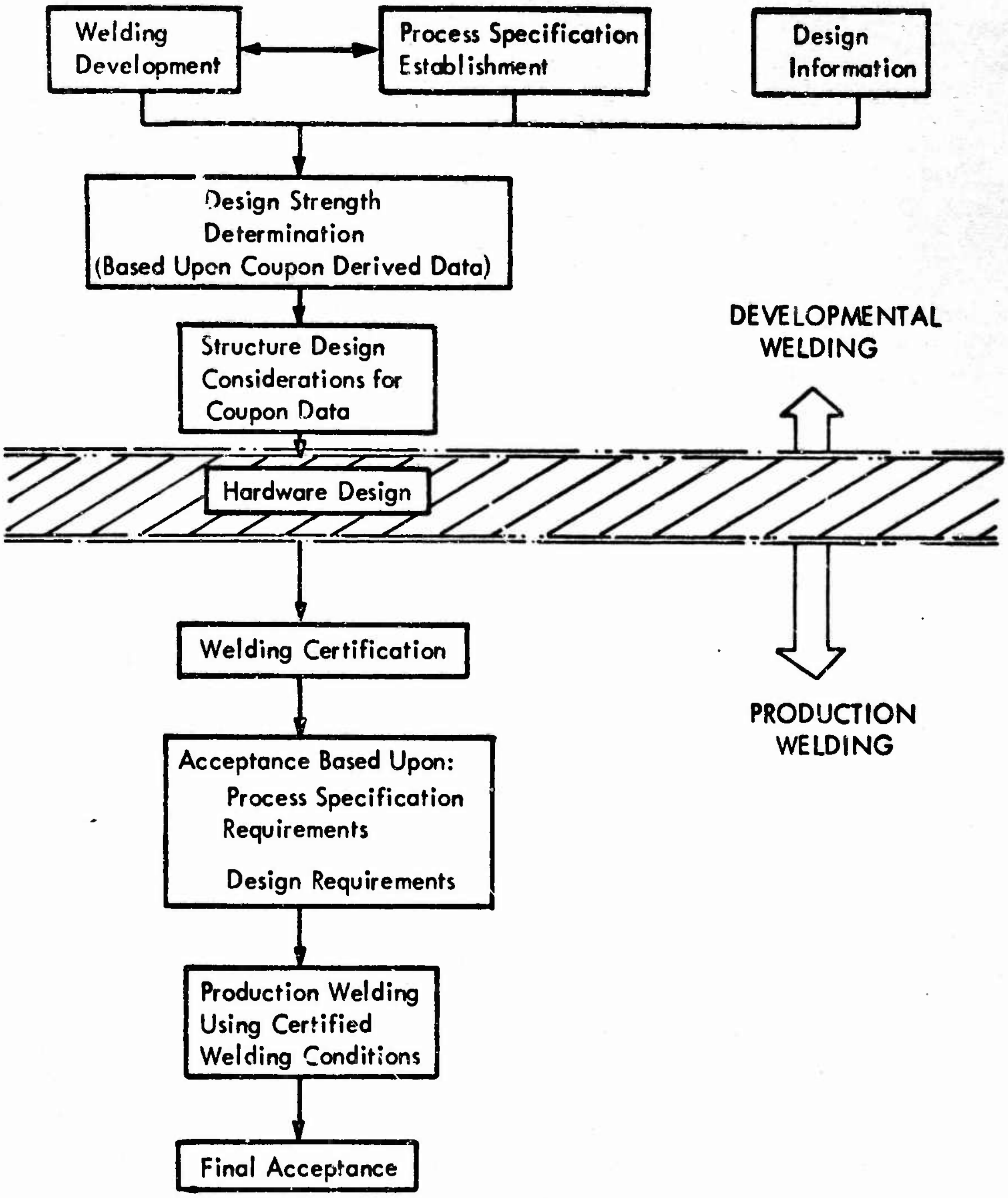


Figure 10: GENERAL PROCEDURES FOLLOWED IN PRODUCING TYPICAL HIGH-QUALITY AEROSPACE WELDED STRUCTURES

economical removal of the underbead. In this case, design consideration must be given to the effect of the underbead. This again illustrates the importance of associating with the design data the exact conditions they represent.

After hardware design, preliminary welding is conducted in accordance with drawing and specification requirements, and a certified setting for the production welding procedure is developed. Certification normally involves three steps: personnel certification, material and equipment certification, and weldment certification. Personnel certification includes both welders and inspectors. This certification is in turn controlled by specifications such as MIL-W-5021 for the welder qualification. The final part of the certification procedure is the weldment itself. The weldment must meet specification and design requirements as determined by destructive and nondestructive test methods. The destructive evaluation requirements may include metallurgical examination, coupon testing or structural testing as in the case of the burst test.

Once the welding procedures have been certified, future production welding is accomplished using these same conditions. A significant change in procedure, such as welding sequence or settings, welding equipment, tooling, or welding operators requires recertification to ensure that consistent weldments will be produced.

During production welding, the nondestructive testing required by the process specification or drawing is carried out on each welded assembly. This would include the normal NDT methods and may involve a proof test, which is finding increased application in conjunction with fracture mechanics as a means of insuring structural integrity. In addition, intermittent destructive tests may be required to ensure compliance with the certified procedures.

Throughout the foregoing discussion, the importance and necessity of the welding process specification is illustrated. With regard to weldment property determination for design use, a description in terms of weldment populations further illustrates this importance.

A population of weldments or weldment properties for given welding conditions will be obtained by welding and inspecting in accordance with a particular specification. By proper testing and data analysis, statistically derived design properties can be obtained for this stated population of weldments. However, in order for the designer to use these properties, he must be able to obtain the same properties when hardware is produced. This can only be accomplished through detailed knowledge of the welding conditions and specifications under which the design properties were derived.

Therefore, it is of utmost importance that the welding conditions and process specifications be associated with the presented design data. Without this information a quantitative approach to useful weldment property determination cannot be established. It must be recognized that present government or industry-wide aerospace specifications do not adequately control the welding variables or procedures. For this reason it is necessary to present with the design data the detailed information normally contained in the welding process specification.

Results of the industrial survey questionnaire with respect to welding variables have given an indication of the variables and conditions that are normally specified or not specified in developing engineering data on welding. In addition to this, a review of the various alloys and alloy systems was conducted to establish their influence on procedures for obtaining engineering data on weldments. In this review the alloy classes examined were: ferrous, aluminum, titanium, and nickel and cobalt base alloys. Within this broad classification, the alloys were further divided by subgroups which are characterized by similarity in metallurgical behavior. From each of these subgroups, a specific alloy was selected to represent the behavior of other alloys within the subgroup. A summary of this alloy classification system is given in Table II. The resulting 10 specific alloys serve to represent each of the subgroups in the particular considerations that may be required when obtaining weldment data for these alloys.

A summary of typical welding conditions and desirable design data for room temperature butt weld properties of a representative alloy is shown in Table III. The welding conditions selected for use in this table may require modification in particular cases. As later described, data analysis must be used to reveal variables of significance. The selection of conditions that should be associated with the design data can then be made based on their influence on design data and their desirability of control.

Those conditions selected as applicable to all of the alloy classifications were: initial heat treat condition; postweld heat treatment, welding process, filler material, joint preparation, joint thickness, and type of welding (manual or mechanized). The initial heat-treat condition or conditions would be those applicable to the particular alloy. The postweld heat treatments are also generally those used in base metal processing. An exception to this is stress relieving, which is required for some alloys. The gas tungsten arc and gas metal arc welding processes are the only two shown in Table III. Other welding processes, such as electron beam or shielded metal arc, could be added where desirable. The selection of filler material is largely dependent on frequency of use within the industry and should be specified. Joint preparation is related to welding process and joint thickness. For this table, a potential differentiation was made between square and other groove-type preparations normally used for single-pass and multiple-pass welding, respectively. The resulting joint thicknesses may require further subdivision depending on the particular alloy and the variation in properties due to thickness. The method of welding was divided into mechanized and manual categories. Since weld repair of mechanized welds is normally accomplished manually, weld repair was grouped with manual welds. There are again some instances where repair and manual versus mechanized welding will show little effect on design properties. However, for the general case this subdivision was made.

The flagnote pertaining to welding specifications is of considerable importance in the table. It is assumed that this specification contains the necessary limitations and controls to provide a meaningful and consequently restrictive population of weldments. In lieu of this specification, reference to the detailed processing information would be required.

In summary, the importance of specifying a given population of weldments has been shown as well as the significance of an adequate welding process specification.

Table II: SUMMARY OF ALLOY CLASSIFICATION

General Classification of Alloys	Major Subgroups		Typical Individual Alloys	Example Alloy Selected as Representative
Aluminum	Non-heat-Treatable		1XXX Series 3XXX Series 5XXX Series	5456
	Heat Treatable		2XXX Series 6XXX Series 7XXX Series	6061
Titanium	Alpha		C.P., Ti-8Al-1Mo-1V Ti-5Al-2.5Sn	C.P.
	Alpha-Beta		Ti-6Al-4V Ti-4Al-3Mo-1V	Ti-6Al-4V
Nickel and Cobalt	Solid Solution		Inconel 600 HS'25 Hastelloy X	Hastelloy X
	Precipitation Hardenable		Rene'41 Inconel 750 Inconel 718	Rene'41
Ferrous	Quench & Temper		4130, 4330, D6AC, 9Ni-4.Co	4130
	Maraging		18Ni(200), (250) or (300)	18Ni(200)
	Corrosion Resistant	Non-heat-Treatable	3XX Series	321
		Heat-Treatable	4XX Series PH 15-7 Mo PH 14-8 Mo	PH 15-7Mo

Table III: SUMMARY OF TYPICAL WELDMENT DATA PRESENTATION

Initial Heat Treat Condition	Post Weld Heat Treatment	Welding Process	Filler Material	Joint Preparation	Joint Thickness Inches	Design Properties [1]							
						Manual Weld or Repair				Mechanized Weld			
						F_{tu}	F_{ty}	F_{su}	K_{ic}	F_{tu}	F_{ty}	F_{sn}	K_{ic}
A	D	GTA	A	A	< -								
			B	A	< -								
		GMA	A	A	< -								
				B	> -								
			B	A	< -								
				B	> -								
B	E	GTA	A	A	< -								
			B	A	< -								
				B	> -								
		GMA	A	A	< -								
			B	A	< ..								
				B	> -								
C	F	GTA	A	A	< -								
			B	A	< -								
				B	> -								
		GMA	A	A	< -								
			B	A	< -								
				B	> -								

[1] Welded in accordance with Specification No. ________

Data obtained from coupon evaluation in accordance with guidelines per ________

DATA GENERATION

Data generation involves the procedures by which the testing of weldments are conducted. A survey conducted in 1961 [13], indicated that 10 basic types of tests were used by the defense industry in evaluating welds. These included determination of tensile, shear, fatigue, bend, impact, stress rupture, creep, crack susceptibility, crack propagation, and weld soundness properties. It was also indicated that 77 different specimen configurations were used for these evaluations.

The need for standardization of test configurations and techniques has become obvious, especially for evaluating properties used quantitatively for the design of structure. The results of past studies and the current industrial and literature surveys have indicated that the pattern established for base metal testing is used as a guide for evaluating properties of weldments.

Base metal allowable strengths have been systematically developed for specific mechanical properties according to established standards as to type of testing and test procedures. Test coupon configurations and testing procedures are defined by appropriate ASTM standards and federal test method standards and are referenced in most material specifications. The availability and industry acceptance of these requirements has led to their attempted application to weldment evaluation.

In the previous section on properties of weldments, the requirements for coupon configurations and testing methods for each of the design properties considered were discussed.

DATA TREATMENT

The method of data treatment used depends on the type of data desired. In some instances individual data points or averaged groupings of data will provide the information desired. However, in determination of design data, a well-defined procedure of obtaining meaningful information is required.

Definition of design strengths is dependent on adequate requirements for sample selection, population definition, coupon definition, and testing procedures. Each of these items may introduce bias into later analysis. If a valid analysis is to be obtained, it is imperative that acceptable standards be established in each area and the data sample be truly representative of the product obtained using these standards.

The considerations associated with population definition, coupon configuration, and testing methods were discussed earlier, and the discussion assumes adequate definition of these items. The determination of design strengths then reduces to the problem of selecting an adequate sample representing particular processing criteria and manipulation of the resultant data.

Definition of an adequate data sample for most wrought base metals consists mainly of specifying a minimum number of tests representing the major producers performing to a particular material specification. This is possible since base metal processing conforms to relatively tight standards which have become established and used throughout the industry. Reference to a particular material specification is sufficient to describe the population of which the sample is representative. Strength requirements are stated in the specifications, and quality control is aimed toward maintaining these strengths.

Acceptable statistical procedures have been defined for the treatment of base metal properties and mechanically fastened joints. Design strength values are presented in Mil-Hdbk-5 at stated reliability levels. The procedures used in determining these values are given in AFML-TR-66-386. These procedures include sample size and selection criteria as well as statistical analysis methods and data presentation formats. In general, these criteria include:

Sample Size:	100 tests from at least 10 heat lots representing each major producer if the data is normally distributed (300 tests required if distribution is undefined).
Statistical Limits:	A values corresponding to 99% probability with 95% confidence. B values corresponding to 90% probability with 95% confidence.
Data Presentation:	Tabulations of room-temperature properties with curves showing the effect of environmental factors such as temperature and exposure.

It is obvious that if weld design properties are to be developed for the same reliability level as that required for the base metals, large quantities of test data must be obtained. These data must also be compatible with respect to coupon configurations and testing techniques to give a legitimate sample of the population being evaluated.

The literature and industrial survey indicated several ways in which test data samples are treated to arrive at design strength values. An example case is cited as an illustration.

Transverse weld tensile ultimate strength data for as-welded 6061-T4 and -T6 sheet was collected, resulting in the example data shown below. This data is for manual GTA square groove welds meeting quality requirements of a common specification. Because large quantities of data are not always available, two cases are cited. Case 1 consists of data representing 23 welders at five different companies, and Case 2 represents data for three welders at a single company.

Example Data	Case 1	Case 2
Number of Tests	391	30
Sample Mean	28.2 ksi	27.2 ksi
Coefficient of Variation	7.4%	3.2%
Standard Deviation	2.099 ksi	0.859 ksi
Data Range	21.8 to 34.3 ksi	25.8 to 29.4 ksi

Various methods of treating the test data to arrive at allowable strength values are indicated below with the resulting number shown for each data case.

Basis of Value	Allowable Case 1	Allowable Case 2
Statistical coupon minimum corresponding to Mil-Hdbk-5, A basis	22.9	24.6
Statistical coupon minimum corresponding to Mil-Hdbk-5, B basis	25.2	25.7
85% of the mean test value	24.0	23.1
Minimum test value	21.8	25.8
85% of minimum test value	18.5	21.9
85% of statistical coupon, A basis minimum	19.5	20.9

It is obvious that significant differences in indicated allowable values occur due to both the sample used and the methods of analysis. In order to judge the adequacy of a data sample, it is necessary to consider the range and significance of variables associated with the sample. This is illustrated by the two cases above where the second case does not represent the same range of variables as the first. However, to quantitatively judge the adequacy of the data sample, more detailed information than that presented above is required concerning the variables involved.

The methods of data treatment also significantly alter the resulting design strength as shown in the two cases. The use of a factor such as 85% does not ensure that a conservative design strength will result as illustrated by comparing the statistically derived 22.9 ksi A value for the first case with the 23.1 ksi, 85% of the mean value, in the second case. This also points out the difficulty in selecting the proper magnitude of the weld factor. In the illustration, as well as in other cases, the magnitude of the weld factor and how it should be applied is necessarily arbitrary and does not result in a design strength of known reliability or validity.

DATA PRESENTATION

The presentation of data on weldments is complicated by the lack of welding specifications suitable for reference. In lieu of these specifications, a description of the pertinent welding conditions must be given in association with the property data. This may be cumbersome in some regards; however, it is necessary in order to provide meaningful and useful engineering data

Since the data presented is based on coupon-derived results, it is also necessary to provide comments on the use of this data in structural design.

Due to the many variables involved in welding, the tabular form of data presentation is preferable. This allows an orderly presentation of the significant welding conditions and their respective design properties. A data presentation of this type was illustrated in Table III. Additional data involving environmental influences, such as effect of temperature, should be presented in graphic form for selected welding conditions.

Specific comments with regard to the various design properties and their presentation were presented in the previous discussion of properties of weldments.

USE OF WELDMENT DATA

It is recognized that coupons may not fail under load in the same fashion as a structure. This is a universal problem and is not peculiar to welded structures alone. This lack of one-to-one correlation between test coupons and structure is due to: potential differences in weldment properties in coupons and structure, and differences in the state of stress of the structure. The interaction of these two items makes it often extremely difficult to account for this lack of correspondence in detail. Structural hardware testing is, therefore, frequently needed to establish a correlation between coupon behavior and structure. Through structural hardware testing, a ratio can be established between coupon and structure test results. This ratio then accounts for uncertainties in both the exact state of stress and potential differences in weldment properties between coupon and structure.

In analyzing the state of stress, the same approach should be taken as in conventional base metal design. Welded joints, however, may require additional analysis to account for discontinuity stress due to weld land transitions or deviations from theoretical contour such as weld mismatch or sink-in, stress concentration, and residual stress in the particular structure being considered. Discontinuity stresses are of particular importance in weldments where weld lands or other geometrical discontinuities in the area of the welded joint may give rise to significant increases in nominal stress patterns. In addition, weld reinforcements may require special analysis due to their influence on stress concentration. It is important that the mismatch, weld reinforcement condition, etc., which was included in the coupon testing program be recognized by the designer when differences in state of stress between coupon and structure are being analyzed.

The most difficult aspect of using coupon-derived design strengths is the recognition of the detailed conditions which the design strength represents. This difficulty would be significantly reduced by standardization of the practices used in arriving at design strengths and an orderly presentation of the design data. Then, by the use of structural testing and rating techniques, welded structure of optimum weight and known reliability can be produced.

SECTION VI

RECOMMENDED GUIDELINES

Guidelines have been developed for establishment of engineering data on weldments. The purpose of these guidelines is to provide a uniform procedure by which meaningful engineering data can be developed for use within the aerospace industry.

These guidelines generally reflect the procedures currently used within the aerospace industry. They are applicable to all types of weldable materials and welding processes. However, recommended test coupon configurations and testing methods have been limited to the evaluation of butt-type joints.

In developing these guidelines, a deliberate attempt was made to provide a procedure by which data on weldments could be generated in a manner similar to that of base metals in Mil-Hdbk-5. The guidelines contain procedures that deal with definitions, population definition, data generation, data treatment, and data presentation.

The guidelines have been prepared such that they can be utilized without reference to the remainder of this report.

The intent of these guidelines is to set forth procedures for generation and presentation of engineering data on weldments. These procedures are applicable to the aircraft and aerospace industry and concern all materials joined by welding processes.

A distinction is made in properties of weldments between those applicable to design and those used for welding development and process control. These guidelines are concerned with those properties applicable to design.

The approach followed establishes coupon-derived design properties for weldments produced under known and defined conditions. Appropriate analysis must be conducted to adapt the coupon-derived data to design of the structure being considered. This is accomplished by determining the state of stress for the component joint and/or by relating structural hardware test results to the coupon-derived design properties. The sequential steps of these procedures are summarized in Figure 11. This approach is consistent with the techniques used to obtain design data for Mil-Hdbk-5 [1], as defined in Reference 26.

These procedures require detailed definition of the welding conditions which the design strengths represent. Current military welding specifications do not contain adequate requirements for defining a meaningful population of weldments. Due to this lack of applicable industry-wide specifications, the necessary information must be presented with the coupon-derived weldment design data.

These guidelines establish procedures for the orderly generation and presentation of design data for weldments and consist of sections covering definitions, population definition, data generation, data treatment, and data presentation. These sections are presented below.

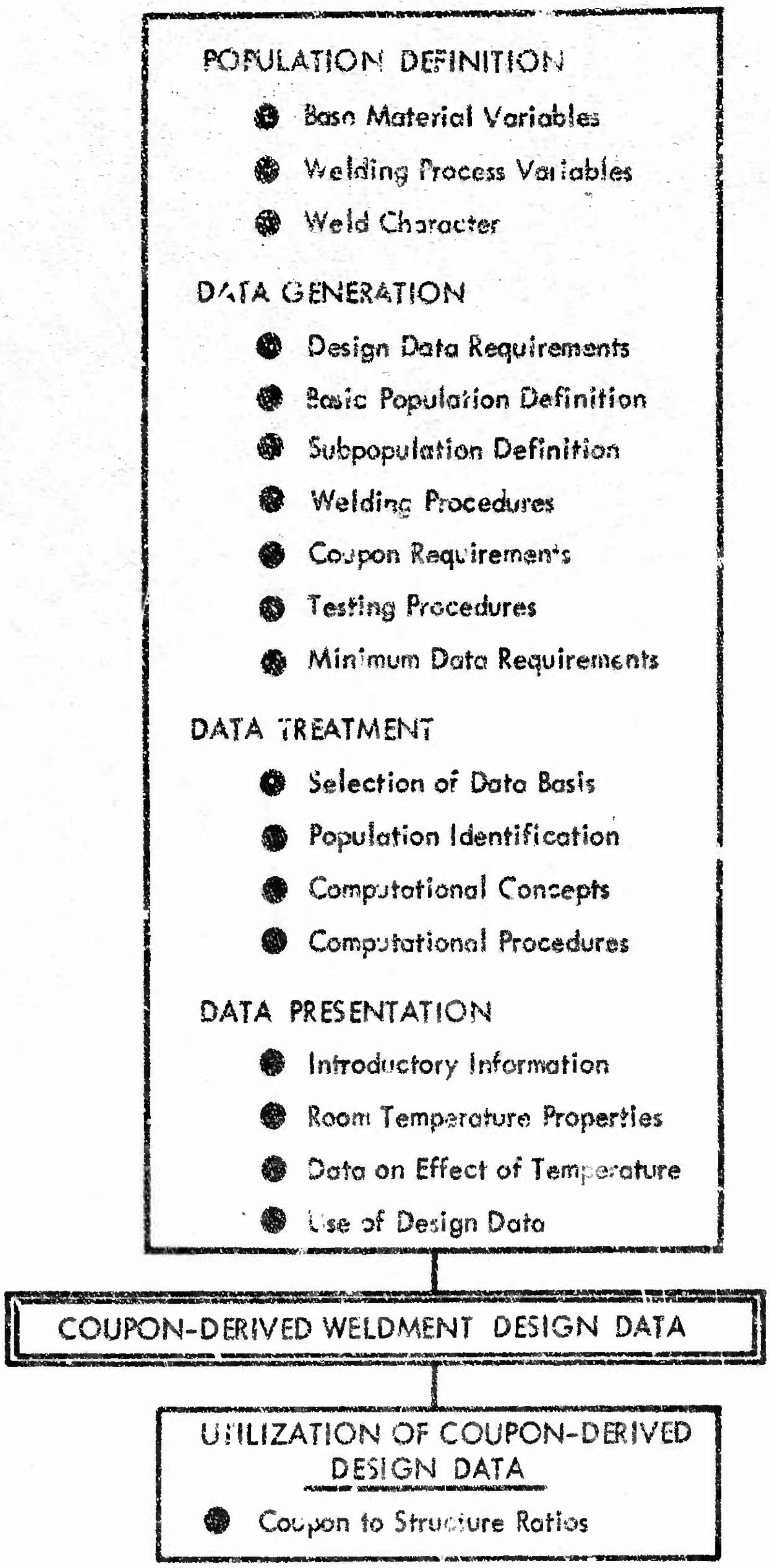


Figure 11: GUIDELINE PROCEDURES FOR COUPON-DERIVED WELDMENT DESIGN DATA

DEFINITIONS

Throughout the guidelines and in the preparation of data, definitions of the American Welding Society [33] will be used for terms relating to welding.

The definitions utilized in References 1 and 26 will be used for other terms relating to material properties and statistical treatment of data.

POPULATION DEFINITION

Determination and presentation of industry-wide properties of weldments requires adequate definition of pertinent welding parameters, including a description of base materials, welding process variables, and weld character. In the case of general metallic material properties, reference to industry-accepted material procurement specifications provides this basis for definition. For weldments, current military process specifications are not sufficiently detailed to adequately describe a given population of weldments. Present industry practice involves the stipulation of requirements and conditions in addition to those of the military specifications in order to obtain consistent, high-quality weldments meeting the requirements of industry. Therefore, at the present time, the procedure of stipulating requirements must be utilized in establishing industry-wide design data in lieu of a referenceable welding specification.

The most significant variables to be considered in weldment characterization (population definition) are divided into three basic categories: base materials, welding process variables, and weld character (see Figure 12). The variables listed are the minimum that must be identified and recorded during the initial portion of the program.

Base Materials

Initial consideration must be given to the base materials. This classification includes appropriate stipulation of alloy, composition, form, preweld and postweld heat-treat condition, filler material, and material thickness. Selection, specification, and control of these variables are generally straightforward, following the same procedures as would be used in base metal design data determination.

Welding Process Variables

The most difficult aspect of weldment characterization is establishment of welding variables. These variables must be sufficiently detailed to represent the population of weldments produced, as well as to allow later reproduction of welds within this population. The appropriate selection of variables to be stipulated must be based on an interpretation of their effect on weldment properties and the desirability of control. Using the variable of thermal-control tooling as an example, it may be found that various types of tooling influence tensile properties of a weld joint by their effect on cooling rate. However, the difficulty in adequately describing thermal-control tooling for more than a single application makes it desirable to treat tooling as a random and uncontrolled variable. This same judgment of effect on properties and desirability of control must be made for each of the welding process variables.

BASE MATERIAL

Alloy, Composition, Form, Pre-and Post-Weld Heat Treat Condition, Material Thickness, Filler Material

WELDING PROCESS VARIABLES

Joint Preparation

- Joint Type
- Edge Preparation
- Cleaning

Tooling

- Alignment
- Restraint
- Thermal Control

Welding Conditions

- Welding Process
- Welding Method
- Welding Position
- Heat Input (Weld Setting)
- Preheat
- Interpass Temperature
- Shielding Gas

Weld Repair

- Number of Repairs
- Type of Repair

WELD CHARACTER

Inspection Methods

- NDT
  - Visual
  - Radiographic
  - Penetrant
  - Magnetic Particle
  - Ultrasonic
- DT
  - Transverse Tensile Test

Acceptance Levels

- External
  - Underfill and Undercut
  - Cracks
  - Pores
  - Reinforcements
- Internal
  - Pores
  - Inclusions
  - Cracks
  - Lack of Fusion
- Tensile Properties
  - Minimum & Minimum Average

Figure 12: SUMMARY OF POPULATION DEFINITION CONSIDERATIONS

Weld Character

The third grouping of welding conditions is weld character, which is viewed from two aspects: actual character, and means of determining character. Appropriate levels of weld character must be prescribed in order to define a population of weldments. This includes a description of internal and external quality levels as well as a minimum joint strength requirement. In most specifications there are several weld classes that serve to identify in detail the quality level requirements. However, in lieu of reference to a specific class in an industry-wide specification, detailed quality levels must be given. In addition, the means of determining these weldment characteristics must be established. This involves stipulation of both nondestructive and destructive test methods.

In summary, the primary concern of population definition for weldments is to describe welding conditions in a manner that will allow reproduction of this same population and be sufficiently detailed to allow proper data analysis.

DATA GENERATION

Data generation concerns the development of a testing program based upon considerations of design data requirements, population definition, subpopulation definition, welding procedures, testing procedures, and minimum data requirements. A graphic summary of each of these elements is shown in Figure 13 and is discussed in the following paragraphs.

Design Data Requirements

Initially the type of data required and the general welding conditions of interest must be established based upon anticipated use of the data. This includes the type of property needed (e.g., tensile, fatigue), the type of data required (statistical or average), and the general welding conditions for which the data will be generated.

Basic Population Definition

The next step is selection of a basic population definition satisfying the general welding conditions previously established. The procedures outlined previously for population definition require a detailed review of applicable welding conditions in order to select a single population which will provide data consistent with the requirements for data treatment. The example shown in Table IV for 6061 aluminum weldments would be typical of a basic population definition. In this example, tooling and heat input have not been specified. It is recognized that these variables have a potential influence upon weldment properties and may require a redefinition of the original population as a result of later data analysis.

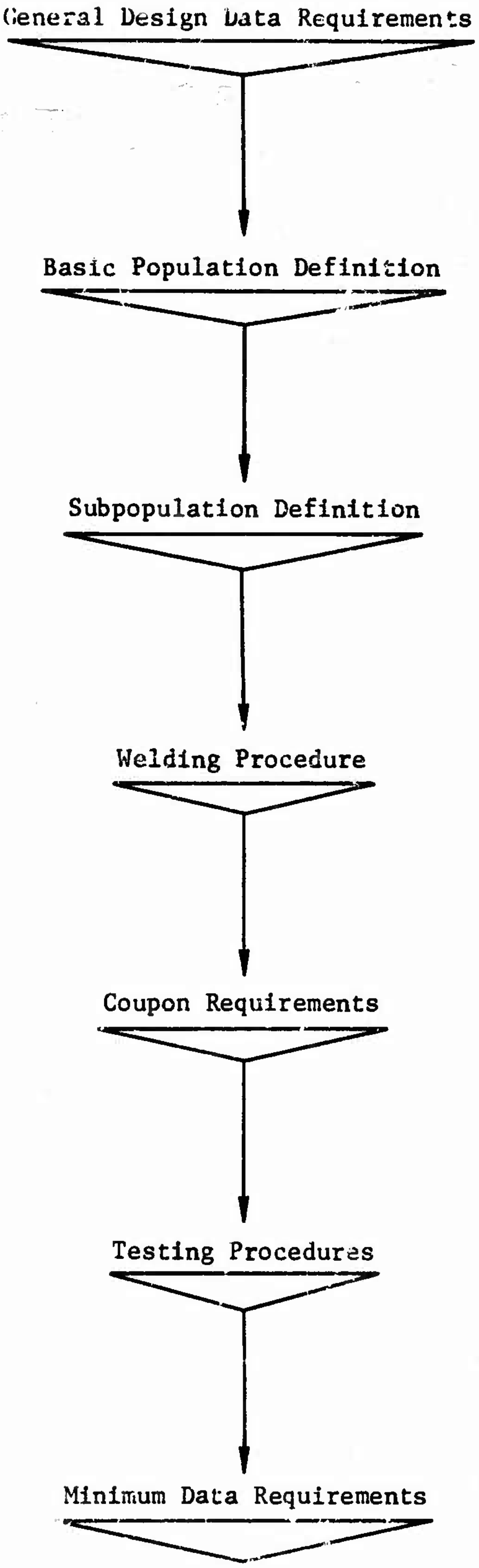


Figure 13: TESTING PROGRAM CONSIDERATIONS

Table IV: EXAMPLE POPULATION DEFINITION

BASE MATERIALS
- Alloy: 6061 Aluminum per QQ-A-250/11
- Form: Sheet
- Preweld Heat Treat Condition: T4 or T6
- Postweld Heat Treat Condition: As-Welded
- Material Thickness: 0.09 inch
- Filler Material: 4043 per QQ-B-655

WELDING VARIABLES
- Joint Preparation
  - Joint Type: Butt
  - Edge Preparation: Square Groove
  - Cleaning: Deoxidize, solvent wipe and hand scrape
- Tooling: None Specified
- Welding Conditions
  - Process: Mechanized GTA
- Sequence: Single Pass
- Position: Flat
- Heat Input: Not Specified
- Weld Repair: None

WELDMENT QUALITY
- Inspection Methods
  - Visual
  - Radiographic, Mil-Std-453
  - Penetrant, Mil-I-6866
- Acceptance Levels
  - External
    - Weld Beads: Removed Flush
    - Underfill and Undercut: None Allowed
    - Cracks: None Allowed
    - Pores: *Maximum size 0.02-inch, one per inch
    - Mismatch: 10% of Thickness Maximum
  - Internal
    - Pores and Inclusions: *Maximum Size 50% T or 0.12 inch whichever is lesser. Maximum accumulated amount less than 2% of cross section area
    - Cracks: None Allowed
    - Lack of Fusion: None Allowed

*Sharp-tailed or crack-like indications not allowed, appropriate acceptance levels will be added.

Subpopulation Definition

Selection of appropriate subpopulations is the next step in test program planning. Obvious subpopulations or associated populations of the previous example would be alternative weld/heat-treating sequences, filler materials, welding processes, weld repair, joint thickness, and weld classes (quality level). The selection of these preplanned subpopulations is dependent upon previous knowledge of their potential effect on weldment properties. However, those mentioned are the most frequently encountered subpopulations required.

Welding Procedure

The variables defining the selected basic and subpopulations must be controlled within their prescribed ranges during test program welding. This requires welding in accordance with a referenced specification and any additional requirements which may limit the population. *The generation of this data requires that welding be conducted under production conditions rather than closely controlled laboratory conditions.* In addition, data for development of design properties must adequately represent the variation allowed in the referenced specification and/or supplemental requirements for each variable.

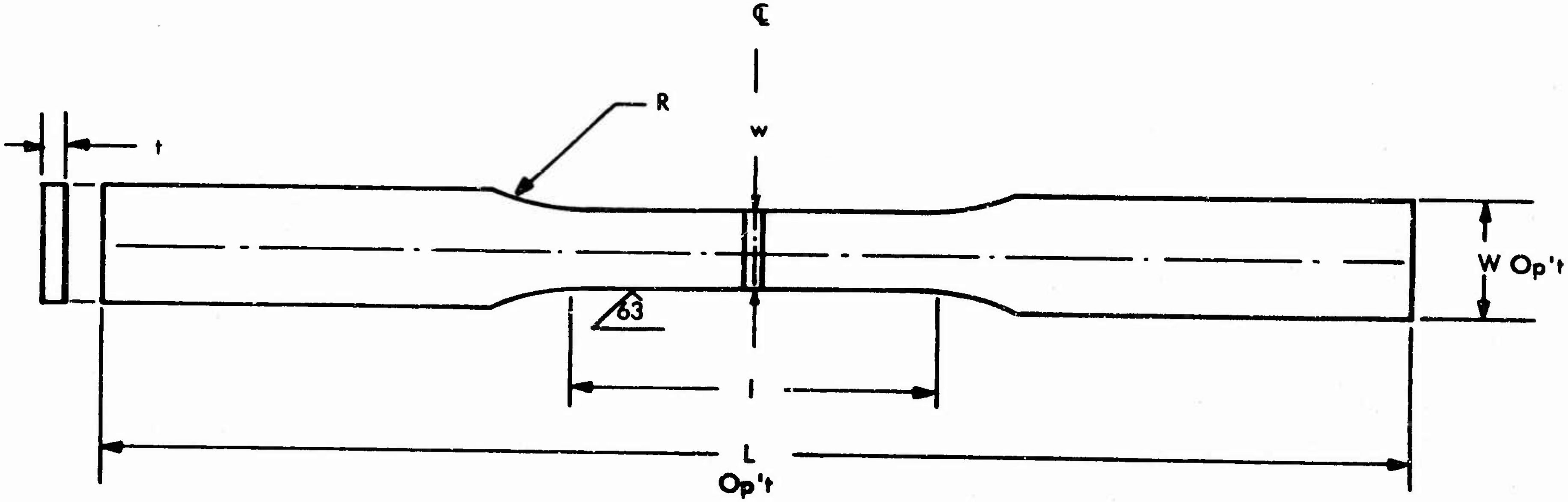
Weldments from which data are generated should represent the product of several welders, welding machines, and weld setups. It is advisable to select test samples from weldments produced at different times by different operators guided only by the specified requirements. Weldment characterization must be representative of final products rather than the idealized characterization used in many weld development studies.

Coupon Requirements

Considerable variation in actual coupon dimensions used within the aerospace industry has resulted in difficulties in obtaining comparative data. To provide the necessary uniform basis for obtaining weldment data, recommended configurations are presented in the following discussion.

Transverse-Weld Tensile Coupons---Two types of transverse-weld tensile coupon configurations are recommended. Flat coupons are to be used for materials up to 0.5-inch thickness. For weld joint thicknesses greater than 0.5 inch, round coupons are recommended. These two configurations are shown in Figures 14 and 15, respectively. Exact specimen dimensions are dependent on the thickness of the weldment being evaluated, but geometric similitude is maintained within each type of specimen. Appropriate dimensions are given for the reduced test section of each coupon. The dimensions of the gripping areas at each end are optional and may be modified to accommodate standard test fixtur

The weld beads should be removed from all flat coupons since industry standards have not been established regarding weld reinforcement configuration. This requirement provides a more uniform base on which data from several sources may be combined. When data is required for welds with reinforcements intact, their configuration must be specified.

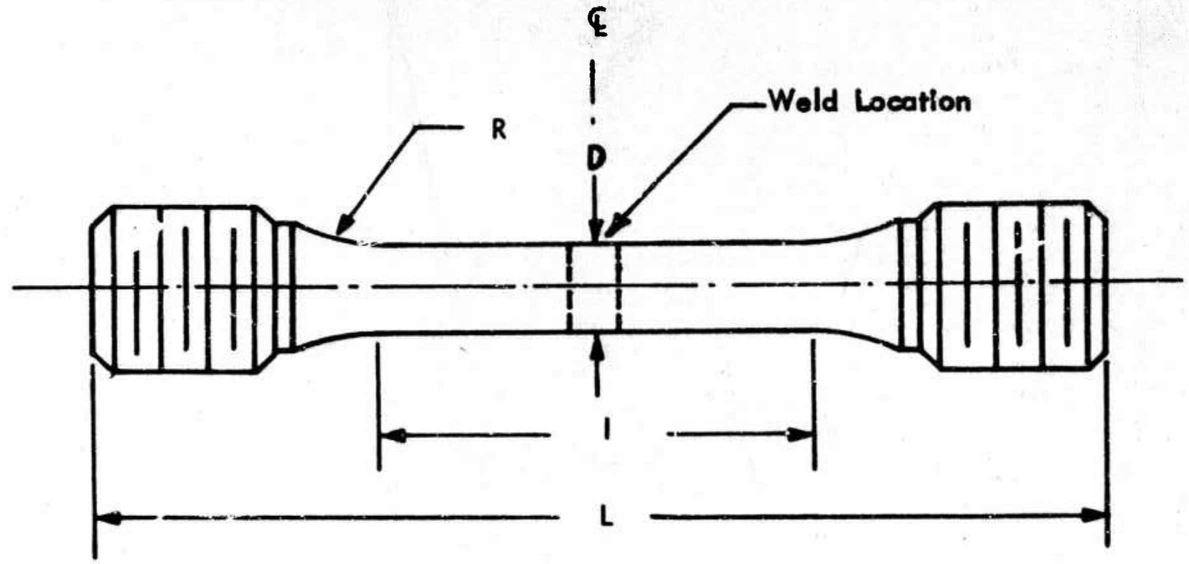


t	w	l	R
<.188	0.5	2.25	1 min.
0.188 to 0.25	0.75	3.0	1.5 min.
0.25 to 0.5	1.0	4.0	2 min.

NOTES:

1. Dimension "W" and "L" optional.
2. Weld bead on or off optional.
3. Fillet radii must fair smoothly into reduced section.
4. Material and grain direction per test requirements.
5. Specimens warped from welding or heat treatment shall not be straightened.
6. Reduced section machined surfaces 63.
7. The reduced section and grip ends must be symmetrical about the longitudinal ℄ within ± 0.01.
8. Tolerances except otherwise noted: Linear ± 0.03, Angular ±1°.

Figure 14: FLAT TRANSVERSE-WELD TENSILE COUPON



D	I	R
0.250	1.25	0.250
0.505	2.0	0.50

NOTES:

1. Dimension "L" and thread size optional.
2. Fillet radii must fair smoothly into reduced section.
3. Reduced section machined surface 32
4. Heat treatment to be performed prior to finish machining.
5. The reduced section and grip ends must be symmetrical about the longitudinal ℄ within ± 0.01.
6. Tolerances except otherwise noted: Linear ± 0.03, Angular ±1°.

Figure 15: ROUND TRANSVERSE-WELD TENSILE COUPON

When round coupons are used in thick weldments, location within the weldment becomes an additional variable which must be described and associated with the data.

Other Weldment Coupons---At present, coupon configuration requirements for the evaluation of properties other than transverse tensile have not been sufficiently defined to be utilized on an industry-wide basis.

Due to the nature of fatigue testing, no specific test configurations are recommended. Configurations selected according to standard base metal practices have been used which may be satisfactory. Weld reinforcements are of particular significance in fatigue testing and should be removed or specified in detail along with a description of the coupon used.

Fracture toughness coupons should conform to the latest requirements defined by the ASTM recommended practice. Crack location with respect to the weldment is of particular importance, and the criteria for validity of the specimen must be met.

The coupons used for evaluation of other weldment properties, such as fillet-weld shear strength and creep or stress rupture, also require definition in order to be used for industy-wide design strengths.

Testing Procedures

The availability of accepted test methods for base metal evaluation, as evidenced by federal and ASTM standards, has resulted in their general application to testing of weldments. Tensile testing per Federal Test Method Standard 151 is recommended. These standards control test equipment, data accuracy, and loading rates. Reference to existing base metal test methods are generally considered satisfactory for mechanical property testing of weldments except for the configuration definition. The testing practice and any deviations should be reported when data samples are generated. In no case may a test result be discarded on the basis of a defect found after final inspection---for example, during posttest examination of the fractured surfaces.

Minimum Data Requirements

The quantity of data that must be collected or generated depends upon the population definition and the basis on which it is to be analyzed. The bases fall into two categories: data to be statistically analyzed, and data to be presented on an average basis as defined under "Data Treatment."

Statistical Sample Requirements---The data sample must be adequate to determine the form and distribution of the population from which it was drawn. If the weldment population definition is broad and allows considerable latitude in the range of parameters defined, it is obvious that larger sample sizes will be required. Certain minimum requirements can be stated, however, based on statistical considerations.

For data to be directly analyzed on a statistical basis, a typical weldment population exhibiting nearly normal distribution characteristics should be represented by a sample containing a minimum of 100 observations. These observations should include at least 10 subsamples representing random variables such as base material lots, filler material lots, weld processing variables, and weld machine operators and setups.

Direct analysis of a data sample that is not normally distributed requires at least 300 tests to adequately define minimum strengths. As in the previous case, these observations should be representative of the total population.

Where subpopulations are defined, the above minimum data requirements apply to each subpopulation which shows a significant difference in properties.

At least 10 pairs of measurements should be used for an indirect analysis based on derived ratios. These paired observations should represent the range of variables in the specified population. If broad ranges in parameters are involved, additional observations may be required.

Average Sample Requirements---No specific data requirements have been established for properties presented on an average basis, but some general considerations are given.

Due to the number of variables inherent in a welding process, it is advisable to make as broad a sampling as practicable within the population definition. The range of material and processing parameters included in the sample will obviously influence the sample size. The total number of observations should be sufficient to identify factors that may be significant within the population such as joint thickness, weld repair, filler material, and heat-treat condition.

DATA TREATMENT

The procedures used in the analysis of test data should be based on uniform techniques that lend themselves to obtaining meaningful results while permitting some variation in approach based on decisions which are not completely arbitrary. Certain concepts have been used in this framework for base metal analyses which lend themselves to analysis techniques for weldments. The guidelines established for analysis of data for inclusion in Reference 1, as presented in Reference 26, are used as a basis for the development of analysis techniques applicable to mechanical property data for weldments.

The exact procedures used for the analysis of test data may vary from one sample to another depending on the type and quantity of data. Selection of the appropriate procedure requires a number of decisions that can best be illustrated by the flow chart shown in Figure 16. These decisions fall into the following categories:

1) Determine the basis on which the data will be presented;

2) Establish the population to which the properties apply;

3) Determine the procedure for computations;

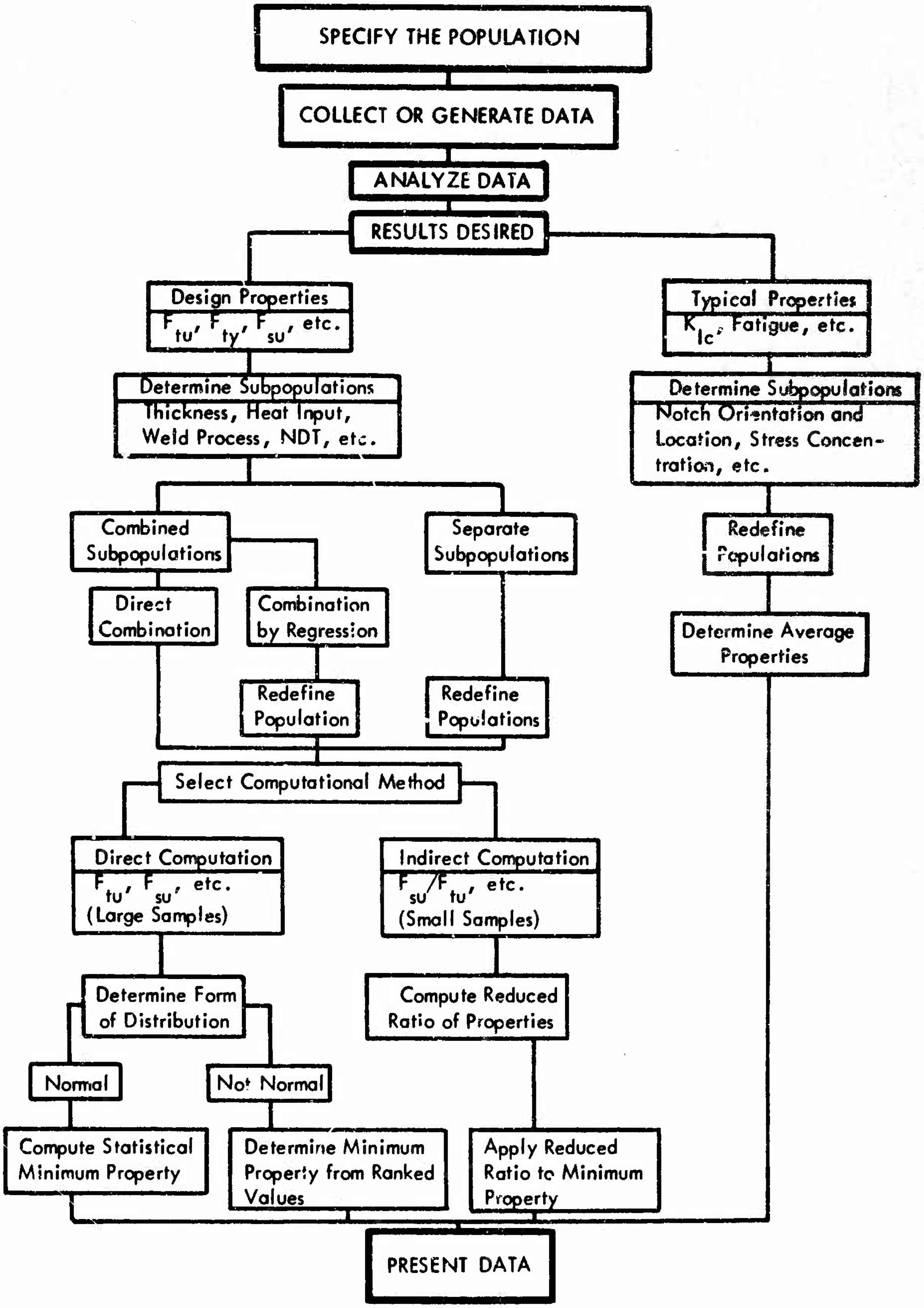


Figure 16: FLOW OF DATA FOR ANALYSIS

4) Perform the computations.

These items are described in greater detail in the following sections.

Selection of Data Basis

The end results desired and the type and quantity of data available are the major factors in selecting the data basis. Certain properties, such as fracture toughness and fatigue, are usually presented on an average basis. For tensile ultimate strength properties, minimum design strengths at stated reliability levels are desired.

The selection of the data basis must be consistent with the quantity of data available and the manner in which it represents the specified population. Calculation of statistical minimum values from a sample that does not adequately represent all of the parameters allowed in the specified population may result in values which are not valid for the intended basis.

To provide weldment data for aerospace applications consistent with the assurance levels associated with design strengths in Mil-Hdbk-5, all data should be presented on one of the following bases:

A Basis---The value above which at least 99% of the population of values is expected to fall, with a confidence of 95%.

B Basis---The value above which at least 90% of the population of values is expected to fall, with a confidence of 95%.

S Basis---The minimum value specified by the governing specification. The statistical assurance associated with this value will depend on the quality control requirements of the specification.

Average Basis---The property is an average value. No statistical assurance is associated with this value.

Population Identification

For computational purposes, the population definition must be restrictive enough to ensure that the computed properties are realistic and useful. This requires the establishment of the range of conditions for which the mechanical property can be characterized by a single distribution. The general procedure for specifying a population has been previously given; however, the analysis of data may indicate that further refinement is necessary.

The specified population will include the more obvious factors such as base material, filler material, heat-treat condition, and weld process; but less obvious factors such as joint thickness, heat input, and welding position may require further evaluation. When previously unspecified parameters or parameters that have a broad range appear to be significant, the data should be grouped in appropriate subpopulations prior to further analysis. For data to be presented on an average basis, the apparent subpopulations should be defined and presented with the data. To resolve the significance of these subpopulations in a sample to be analyzed for minimum properties, appropriate statistical tests of significance should be performed on the respective groups of data.

The statistical tests of significance are conducted for specific confidence levels and provide a sound basis for decision-making. Data groups showing no significant differences may be combined for further analysis. If differences exist, the subpopulations representing the data groups should be defined and the groups analyzed separately. The minimum strength representing the total population is determined from the subpopulation exhibiting the lowest strength.

In some cases, properties may vary continuously with some characteristic such as thickness. A correlation may be established between the property and the characteristic through regression analysis. The use of regression analysis provides a tool whereby the data groups may be recombined for further analysis.

Computational Concepts

The development of average property values requires only the calculation of the average property. If the range of values for the property varies more than ±5% from the average value, it is advisable to report the range as well. No statistical confidence is associated with this value.

Two statistical concepts may be logically applied to the analysis of weldment data. The first concept requires a direct statistical analysis of data to arrive at design properties of stated reliability. The second concept uses an indirect computational method whereby the properties of interest are established through their relationship to a property for which direct calculations are available. The statistical regression analysis is usable with either of these concepts.

Direct analysis requires relatively large amounts of data. This technique requires sufficient data to describe the form of the distribution as well as its dispersion characteristics. The form of the distribution is determined on a statistical basis by applying the chi-squared test for normality. For populations exhibiting nearly normal behavior, the computational procedures for the normal distribution are used. If the distribution is not normal, a nonparametric analysis is used which assumes a random selection of data points and uses a ranking of the individual values to arrive at the required minimum value.

The indirect analysis operates on ratios of paired properties. This procedure requires the pairing of values determined for the property being evaluated with a corresponding property for which a direct statistical distribution is known. A statistical analysis is performed on ratios of the paired observations to arrive at a reduced ratio at a stated confidence level. This reduced ratio is applied to the minimum value for the known property to derive the appropriate minimum value for the required property. Proper selection of confidence limits gives derived property values of approximately the same assurance levels as for the direct property. This procedure is applicable for relatively small data samples. As few as 10 pairs of measurements may be used if the data adequately covers the range of parameters inferred in the population definition.

The large data samples required for direct statistical analysis will usually limit its use to tensile ultimate strength of weldment coupons. The indirect analysis may be used to derive other properties of interest using smaller samples. One example would be to derive the minimum shear strength for the cases where only the tensile distribution is known; one would operate on the ratio SUS/TUS in this case.

The indirect computation method also provides a tool for rational development of weld factors to be used in translating coupon-derived minimum properties to hardware design. In this case, the ratio of hardware failure stress to control coupon failure stress is used as discussed under use of design data.

Computational Procedures

The computational procedures used for the development of minimum design strengths for weldments in aerospace structure should result in values consistent with the assurance levels associated with design strength values in Reference 1. As such, the computational procedures and statistical assurance limits required are consistent with those presented in Reference 26. Reference to AFML-TR-66-386 will provide examples in the use of the various computational forms and values for the statistical factors needed for the computations of: (1) direct computation for the normal distribution; (2) direct computation for the unknown distribution; and (3) indirect computation of property values.

DATA PRESENTATION

The presentation of data on weldments is complicated by the lack of welding specifications suitable for reference. In lieu of these specifications, a description of the pertinent welding conditions must be given in association with the property data. This may be cumbersome in some regards; however, it is necessary in order to provide meaningful and useful engineering data.

A minimum number of welding conditions should be shown in the data presentation for each basic population of weldments considered. These would include the conditions of major significance to the potential users of the data. In the population definition discussion, the many potential welding variables were discussed. Among these many variables, the following variables are the minimum that should always be specified where applicable:

1) Alloys,
2) Weld heat-treat conditions,
3) Filler materials,
4) Welding processes,
5) Weld repairs,
6) Joint thicknesses,
7) Joint types,
8) Weld quality levels,
9) Welding method, i.e., manual or mechanized.

Since the data presented are based on coupon-derived results, it is also necessary to provide comments on use of the data in structural design.

Introductory Information

When weldment data is presented it should include introductory comments to aid designers in selecting appropriate welding processes or conditions. In addition, comments alerting a designer to possible fabrication problems or environmental effects should be included. These may include: (1) potential weld heat-treating sequences for the alloy; (2) applicable welding methods; (3) comments on weldment properties; (4) discussion of pertinent welding process variables such as heat input sensitivity or restrictions, preheat requirements, atmospheric contamination, and significant metallurgical phenomena.

Room Temperature Properties

Data on room temperature properties of weldments are presented in tabular form as illustrated in Table V. The table describes base material, welding variables, and weld character conditions that the data represents, as well as the properties of interest. As footnotes to this table, the additional information required to describe these conditions is presented. Precautionary notes for use of the data in design also must be given, and are discussed below.

Data on Effect of Temperature

A typical effect-of-temperature curve of weldment properties is shown in Figure 17. This type of curve would be presented in conjunction with room temperature properties and would reference the welding conditions and precautionary notes of the room temperature case.

Use of Design Data

As a footnote to the coupon-derived design data, it is necessary to present precautionary notes on the use of the data in structural design. It is recognized that coupons may not fail under load in the same manner as a structure. This lack of one-to-one correlation may be due to either differences in weldment character resulting from the potentially higher variability of production welding or state of stress. Coupon-structure ratios are used to account for these differences.

Correlations developed using the ratioing techniques described in the computational concepts discussion may be used to determine appropriate ratios. The determination of an adequate design requires the application of the appropriate structure-coupon ratio to the coupon-derived property.

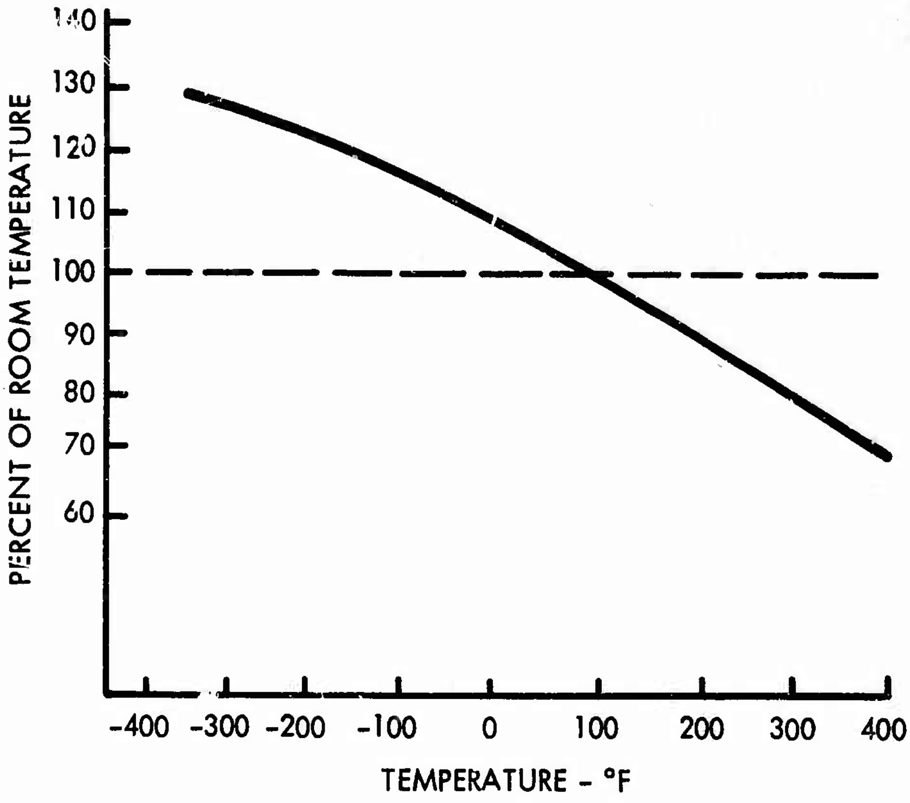
Table V: TYPICAL FORMAT FOR PRESENTATION OF ROOM TEMPERATURE PROPERTIES OF WELDMENTS

					Properties ▷1				
					F_{tu} ▷2		F_{tu} ▷3		Other Properties or ——▷ ——▷ Welding Conditions
Material	Material Thickness	Weld Joint Type	Filler Wire Alloy	Heat Treat After Welding	A	B	A	B	
6061-T4	Up to 0.30	Sq. Butt	4043	Aged to T6					
	Above 0.30	Groove	4043						
6061-T4	Up to 0.30	Sq. Butt	4043	As-Welded					
6061-T6	Above 0.30	Groove	4043						
6061-F	Up to 0.30	Sq. Butt	4043	Sol. HT and Age to T6					
	Above 0.30	Groove	4043						

▷1 These coupon-derived properties are subject to the usage limitations discussed under "Use of Design Data."

▷2 For the following welding conditions - - - - - -

▷3 For the following welding conditions - - - - - -



TRANSVERSE TENSILE ULTIMATE STRENGTH

ADD ADDITIONAL DESCRIPTIVE INFORMATION

Figure 17: TYPICAL EFFECT OF TEMPERATURE PRESENTATION

SECTION VII

VERIFICATION TESTING PROGRAM

The testing program objective was to verify and illustrate the applicability of the preliminary guidelines established as a result of Phase 1. This was accomplished by following the guideline procedures in the evaluation of tensile properties for two alloys welded under various conditions. In addition, two types of simulated structure were evaluated for a single alloy. The program involved a step-by-step application of the guideline procedures for: population definition; data generation; data treatment; data presentation; and use of design data.

POPULATION DEFINITION

Two basic weldment populations were selected for evaluation. They involved the 6061 aluminum alloy and the Ti-6Al-4V titanium alloy welded by the gas tungsten arc process. The GTA welding process was selected due to its predominant usage within the industry. For the same reason, the 6061 aluminum alloy was selected in order to provide information that would be relatable to the extensive data and experience available for this alloy. The as-welded and welded-plus-heat-treated conditions for the 6061 aluminum alloy were selected to contrast their sensitivity to welding variables and, therefore, illustrate the usefulness of the guideline techniques. The titanium alloy illustrates the guideline procedures application to diverse alloy systems. In each case the weldment characterization of base materials, welding variables, and weld character were established by selecting the desired variables and specifying the remaining pertinent welding conditions.

Base Materials

The base-material variables selected for evaluation were those shown in Tables VI and VII for the 6061 aluminum and Ti-6Al-4V alloys, respectively. In addition, the base-material conditions are summarized in Tables VIII and IX for each of the alloys. A distinction between variables and conditions is made in that variables are specifically varied to provide potentially different populations or subpopulations while conditions involve uncontrolled or random variation.

Weld/heat-treating sequence and material thickness were the two base-material variables for the 6061 aluminum alloy; no base-material variables were evaluated for the titanium alloy.

The 0.09-inch-thick 6061 aluminum alloy used for the flat panels and pressure vessels included three sheets of material representing three different heats. The other thicknesses of aluminum and the titanium samples were taken from a single sheet or plate of each gage. The material used for tension tubes was 6061 alumunium alloy extrusion. The test program did not evaluate the influence of the base-material differences with respect to heat treatments or form. However, it should be recognized that the extruded material is significantly different in properties than sheet.

	BASE MATERIAL VARIABLES		WELDING VARIABLES		
TEST OBJECTIVES	WELD-HEAT TREATING SEQUENCE	JOINT THICKNESS INCHES	TOOLING	MANUAL REPAIR	MECHANIZED REPAIR
Tensile Coupon Basic Property	-T6 As-Welded	0.09	Chill		
			Insulated		
Tensile Coupon Joint Thickness Variable	-T6 As-Welded	0.06 0.125 0.25 0.375	Chill		
Tensile Coupon Weld/Heat Treating Sequence	Solution Treat And Age After Welding To T6	0.09	Chill		
			Insulated		
Tensile Coupon Weld Repair	-T6 As-Repaired	0.09	Chill	X	
					X
Tensile Coupon Weld Reinforcement	-T6 As-Welded	0.09	Chill		
Tension Tube To Coupon Ratios	-T6 As-Welded	0.09	None		
				X	
Pressure Vessel To Coupon Ratios	-T6 As-Welded	0.09	Chill		
				X	

A

BLES	WELD CHARACTER VARIABLES			COUPON OR SPECIMEN QUANTITIES		
ECHANIZED EPAIR	WELD REINFORCEMENTS		JOINT MISMATCH	NUMBER OF WELDERS	NUMBER OF COUPONS PER WELDED PANEL	NUMBER OF COUPONS OR SPECIMENS
	ON	OFF				
		X		10	3	60
		X		10	3	60
		X		3	3	9
		X		3	3	3
		X		3	3	9
		X		3	3	9
		X		10	3	30
		X		5	3	15
				5	1	15
X				5	3	15
	X			5	2	10
		X		5		10
				5		5
	X			5		5
		X		4		8
		X		3		3
		X	X	3		3

Table VI: 6061 ALUMINUM ALLOY WELDING SUMMARY

B

Table VII: TITANIUM 6Al-4V TENSILE COUPON EVALUATION SUMMARY

TEST OBJECTIVE	BASE MATERIAL VARIABLES	WELDING VARIABLES		WELD CHARACTER VARIABLES	NUMBER OF WELDERS	COUPONS PER WELDED PANEL	TOTAL COUPONS
		UNREPAIRED	REPAIRED				
Tensile Coupon Property	None	X		None	10	3	60
Influence of Manual Repair	None		X	None	8	1	24
Supplementary Basic Property Data [1]							20

[1] Coupon Results From Availability Data

Table VIII: 6061 ALUMINUM WELDING CONDITIONS

BASE MATERIALS

*Alloy: 6061 Aluminum per QQ-A-250/11

*Form: Sheet and Plate

*Preweld Heat Treat Condition: -T6

*Postweld Heat Treat Condition: Variable (As-welded or solution treat and age to T62)

*Material Thickness: Variable (0.06 to 0.38 inch)

*Filler Material: 4043 per QQ-B-655

WELDING VARIABLES

Joint Preparation
  Joint Type: Butt
  Edge Preparation: Square Groove
  Cleaning: Deoxidize, solvent-wipe, and hand-scrape

*Tooling: Variable (Conventional or insulated)

*Welding Conditions
  Process: Mechanized GTA, D.C.

*Sequence: Single Pass

*Position: Downhand

*Weld Repair: Variable (Manual or mechanized)

WELD CHARACTER

*Inspection Methods
  Visual
  Radiographic, Mil-Std-453
  Penetrant, Mil-I-6866

Acceptance Levels ▷1

External
  Cracks: None
  Mismatch: Variable (Normally 10% T max)
  Porosity open to the surface: One per inch, max. size 30% of T or 0.10-inch ▷2
  Weld Reinforcement: Variable (Reinforcements on or off)
  Undercut: 10% of thickness or 0.03-inch ▷2
  Overlap: 1T or 0.10-inch length ▷2
  Concavity: 20% T or 0.03-inch ▷2 1T max. length
  Crators: 20%T or 0.30-inch depth ▷2 1T max. length

Table VIII: (Concluded)

Underbead Drop Through: 20% T or 0.04 inch for T up to 0.25-inch and 0.07 inch for T 0.25 inch and over
Thinning: None to thickness less than minimum T
Incomplete Penetration: 20% T or 0.03-inch depth, 1T max. length
Cold Shut: 1T or .10 inch length
Accumulation of the above: 10T min. between any 2 defects

Internal

Subsurface defects such as inclusions, porosity, etc.: Max. dimension of any single defect shall be 50%T or 0.12 inch[2]. Accumulation of defects shall be per Figure 18. Aligned fine porosity is acceptable in 1/4 inch length if less than 1/2 of length is composed of voids. Aligned defects (4 or more) shall not be accepted when the spacing between them is less than three times the smallest defect.

[1] "T" signifies thickness

[2] whichever is lesser

* Conditions identified by asterisk were specified by drawing in the verification testing program; remaining conditions were specified by welding specification

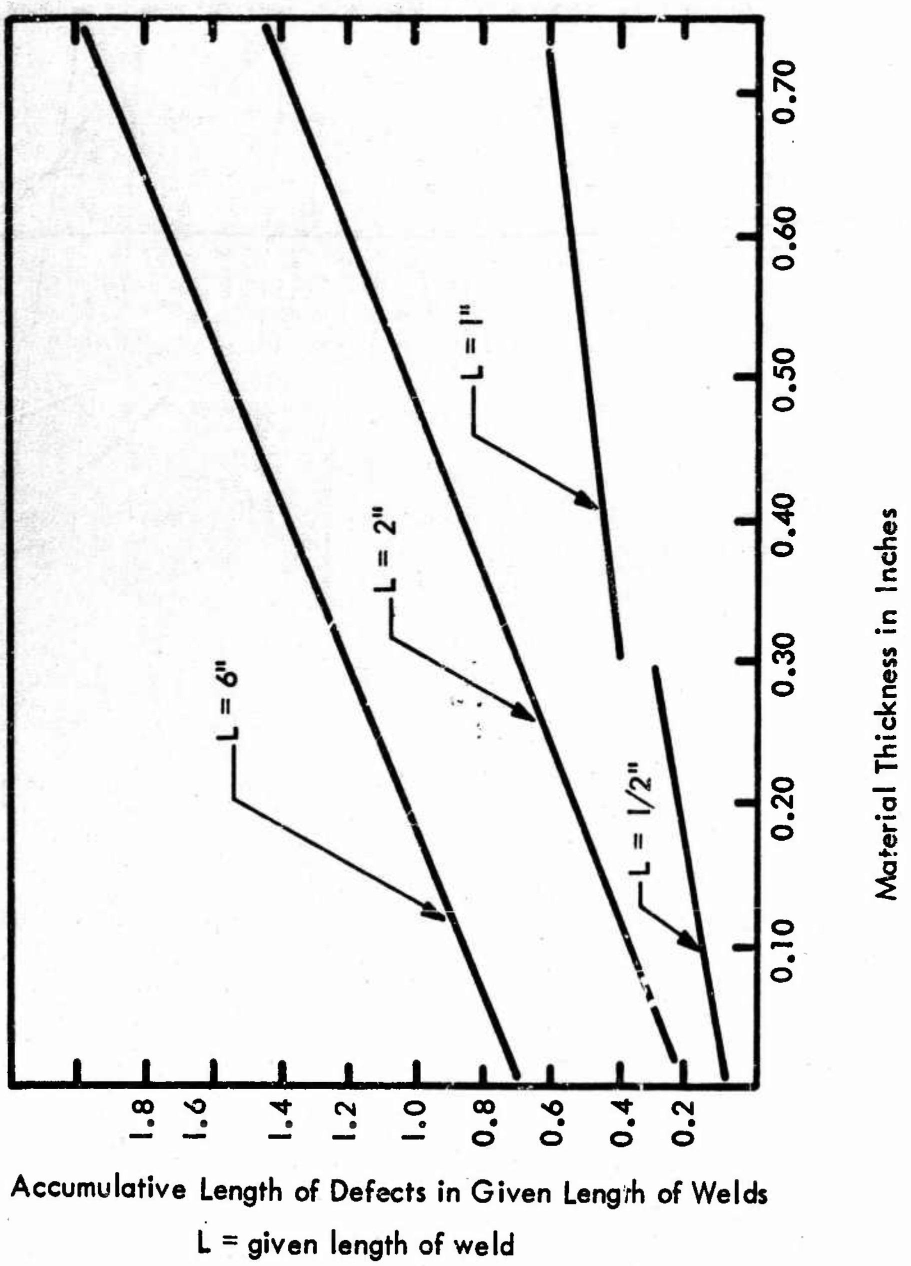


Figure 18: ALLOWABLE ACCUMULATIVE SUBSURFACE DEFECTS

Table IX: TITANIUM 6Al-4V ALLOY WELDING CONDITIONS

BASE MATERIALS

- Alloy: Ti-6Al-4V per MIL-T-9046 Type III, Comp. C
- Form: Sheet
- Thickness: 0.06-inch
- Heat Treat Condition: Solution Treated and Aged (1725°F, W.Q., 1000°F for 2 hrs.)
- Postweld Heat Treatment: 1000°F - 2 Hours
- Filler Material: C. P. Titanium per AMS 4951

WELDING PROCESS VARIABLES

- Welding Process: Mechanized Gas Tungsten Arc
- Joint Type: Butt
- Joint Preparation: Square Groove
- Cleaning: Alkaline Clean, Rinse, Nitric Hydrofluoric Acid Etch, Water Rinse
- Welding Position: Flat
- Welding Sequence: Single Pass
- Weld Repair: Manual (machine out and fill), Variable

Weld Character

- Inspection Methods
    - Visual
    - Radiographic, MIL-STD-453
    - Penetrant, MIL-I-6866

Acceptance Levels [1]

External Quality

Cracks: None allowed
Lack of Fusion: None allowed
Undercut: 12% of T, max. of 0.25-inch long, shall not exceed 10% of weld length
Overlapping: Not allowed
Weld Reinforcements: Approximately 1/3 T in height and shall merge smoothly with top surfaces
Porosity and Inclusions: Surface porosity or inclusions not allowed
Overlap: Not allowed
Craters: Max. depth 20% of T provided they are crack free with smooth rounded contours
Underfill: Not allowed

Internal Quality: As shown in Table VIII

[1] T signifies joint thickness

* Conditions identified by asterisk were specified by drawing in the verification testing program, remaining conditions were specified by welding specification.

Welding Variables

The major welding variable evaluated was repair welding. For the titanium alloy (Table VII) manual repair was used; in the case of 6061 aluminum (Table VI) manual repair, mechanized repair, and tooling type were evaluated. The tooling was specified as chill (hold-down and back-up bars used as required), or thermally insulated (no metal tooling in contact with the weld joint area). The welding conditions specified for each of the alloys are shown in Tables VIII and IX.

Weld Character

No weld-character variables were included in the titanium evaluation. In the case of 6061 aluminum, weld reinforcement and weld mismatch variables were included as shown in Table VI. The weld character conditions used for each of the alloys are shown in Tables VIII and IX.

DATA GENERATION

The data generation phase of the program involved welding procedures, panel welding, simulated structure welding, test specimen preparation, testing, and data presentation.

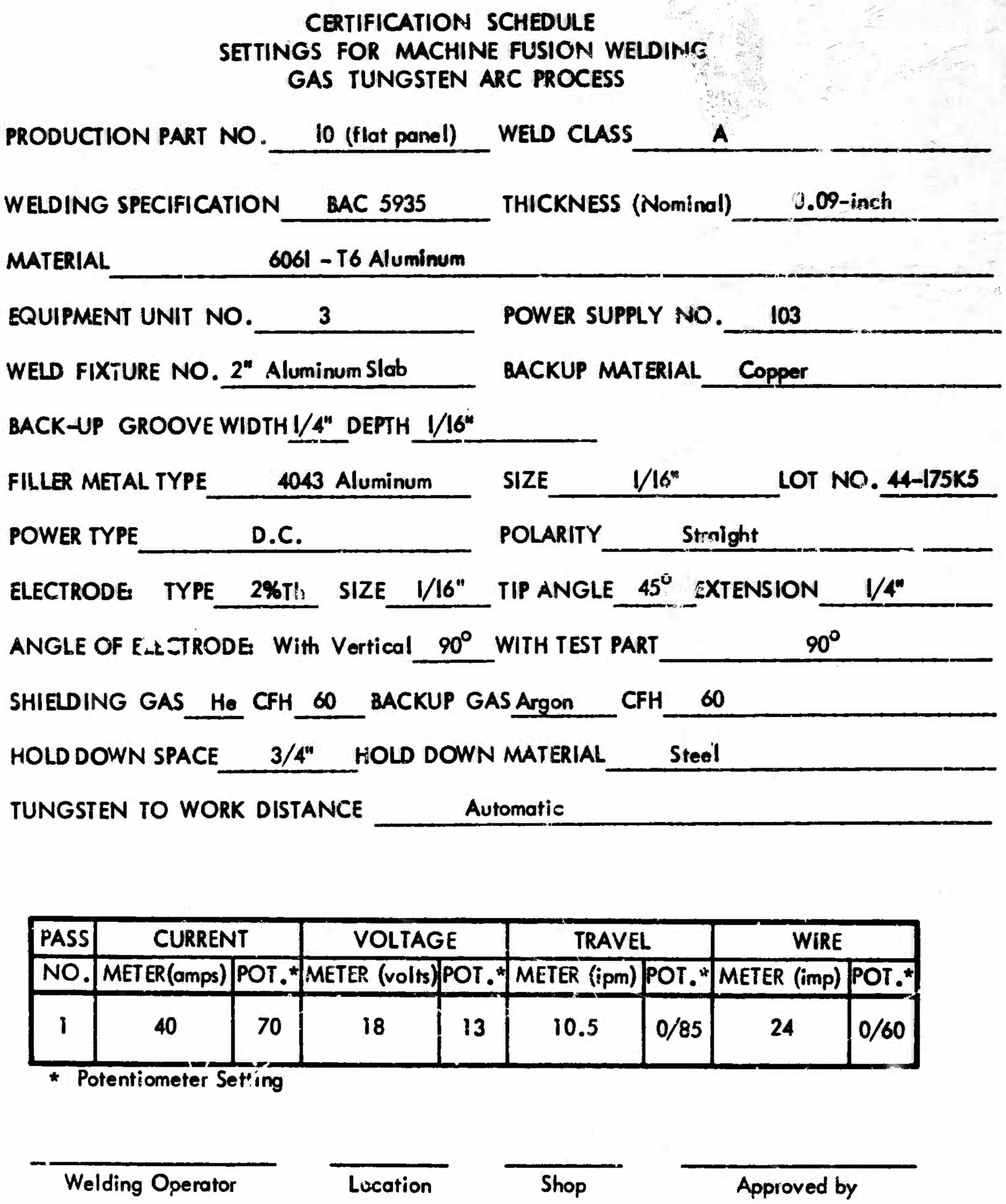
Welding Procedures

The required welding was accomplished in production shops in a manner similar to routine production welding. Welding conditions were specified by drawings and specifications as shown in Tables VIII and IX. For each different weldment produced by a given welder, a "certified setting" was developed and used to weld all panels, tubes, or pressure vessels. An example certified setting is shown in Figure 19 for a typical 6061 aluminum alloy weldment. As shown in this example, information in excess of that required for population definition, such as volts, amperes, and travel speed, was recorded for each weldment in the event that later data analysis would demonstrate the need for further population definition.

Equal importance was given to the welding conditions not specified to the welder in order that weldments representative of the stated population would be obtained.

Panel Welding

All panels welded were 10-inches wide and 12-inches long with the joint in the panel center running parallel to the 12-inch dimension. Mechanized repair welding was accomplished by rewelding with full penetration a minimum of 6 inches of weld. Manual repair welding was conducted by filling a groove 75% of the joint thickness deep and 0.2-inch wide. The nominal length of each groove was 2 inches. Grooves in aluminum were prepared by hand grinding with an abrasive wheel and in titanium by a milling machine.



CERTIFICATION SCHEDULE
SETTINGS FOR MACHINE FUSION WELDING
GAS TUNGSTEN ARC PROCESS

PRODUCTION PART NO. 10 (flat panel) WELD CLASS A

WELDING SPECIFICATION BAC 5935 THICKNESS (Nominal) 0.09-inch

MATERIAL 6061 - T6 Aluminum

EQUIPMENT UNIT NO. 3 POWER SUPPLY NO. 103

WELD FIXTURE NO. 2" Aluminum Slab BACKUP MATERIAL Copper

BACK-UP GROOVE WIDTH 1/4" DEPTH 1/16"

FILLER METAL TYPE 4043 Aluminum SIZE 1/16" LOT NO. 44-175K5

POWER TYPE D.C. POLARITY Straight

ELECTRODE: TYPE 2%Th SIZE 1/16" TIP ANGLE 45° EXTENSION 1/4"

ANGLE OF ELECTRODE: With Vertical 90° WITH TEST PART 90°

SHIELDING GAS He CFH 60 BACKUP GAS Argon CFH 60

HOLD DOWN SPACE 3/4" HOLD DOWN MATERIAL Steel

TUNGSTEN TO WORK DISTANCE Automatic

PASS	CURRENT		VOLTAGE		TRAVEL		WIRE	
NO.	METER (amps)	POT.*	METER (volts)	POT.*	METER (ipm)	POT.*	METER (imp)	POT.*
1	40	70	18	13	10.5	0/85	24	0/60

* Potentiometer Setting

Welding Operator

Location

Shop

Approved by

Figure 19: TYPICAL CERTIFIED SETTING INFORMATION

Simulated Structure Welding

The tension tubes and cylindrical pressure vessels were welded using the same procedures as the flat panels.

Figure 20 shows a typical tension tube after testing. The tubes were machined from 0.25-inch wall, 4-inch-diameter extruded tubing. In this case no tooling, either chill or insulated type, was used during welding. Tubes were mechanized-welded in a rotating fixture by manual intermittent tacking followed by a single-penetration welding pass. In this type of a circumferential weld, a tailout is necessary, which constitutes an area in the weld that has been rewelded or overlapped. Manual repair welding of the tubes was accomplished in the same manner as the flat panels.

The cylindrical pressure vessels were of the roll and weld type as shown in Figure 21. The cylindrical sections were fabricated from the same sheets of material used for the flat panel welding. They were rolled to a nominal 8-inch diameter and prepared for longitudinal welding. After welding and inspection, the cylinders were trimmed for length and the hemispherical domes manually welded to complete the pressure vessels.

The planned mismatch in the longitudinal weld was provided by a shim of 0.03-inch thickness. Inspection after welding revealed that unintentional mismatch occurred in several of the longitudinal welds. The amount of this mismatch was recorded for later data analysis.

Test Specimen Preparation

The required number of tensile coupons was removed from each of the flat panels in the form of 1-inch-wide blanks. These were processed according to the testing plan (Tables VI and VII). In most cases, three coupons for a particular condition were removed from a single welded panel. These coupons were taken from random locations within the panel.

The majority of coupons had the weld bead removed, which was accomplished by milling to within 0.03 inch of the surface and hand-filing flush with the base metal.

Dimensions of the tensile test coupons were those shown in Figure 14. Gage width was 0.5 inch for thicknesses up to and including 0.25 inch and 0.75 inch for the 0.38-inch-thick material.

With the exception of weld bead removal, the tension tubes and pressure vessels were complete and ready for testing after initial welding. Weld beads were removed from these specimens in the same manner as in the tensile coupons.

Testing

Tensile testing was conducted in accordance with the requirements of Federal Test Method 151. The equipment used for testing was a 60-kip Tinius Olsen machine. In addition to failure load of tensile coupons, a stress-strain curve and elongation measurements were obtained. The extensiometer

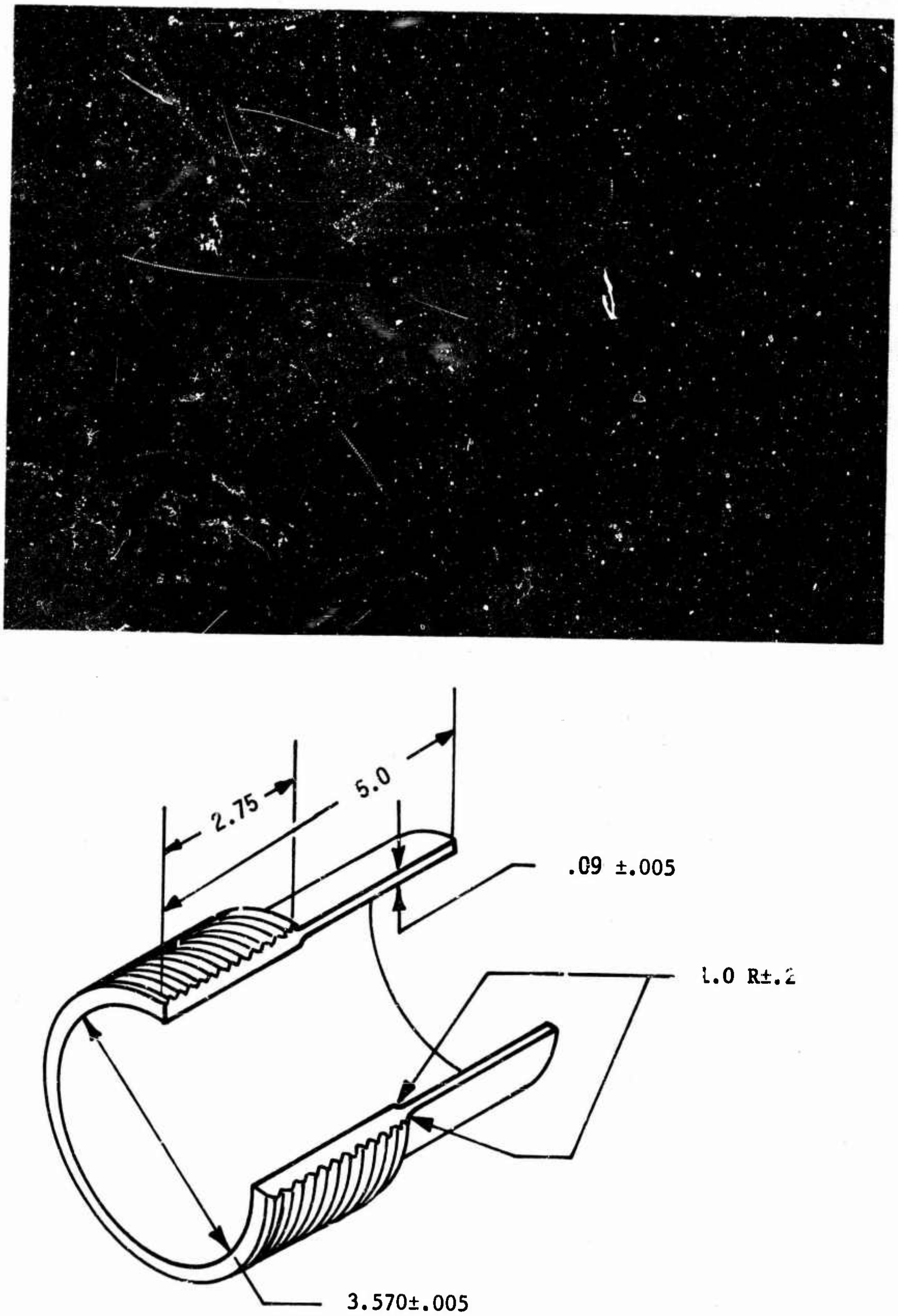


Figure 20: TENSION TUBE, TYPICAL FAILURE AND DIMENSIONS

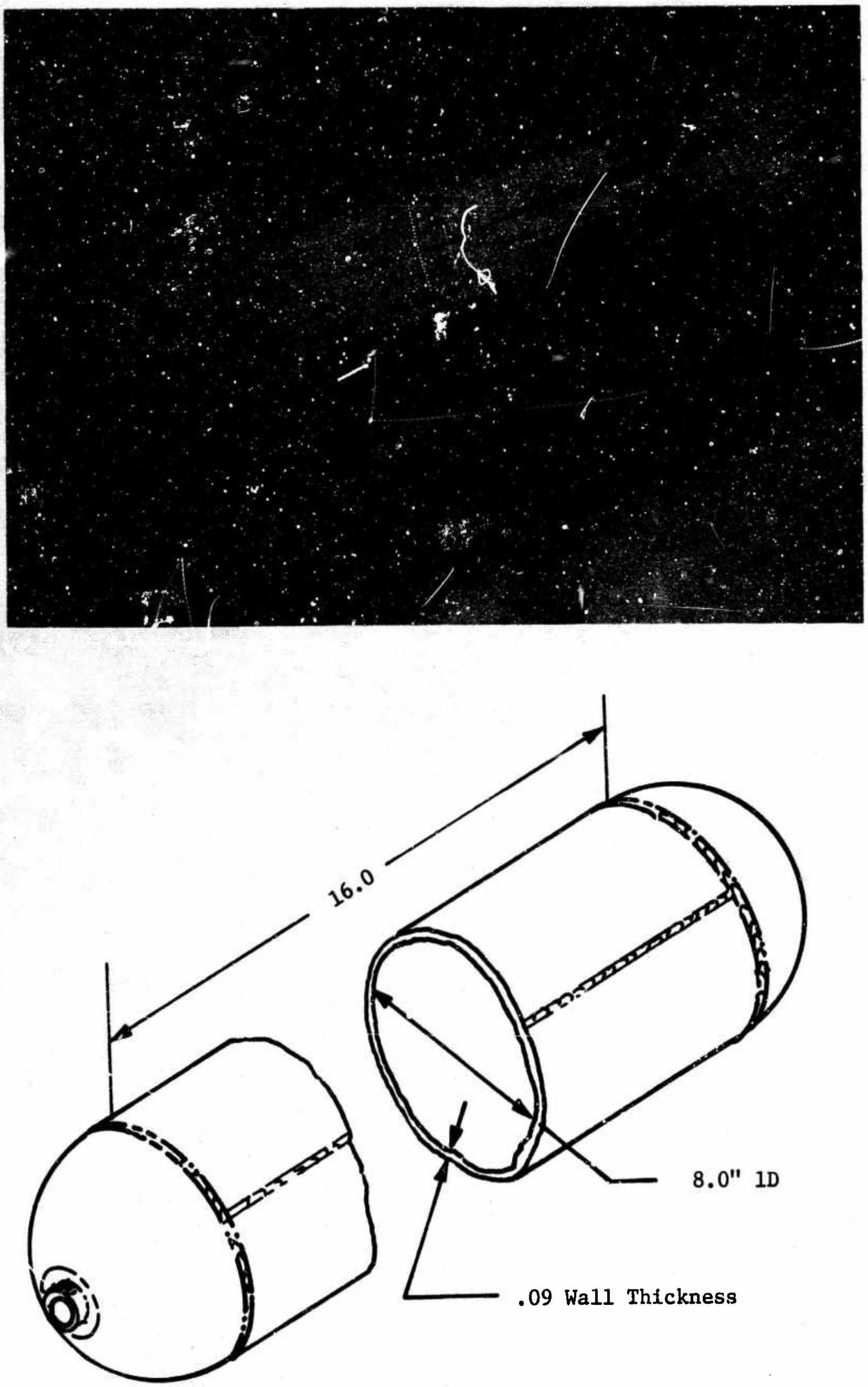


Figure 21: PRESSURE VESSEL, TYPICAL FAILURE AND DIMENSIONS

used measured strain over a 2-inch gage length. In conducting the room temperature tests of tensile coupons, a strain rate of 0.005 inch per minute was used to yielding, at which time the rate was increased to 0.05 inch per minute to failure.

Testing of tension tubes was accomplished using appropriate end fittings and the same testing equipment. Loading rate in this case was 0.005 inch per minute to 40-kip load, followed by an increase to 0.05 inch per minute to failure. No attempt was made to obtain data on yielding behavior of the tension tubes.

Burst testing of the cylindrical pressure vessels was accomplished at room temperature by pressurizing with water at a rate of 500 pounds per minute to failure. Results obtained from the burst tests were ultimate failure pressure.

Data Presentation

Tensile Coupon Results---Individual results of the tensile coupon testing are presented in Appendix C. These results include welder identification, ultimate strength, yield strength, percent elongation in 0.5 and 2.0 inches and failure location. For ease of presentation, the data has been grouped by welding condition in appropriate tables. For each table, individual results are identified by a coupon coding which defines the welding conditions.

Simulated Structure Results---The results of simulated structure tests are also presented in Appendix C. Results of the tension tube tests include welder identification, failure load, failure stress, and failure location. The failure stress was calculated from failure load and nominal tube cross section.

The pressure vessel results include welder identification, burst pressure, failure location, failure stress, and comments on mismatch. The failure stress was calculated using the simple hoop-stress equation.

DATA TREATMENT AND ANALYSIS

The data samples generated during this portion of this program and other data collected from previously conducted tests were analyzed to illustrate the applicability of analysis techniques for determining design strengths for weldments. This not only illustrates the analysis of data from a single program, but shows how data from other sources may be used to expand sample sizes or evaluate additional parameters.

The conclusion reached from the results of the industrial and literature survey discussed in this report indicated that the most desirable basis for presentation of weldment design strengths was the statistical A basis of Mil-Hdbk-5. This basis is used in the example cases that follow and corresponds to a design strength above which 99% of the population strengths will fall with a confidence level of 95%. The example cases treat tensile ultimate strengths because this property is of interest to the majority of users. The techniques illustrated can be applied equally well to other properties or for other statistical assurance levels, provided sufficient data is available.

The development of design strengths involves the analysis of coupon-generated data and the interpretation of these strengths with respect to a particular type of application. Two examples of coupon-structure correlations are included to illustrate methods of data analysis and the magnitude of its importance.

Two statistical concepts are illustrated in the analysis of weldment data. The first concept uses a direct statistical analysis to arrive at a minimum property of stated reliability. The second concept uses an indirect computational method whereby the property of interest is established through its relationship to a property for which a direct analysis is available. Regression analysis techniques are used to account for properties that vary with some dimensional parameter and are illustrated for both direct and indirect concepts. The statistical bases for these analysis concepts are shown in Appendix C.

In the following discussion, the direct analysis of the re-heat-treated 6061 aluminum alloy and the Ti-6Al-4V alloy weldments is presented first, followed by the analysis of the complex data sample for the as-welded 6061 aluminum alloy.

Direct Analysis of Coupon Strengths

The direct analysis of coupon-generated data is illustrated for two different alloy systems. The processing of each material was limited to represent a specific population so as to minimize arbitrary decisions during analysis. The two illustrations analyze the tensile ultimate strengths of GTA welded 6061 aluminum sheet, re-solution treated and aged after welding, and GTA welded 6Al-4V sheet, stress-relieved after welding. Full processing details have been given previously.

The test plan for each of these materials included definition of an additional parameter that may or may not be significant. This parameter was tooling for the 6061 aluminum alloy and manual repair for the Ti-6Al-4V sample. The techniques used illustrate the necessity of having adequate processing information during the analysis of test data. Figure 22 shows flow charts representing the paths used for analysis of the two materials.

Analysis of Re-Heat-Treated 6061-T6 Welds---The data sample consisted of 30 coupon test results representing five welders using chill-type tooling plus 15 coupon results representing the same five welders using insulated-type tooling. The statistics were calculated for these two subpopulations and are shown in Table X.

To determine whether tooling is a significant factor and must be considered in the definition of the population the analysis represents, a test for significance was conducted between the two subsamples. The results (Table X) indicate that the data for insulated tooling does not differ significantly from that for chill-type tooling. The data was therefore combined for further analysis.

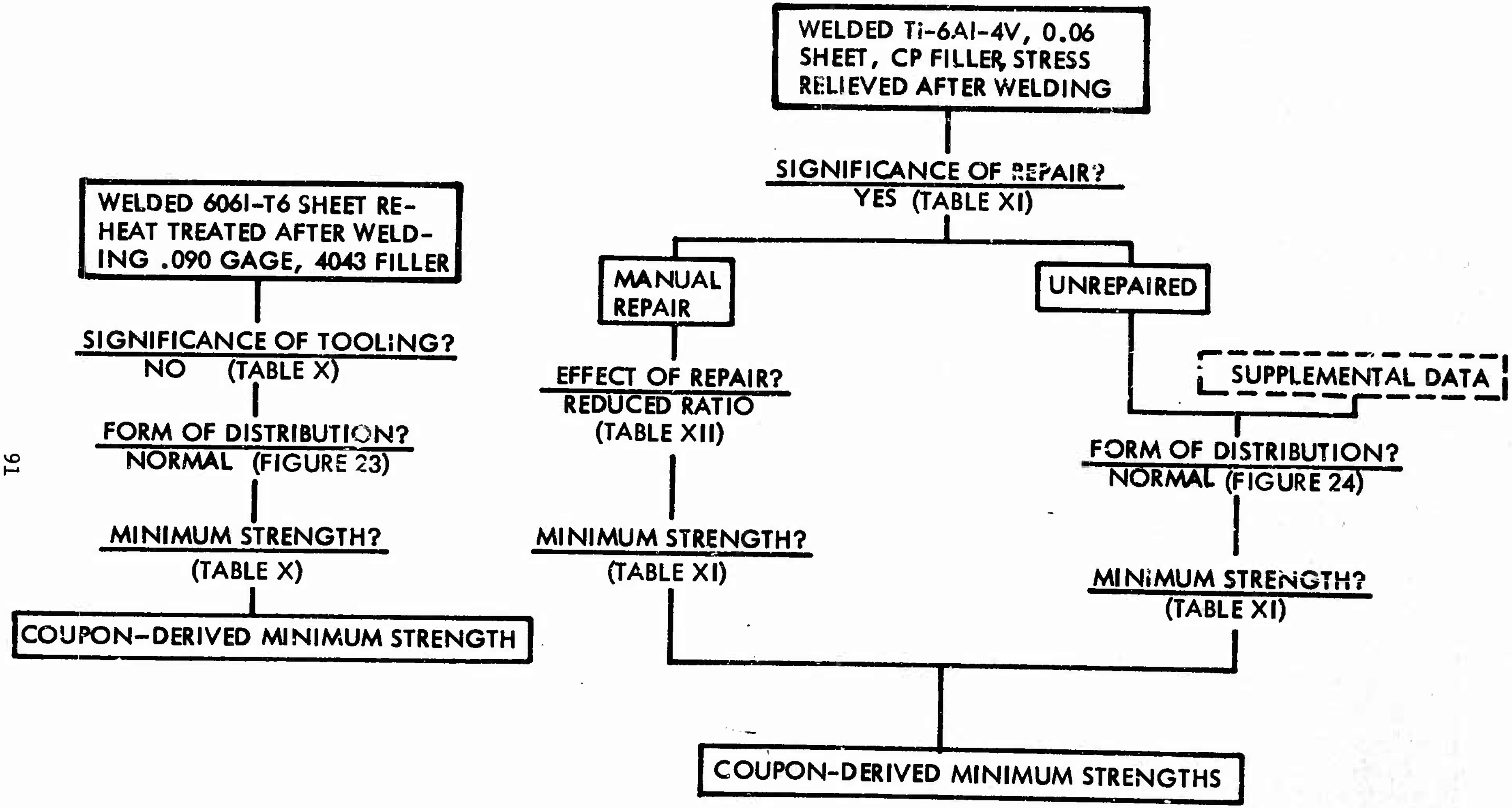


Figure 22: FLOW CHARTS FOR ANALYSIS OF 6061-T6 AND Ti-6Al-4V DATA

Table X: STATISTICAL SUMMARY OF TENSILE ULTIMATE STRENGTH OF RE-HEAT-TREATED 6061-T6 WELDS

	Tooling	No. Tests n	Avg TUS $\overline{X}$, ksi	Range of Test Values, ksi	Std Deviation S, ksi	Coefficient of Variation, $S/\overline{X}$
Data Sample Statistics	Chill	30	47.14	42.7 - 51.4	1.583	3.4%
	Insulated	15	47.11	44.5 - 51.0	1.615	3.4%
	Both	45	47.13	42.7 - 51.4	1.576	3.3%
Difference in Variance	Insulated/ Chill	$F = 1.04$ $F_{.975} = 2.37$ Not Significant, $F_{.975} > F$				
Difference in Means	Insulated/ Chill	$D_{\overline{X}} = 0.03$ $S_p = 1.594$ $t_{.975} = 2.018$ $u = 1.02$ Not Significant, $u > D_{\overline{X}}$				
Minimum Strength	Both	$F_{.99} = \overline{X} - k_{.99}\ S = (47.13) - (2.898)\ (1.576) = 42.5$ ksi				

The statistics for the combined sample were calculated as shown in Table X, and the distribution of the resulting sample was checked for normality prior to calculation of minimum strength. Figure 23 shows the distribution of test data and the χ^2 calculations for determining normality. The assumption of normality cannot be rejected, so calculations using normal statistics were used to arrive at the minimum tensile ultimate strength of 42.5 ksi.

The data sample in this case is not as large as is suggested in the guidelines for determining design strengths due to the limited testing allowed in this program, but the method of analysis illustrates the technique required to develop adequate minimum strengths.

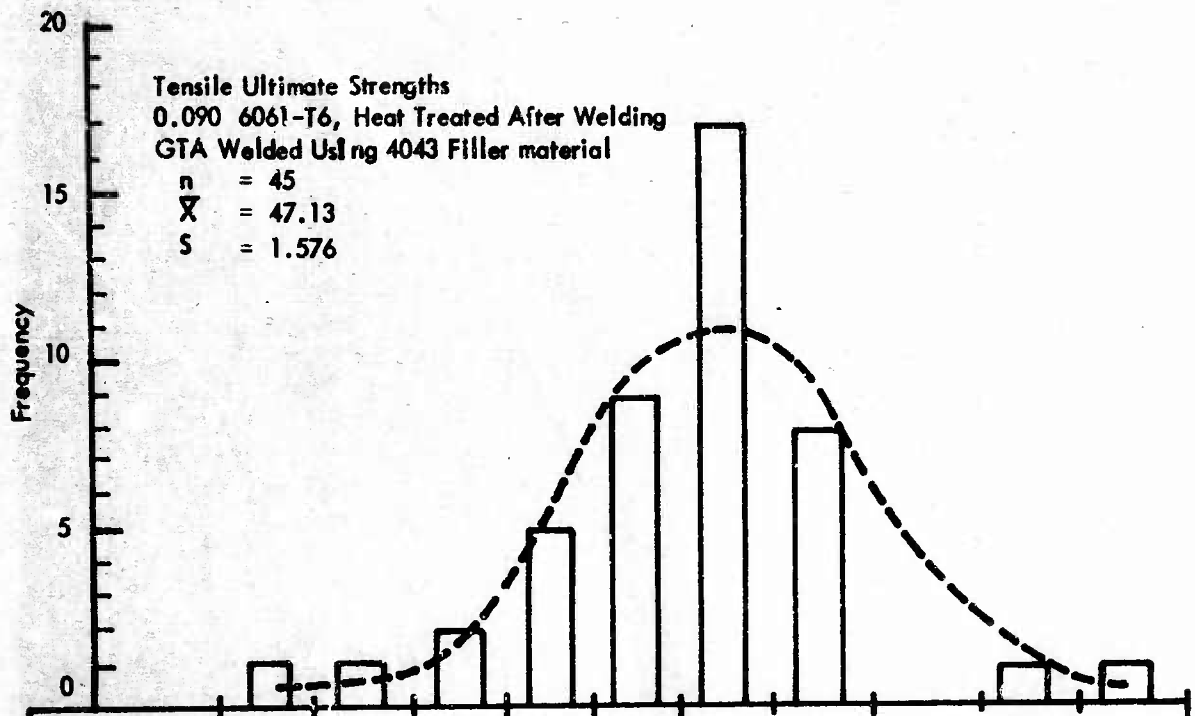
Analysis of Ti-6Al-4V Weld Data---The data sample consisted of 62 coupon test results representing 10 welders plus 24 tests of manually repaired welds. To supplement the data generated in this program, an additional 26 values were collected from previous tests. Sample statistics were calculated for each group of data and are summarized in Table XI.

The significance of repairing was examined by comparing the unrepaired- and repaired-weld data generated in the current program. The tests for significance indicated that significant differences occurred between the repaired and unrepaired samples with respect to both the variability and mean strength (Table XI). This requires the definition of two subpopulations to represent the data, according to the groundrules established in the guidelines. The data was separated into two subsamples, one representing the manually repaired welds and the second representing the current unrepaired tests, plus the supplemental data on unrepaired welds.

The analysis of the unrepaired-weld data was accomplished using direct analysis techniques. The statistics for all 88 test values are included in Table XI. The distribution of the resulting sample was examined for normality as shown in Figure 24. The distribution can be assumed normal. Therefore, direct statistical computation was used to find the minimum unrepaired ultimate tensile strength of 129.6 ksi as indicated in Table XI.

The data sample representing the repaired welds included 24 test values. The effect of manual repair was determined by comparing the results of the repaired welds to the unrepaired welds. Table XII shows the results obtained for the various combinations of original welders and repair welders. Because of the limited amount of data, an indirect analysis, using the derived property ratioing technique, was used for further analysis of repaired welds. The sample statistics for the ratios are shown in Table XII. The reduced ratio was determined at the 95% confidence level and applied to the minimum unrepaired strength value to arrive at the minimum repaired coupon strength of 96.9 ksi (Table XI).

This example illustrates the requirement for a subpopulation definition. The statistical tests for significance do not permit this decision to be made on an arbitrary basis. Two largely differing minimum strengths are indicated for each subpopulation. The analysis techniques carried out by the suggested guideline procedures have resulted in recognition of two distinct subpopulations representing repaired and unrepaired welds.



TUS, ksi	42	43	44	45	46	47	48	49	50	51	52
$\frac{TUS - \bar{X}}{S}$	-3.25	-2.62	-1.99	-1.35	-0.72	-0.08	0.55	1.18	1.82	2.45	3.09

Area Under Normal Curve	0.0038	0.0189	0.0652	0.1473	0.2323	0.2407	0.1742	0.0826	0.0273	0.0061
f_e	0.17	0.85	2.93	6.63	10.45	10.83	7.84	3.72	1.23	0.27
f_o	1	1	2	5	9	17	8	0	1	1
χ^2	-	-	0.295	0.401	0.201	3.515	0.003	3.720	0.043	-

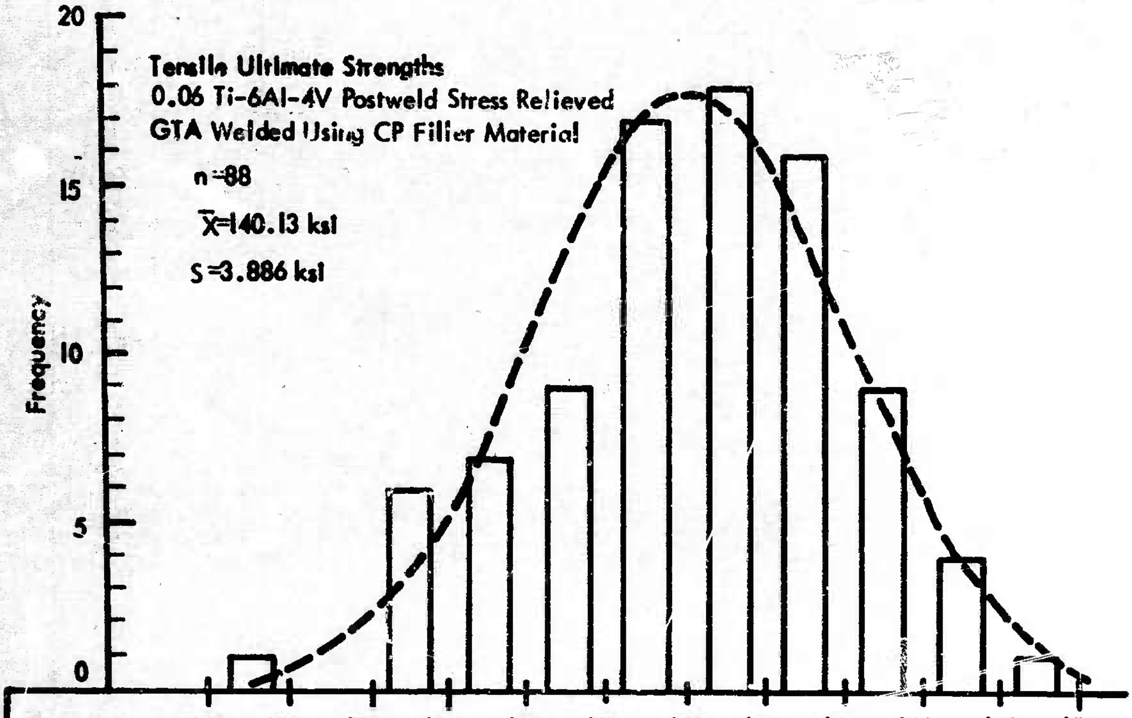
$\Sigma\chi^2 = 8.178 < \chi^2_{.95} = 12.59$, (distribution may be assumed normal).

Figure 23: DATA DISTRIBUTION FOR RE-HEAT-TREATED 6061-T6 WELDS

Table XI: STATISTICAL SUMMARY OF TENSILE ULTIMATE STRENGTH OF STRESS RELIEVED Ti-6Al-4V WELDS

Data Sample Statistics	Item	No. Tests n	Avg TUS $\bar{X}$, ksi	Range of Test Values, ksi	Std Deviation S, ksi	Coefficient of Variation, $S/\bar{X}$
	Current Tests [1]	62	138.92	132.6 - 144.6	3.042	2.2%
	Supplemental Data	26	143.02	129.8 - 148.8	4.043	2.8%
	Both	88	140.13	129.8 - 148.8	3.886	2.8%
	Manual Repaired	24	105.16	95.9 - 116.1	4.762	4.5%
Difference in Variance (Current Tests)	Repaired / Unrepaired	$F = 2.45$ $F_{.975} = 1.90$ Significant, $F > F_{.975}$				
Difference in Means (Current Tests)	Repaired / Unrepaired	$D_{\bar{X}} = 33.76$ $S_p = 3.592$ $t_{.975} = 1.989$ $u = 1.71$ Significant, $D_{\bar{X}} > u$				
Minimum Strengths	Unrepaired	$F_{.99} = \bar{X} - k_{.99}, S = (140.13) - (2.711)\ (3.886) = 129.6$ ksi				
	Manual Repaired	$F = R_{.95}\ F_{.99} = (0.748)\ (129.6) = 96.9$ ksi				

[1] Collected from Unpublished Sources



T_{us}, KSI	128	130	132	134	136	138	140	142	144	146	148	150
$\frac{T_{us} - \bar{X}}{S}$	-3.12	-2.61	-2.09	-1.58	-1.06	-0.55	0.03	0.48	0.99	1.51	2.03	2.54

Area under Normal Curve	0.0036	0.0138	0.0388	0.0875	0.1466	0.1968	0.1964	0.1545	0.0956	0.0443	0.0157
f_e	0.31	1.21	3.41	7.70	12.90	17.32	17.28	13.60	8.41	3.90	1.38
f_o	1	0	6	7	9	17	18	16	9	4	1
χ^2	-	-	1.967	0.064	1.179	0.006	0.030	0.423	0.041	0.003	-

$\Sigma\chi^2 = 3.713 < \chi^2_{.95} = 14.07$, Distribution may be assumed normal

Figure 24: DATA DISTRIBUTION FOR WELDED Ti- 6Al-4V COUPONS

Table XII: EFFECT OF MANUAL REPAIR ON TENSILE ULTIMATE STRENGTH OF Ti-6Al-4V WELDS

	Welder	Repair Welder	Tensile Ultimate Strength		
			Unrepaired ksi	Repaired ksi	Ratio
Data Sample	1	3	140.0	110.9	0.792
	1	5	140.0	104.5	0.746
	1	11	140.0	103.2	0.737
	1	13	140.0	108.9	0.778
	2	9	135.8	100.9	0.743
	2	12	135.8	101.9	0.750
	2	12	135.8	99.6	0.733
	2	13	135.8	195.1	0.774
	3	1	139.4	110.4	0.792
	3	11	139.4	100.0	0.717
	3	11	139.4	101.8	0.730
	3	12	139.4	107.9	0.774
	4	1	138.0	101.0	0.732
	4	3	138.0	106.6	0.772
	5	3	136.9	110.4	0.806
	5	4	136.9	106.1	0.775
	6	4	142.5	106.2	0.745
	6	9	142.5	116.1	0.814
	7	4	140.7	107.1	0.761
	7	5	140.7	102.8	0.731
	8	1	133.4	102.2	0.766
	8	5	133.4	101.4	0.760
	9	13	141.9	112.9	0.795
	10	9	140.0	95.9	0.685
Sample Statistics	$n = 24$ $\bar{R} = 0.7586$ $S = 0.0308$ $t_{.95} = 1.714$ $c = 0.204$				
Reduced Ratio	$R_{.95} = \bar{R} - t_{.95}\, c\, S = 0.748$				

Analysis of Complex Data Sample for As-Welded 6061 Aluminum

A complex data sample was collected consisting of 476 individual test results representing 6061-T6 sheet material welded with 4043 filler wire and tested in the as-welded condition. In the reported program, 194 of these tests were conducted and represent the mechanized welding process. An additional 282 results representing the manual weld process were collected from company test records. These manual welds represent the results of welder qualification tests per MIL-T-5021, meeting the same quality levels specified for the current mechanized welds. Although this sample size appears substantial, when the parameters of sheet thickness, weld method, tooling, repair, and weld bead configuration are considered, the sample is not sufficient to provide a firm basis for design strength determination in all cases.

Table XIII shows a breakdown of the number of tests representing the various parameters. The number of welders is also shown to indicate the number of uncontrolled conditions, such as welding equipment and setups, represented by the sample. This points out the necessity for having an adequate description of material and processing parameters so that they can be considered during data analysis.

Figure 25 is a flow chart showing the path that resulted during the analysis of this data sample. It is evident that several of the identifiable process parameters have a significant influence on the analysis. The importance of these parameters is discussed below.

Significance of Welding Method---The first item accomplished was to determine if there was a significant difference in tensile ultimate strengths between manual and mechanized welds. Two data subsamples were selected to represent the two weld methods. These samples were selected to represent unrepaired weldments in the 0.06- to 0.09-gage range without respect to tooling for the weld-bead-off configuration. This criterion provided the greatest commonality between samples while still maintaining adequate sample sizes. A statistical test for significance was accomplished on the two samples. These tests, as shown in Table XIV, indicate that the manual and mechanized welds differ with respect to both variability and mean strength. Thus, further analysis was based on the definition of two subpopulations of mechanized and manual weldments.

Analysis of Manual Welds---The manual weld sample consisted of 282 tests representing 16 different welders and seven thicknesses ranging from 0.03 to 0.125 inch. A statistical summary of the data is presented in Table XV. Since considerable variation is evident between individual welders and welds representing different thicknesses, the total sample was examined to see if the gross distribution was normal. The χ^2 test, as shown in Table XVI, indicates that the gross sample is not normally distributed.

The only major identifiable parameter in this sample is material thickness. The next analysis step was to attempt to normalize the data in terms of thickness. A regression analysis of tensile strength versus thickness was accomplished, and the calculations are shown in Table XVII.

Table XIII: SUMMARY OF TEST QUANTITIES REPRESENTING AS-WELDED 6061 SHEET

WELD METHOD	TOOLING	SHEET THICKNESS	WELD BEAD	WELD REPAIR	NO. OF TESTS	NO. OF WELDERS REPRESENTED
Mechanized	Chill Type	0.06	OFF	-	9	3
		0.125	OFF	-	9	3
		0.25	OFF	-	9	3
		0.375	OFF	-	9	3
		0.09	OFF	-	59	10
				Manual	14	5
				Mechanized	15	5
			ON	-	10	5
	Insulated	0.09	OFF	-	60	10
Manual	Not Controlled	0.03	OFF	-	58	10
		0.04	OFF	-	86	12
		0.05	OFF	-	6	1
		0.06	OFF	-	88	13
		0.07	OFF	-	10	2
		0.09	OFF	-	22	4
		0.125	OFF	-	12	3

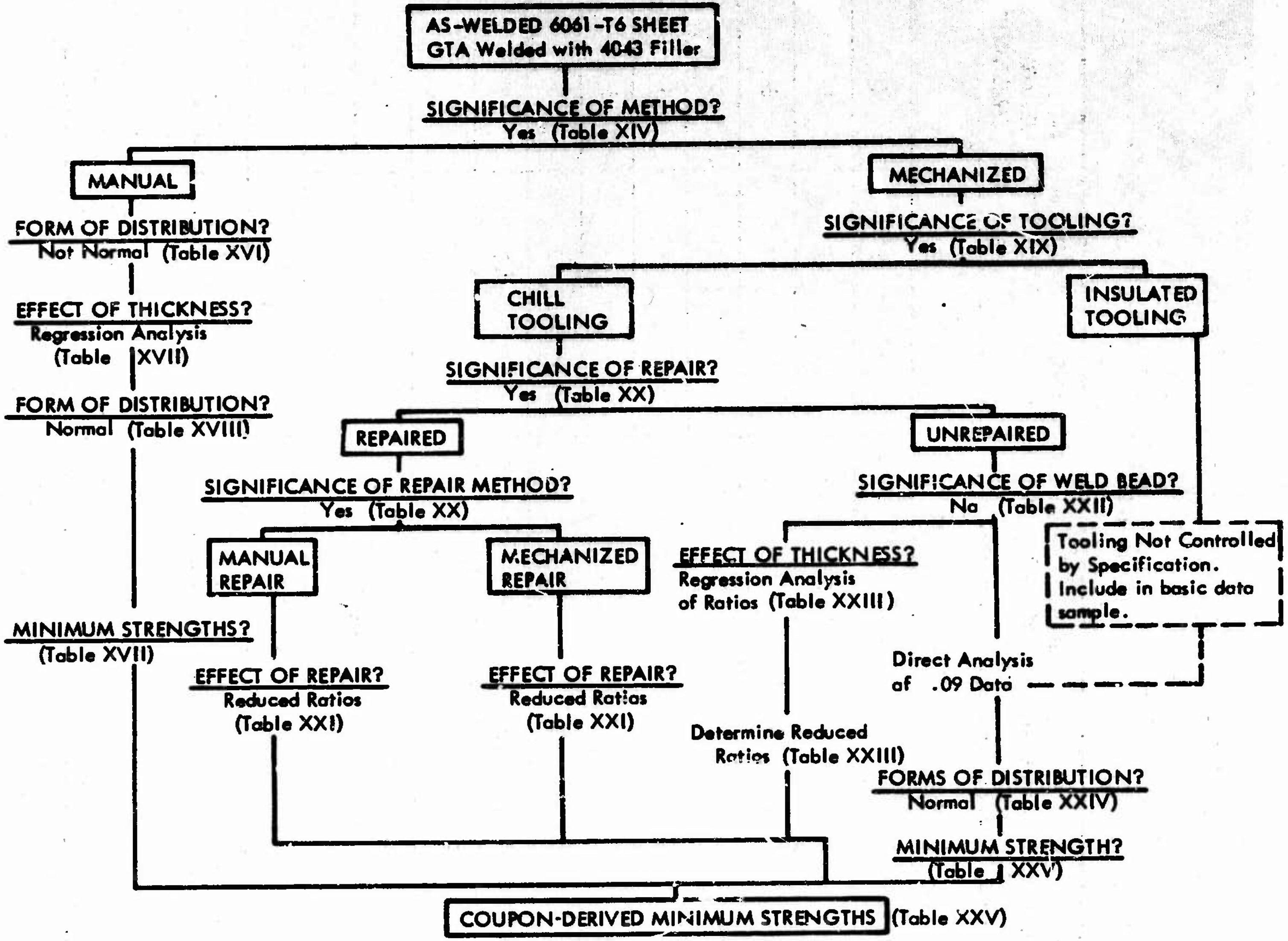


Figure 25: FLOW CHART FOR ANALYSIS OF AS-WELDED 6061 SHEET

Table XIV: SIGNIFICANCE OF MANUAL VS MECHANIZED WELDING OF 0.06-0.09-INCH 6061 SHEET

<table>
<tr><td rowspan="4">DATA
SAMPLE
STATISTICS</td><td></td><td>MANUAL</td><td>MECHANIZED</td></tr>
<tr><td>Sample Size
n</td><td>120</td><td>128</td></tr>
<tr><td>Std Deviation
S, ksi</td><td>2.054</td><td>1.676</td></tr>
<tr><td>Avg TUS
$\bar{X}$, ksi</td><td>27.97</td><td>33.48</td></tr>
<tr><td colspan="2">Difference in Variance</td><td colspan="2">$F = 1.502$
$F_{.975} = 1.43$
Significant, $F > F_{.975}$</td></tr>
<tr><td colspan="2">Difference in Mean Strength</td><td colspan="2">$D_{\bar{X}} = 5.51$
$Sp = 1.868$
$t_{.975} = 1.971$
$u = 0.06$
Significant, $D_{\bar{X}} > u$</td></tr>
</table>

Table XV: STATISTICAL SUMMARY OF TEST DATA, MANUAL WELDED 6061-T6 SHEET
(Data Collected from Unpublished Sources)

WELDER	NUMBER OF TESTS PER GAGE							TOTAL SPEC.	AVG. UTS,	COEFF. OF VARIA.	DATA RANGE
	0.03	0.04	0.05	0.06	0.07	0.09	0.125	n	$\bar{X}$, KSI	S/$\bar{X}$	MIN-MAX.
1.	3			4				7	27.37	7.7%	24.4-30.0
2.	5	4		9				18	28.21	6.8%	23.3-30.3
3.		7		4			4	15	27.94	8.6%	22.6-31.9
4.	8			8				16	27.96	7.4%	25.2-31.2
5.	9	4			5			18	29.34	4.5%	25.6-30.8
6.	5	4			5		4	18	28.18	6.9%	24.9-30.4
7.		10		10				20	29.78	6.7%	27.0-32.6
8.	8			8				16	29.12	8.5%	22.9-33.7
9.		13		4		5	4	26	26.20	5.3%	23.9-28.9
10.	5	5		10				20	27.26	3.9%	25.8-29.5
11.	7			7				14	26.01	6.3%	23.0-28.3
12.		7		3		4		14	29.35	4.7%	27.4-31.2
13.		8				8		16	29.85	5.6%	26.2-31.7
14.		4		4				8	28.45	3.9%	26.6-30.0
15.	4	9		8		5		26	27.66	10.1%	23.2-34.1
16.	4	11	6	9				30	28.36	5.3%	23.9-30.6
Total Spec., n	58	86	6	88	10	22	12	282			
Avg. UTS, $\bar{X}$,KSI	28.253	28.541	28.600	28.010	29.010	27.332	26.533	28.154			
Sum Sq., X^2	46639	70424	4919	69291	8432	16651	8465	224821			
Std. Dev., S	2.448	2.083	1.519	1.694	1.350	3.209	1.240	2.147			
Coef. Var., S/$\bar{X}$	8.7%	7.9%	5.3%	6.0%	4.7%	11.7%	4.7%	7.6%			
Data Range	22.9-34.1	22.6-32.6	26.6-30.6	23.3-30.7	27.4-30.8	23.2-31.7	24.9-28.7	22.6-34.1			

Table XVI: CHI-SQUARED TEST FOR NORMALITY OF DATA, GROSS SAMPLE FOR MANUALLY WELDED 6061 ALUMINUM

STRENGTH RANGE	$\frac{UTS-\bar{X}}{S}$	AREA UNDER NORMAL CURVE	FREQUENCY		$\chi^2 = \frac{(f_o - f_e)^2}{f_e}$
			OBSERVED f_o	EXPECTED f_e	
≤ 23	-2.40	0.0082	3	2.31	0.20
23-24	-1.93	0.0186	10	5.25	4.29
24-25	-1.47	0.0440	11	12.40	0.16
25-26	-1.00	0.0879	30	24.79	1.09
26-27	-0.54	0.1359	26	38.32	3.96
27-28	-0.07	0.1775	36	50.05	3.94
28-29	0.39	0.1796	64	50.66	3.51
29-30	0.86	0.1534	54	43.27	2.66
30-31	1.33	0.1031	29	29.07	0.00
31-32	1.79	0.0551	13	15.54	0.41
32-33	2.26	0.0248	3	6.99	2.27
> 33		0.0119	3	3.35	0.04
			282		22.53

DATA MAY NOT BE ASSUMED NORMALLY DISTRIBUTED

$$\Sigma\chi^2 = 22.53 > \chi^2_{.95} = 19.68$$

Table XVII: REGRESSION CALCULATION FOR MANUALLY WELDED 6061 ALUMINUM

	$n = 282$ $X = T_{us},$ KSI $Y =$ thickness, inches
Regression Statistics	$\Sigma X = 7940.3$ $\Sigma Y = 15.035$ $\Sigma X^2 = 224821.43$ $\Sigma Y^2 = 0.942579$ $(\Sigma X)^2 = 63048364$ $(\Sigma Y)^2 = 226.06626$ $\Sigma XY = 420.74073$ $(\Sigma X)(\Sigma Y) = 119386.38$
Regression Constants	$b = -18.558$ $a = 29.146$ $S = 2.067$ $c^2 = 1.0035 + \frac{(Y_o - .0533)^2}{.14092}$ $k_{.99} = 2.529$
Regression Equations	$\bar{X} = 29.146 - 18.558 Y_o$ $F_{.99} = \bar{X} - kcs$

	thickness Y_o	Regressed Avg. TUS $\bar{X}$ KSi	Regression Factor c	Minimum Strength $F_{.99}$, KSI
Minimum Strengths	0.03	28.59	1.004	23.3
	0.04	28.40	1.002	23.1
	0.05	28.22	1.002	23.0
	0.06	28.03	1.002	22.8
	0.07	27.85	1.003	22.6
	0.09	27.48	1.006	22.2
	0.125	26.83	1.020	21.5

This analysis indicates minimum tensile ultimate strengths ranging from 23.3 ksi for 0.03-inch thickness to 21.5 ksi for 0.125 inch thickness.

To check the validity of the minimum strength values thus calculated, the distribution of data was checked for normality about the regression line. In this case, the data may be assumed normal according to the χ^2 test shown in Table XVIII. A graphic presentation of the distribution is shown in Figure 26.

Analysis of Mechanized Welds---The mechanized weld sample consisted of 194 test results representing two types of weld tooling, five thicknesses of material, weld bead on and off, and both mechanized and manual repair. The analysis of this sample involved much more detail than the analysis of the manual welds due to the increased number of parameters. This analysis, however, illustrates the importance of having adequate definition of the material and processing history for a particular set of data so that an adequate analysis can be performed.

Significance of Tooling---It was shown previously that tooling was not a significant parameter for re-heat-treated 6061-T6 aluminum welds. An analysis was performed to determine whether one could assume the same thing for as-welded 6061 aluminum. Two subsamples for 0.09 thickness, representing identical processing except for tooling, were used to examine the significance of tooling on the tensile strength of the as-welded material. A statistical summary of the data along with the tests for significance is shown in Table XIX. In this case, the chill and insulated tooling show a significant difference in mean strength, although the variance was not significantly different.

Although tooling is not generally controlled by processing specifications, the fact that it does affect strength must be recognized when making data comparisons.

Significance of Weld Repair---Both manual and mechanized repair welding were represented by repair weld subsamples only for the 0.09 thickness. An analysis of the repair welds was conducted to determine whether the strength was influenced by repair method and was significantly different from the unrepaired mechanized or manual welds.

Table XX presents a statistical summary of the test data. Included is a summary of two additional samples representing the unrepaired mechanized and manual welds. The unrepaired sample for mechanized welds includes all of the basic data for 0.09 thickness. The unrepaired manual weld sample included the same data used previously in the effect of weld method analysis.

Statistical tests for significant differences were used to compare:

1) Manual repair of mechanized welds to mechanized repair of mechanized welds;

2) Mechanized repair of mechanized welds to unrepaired mechanized welds;

Table XVIII: REGRESSION DATA SAMPLE---TEST FOR NORMALITY

LOWER LIMIT OF INTERVALS	n	$\frac{f_o}{\Sigma n}$	$\frac{f_e}{\Sigma n}$	$\chi^2/\Sigma n$
$\bar{X} - 3.0S$	3	0.0106	0.0049	0.00663
$\bar{X} - 2.5S$	8	0.0284	0.0166	0.00838
$\bar{X} - 2.0S$	12	0.0426	0.0440	0.00004
$\bar{X} - 1.5S$	25	0.0887	0.0919	0.00011
$\bar{X} - 1.0S$	33	0.1170	0.1498	0.00718
$\bar{X} - 0.5S$	45	0.1596	0.1915	0.00531
$\bar{X}$	70	0.2482	0.1915	0.01678
$\bar{X} + 0.5S$	48	0.1702	0.1498	0.00277
$\bar{X} + 1.0S$	21	0.0745	0.0919	0.00329
$\bar{X} + 1.5S$	11	0.0390	0.0440	0.00056
$\bar{X} + 2.0S$	5	0.0177	0.0166	0.00007
$\bar{X} + 2.5S$	1	0.0035	0.0049	0.00040
Σ	282			0.05152

$$\chi^2 = 0.05152\,\Sigma n = 14.53, \quad \chi^2_{.95} = 19.68$$

DATA MAY BE ASSUMED NORMALLY DISTRIBUTED ABOUT THE REGRESSION LINE

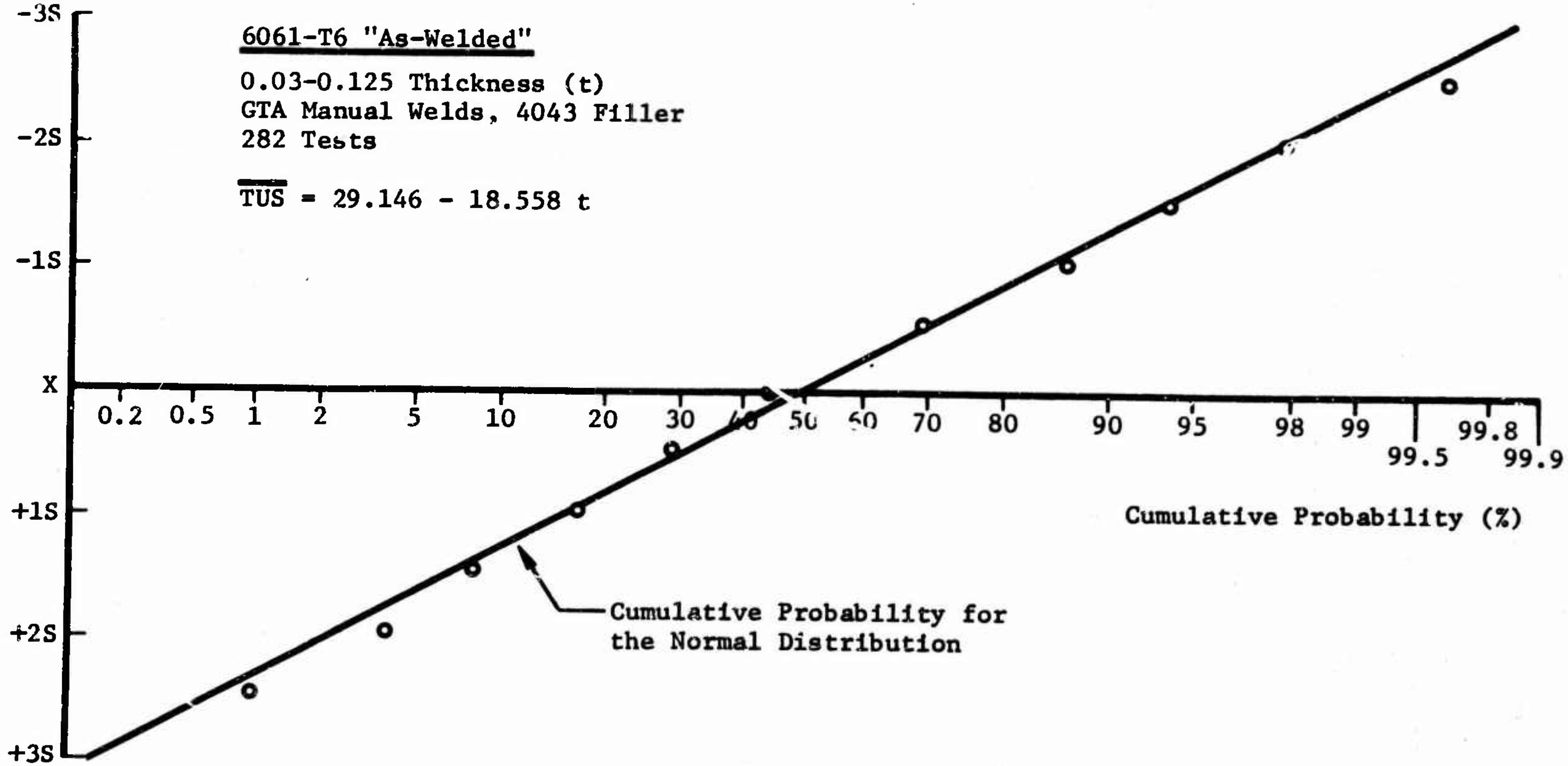


Figure 26: DISTRIBUTION OF REGRESSED DATA SAMPLE FOR MANUAL WELDED 6061 ALUMINUM

Table XIX: SIGNIFICANCE OF TOOLING ON STRENGTH OF AS-WELDED 6061

TOOLING	WELDER	n	TENSILE ULTIMATE STRENGTH, KSI			S/$\bar{X}$
			$\bar{X}$	RANGE	S	
CHILL (A)	1	5	34.66	33.4 - 35.3	0.760	2.19%
	2	6	33.08	31.7 - 34.5	1.122	3.39%
	3	6	32.18	30.2 - 34.1	1.282	3.98%
	4	6	35.05	33.7 - 36.2	0.882	2.52%
	5	6	33.40	31.0 - 34.9	1.338	4.00%
	6	6	33.85	32.2 - 34.6	0.922	2.72%
	7	6	35.11	33.8 - 35.9	0.787	2.24%
	8	6	35.30	34.6 - 36.5	0.740	2.10%
	9	6	35.95	34.3 - 37.6	1.127	3.13%
	10	6	35.57	34.8 - 36.1	0.450	1.27%
	ALL	59	34.41	30.2 - 37.6	1.529	4.44%
INSULATED (B)	1	6	34.75	33.8 - 36.6	1.019	2.93%
	2	6	32.27	31.2 - 34.5	1.157	3.58%
	3	6	31.23	29.8 - 32.5	1.116	3.57%
	4	6	33.05	31.8 - 34.5	0.905	2.74%
	5	6	32.27	30.6 - 33.5	1.140	3.53%
	6	6	32.57	32.3 - 32.8	0.226	0.69%
	7	6	33.32	32.9 - 34.3	0.512	1.54%
	8	6	31.16	30.9 - 31.7	0.281	0.90%
	9	6	33.65	33.4 - 33.9	0.187	0.56%
	10	6	31.75	30.9 - 32.6	0.589	1.86%
	ALL	60	32.60	29.8 - 36.6	1.346	4.13%

Difference in Variance		Difference in Means	
$F = (S_A / S_B)^2$	1.290	$D_{\bar{X}} = \lvert \bar{X}_A - \bar{X}_B \rvert$	1.81
$F_{.975}$	1.55	S_p	1.439
Significant Difference ($F > F_{.975}$)	NO	$t_{.975}$	1.980
		u	0.52
		Significant Difference ($D_{\bar{X}} > u$)	YES

Table XX: SIGNIFICANCE OF REPAIR WELDING ON AS-WELDED 6061 STRENGTH

TEST GROUPS		REPAIR WELDER	n	TENSILE ULTIMATE STRENGTH, ksi			$S/\bar{X}$
				$\bar{X}$	RANGE	S	
Repaired	Mechan.	1	3	34.27	33.7 - 35.1		
		9	3	31.13	30.9 - 31.3		
		3	3	31.10	30.3 - 31.7		
		4	3	32.43	30.3 - 33.7		
		5	3	33.37	32.8 - 34.3		
		TOTAL	15	32.46	30.3 - 35.1	1.549	4.77%
	Manual	1	3	27.43	26.7 - 27.8		
		9	2	29.90	29.6 - 30.2		
		11	3	28.67	26.9 - 30.8		
		3	3	32.90	31.3 - 34.5		
		4	3	33.90	33.4 - 34.5		
		TOTAL	14	30.61	26.7 - 34.5	2.848	9.30%
Un-Repaired	Mechan.	-	119	33.50	29.8 - 37.6	1.645	4.91%
	Manual	-	120	27.97	23.2 - 31.7	2.054	7.34%

SIGNIFICANT DIFFERENCES	MAN. REP. MECH. REP.	MECH. REP. MECH. UNREP.	MAN. REP. MECH. UNREP.	MAN. REP. MAN. UNREP
In Variance				
F	3.38	0.887	2.99	1.92
$1/F_{.975}$ or $F_{.975}$	3.02	0.508	2.02	2.02
$F_{.975} < F < 1/F_{.975}$	YES	NO	YES	NO
In Mean Strength				
$D_{\bar{X}}$	1.85	1.04	2.89	2.64
Sp	2.269	1.634	1.800	2.145
$t_{.975}$	2.052	1.979	1.979	1.979
u	1.73	0.89	1.00	1.20
$D_{\bar{X}} > u$	YES	YES	YES	YES

3) Manual repair of mechanized welds to unrepaired mechanized welds;

4) Manual repair of mechanized welds to unrepaired manual welds.

In all cases, the mean strengths differed significantly as shown in Table XX. The variance of the samples differed significantly only for the two cases where the manual process was compared to the mechanized process. This indicates that process control may differ significantly between manual and mechanized welding. This is also suggested by referring to the coefficients of variation $(S/\bar{X})$ shown for the two processes (Table XX). In both the repaired and unrepaired samples, the coefficient of variation for the manual process is greater than for the mechanized process.

The effect of repair on the tensile ultimate strength was analyzed by ratioing the repaired strength to the unrepaired strength for test coupons representing particular welders. Because manual and mechanized repair were shown to differ, an analysis was conducted for each.

The average strength indicated for a repaired panel was compared to the average strength for an unrepaired panel by the original welder. In most cases repair was conducted by other than the original welder. For the mechanized repair welds, several test coupons were taken from each mechanized repair, and the average of these was compared to the average unrepaired tests for each combination of welders. For manual repairs, individual test results representing a nearly random mix of original and repair welders were compared to the average strength indicated for the unrepaired panels for each original welder.

A summary of the test data is shown in Table XXI. Reduced ratios at .95 confidence level were calculated for both repair methods. These calculations, included in Table XXI, indicate a reduction in strength of approximately 8% due to mechanized repair and approximately 15% due to manual repair.

Significance of Weld Bead to Coupon Strength---A series of test results for 0.09-inch-thick material representing five different welders using chill-type tooling was used to evaluate the significance of having the weld bead on test coupons. Ten test results were obtained for the weld-bead-on configuration, which were compared to 29 results from the same series of weldments for the weld-bead-off configuration.

Table XXII gives a summary of the data and tests for significance. The average strength for the bead-on configuration was approximately 1 ksi higher, and the coefficient of variation was also greater than for the bead-off configuration. The significance tests indicate that these differences in mean strength and variance are not significant.

Effect of Thickness on Strength---A limited sample of 45 individual test results representing 3 welders and 5 material thicknesses from 0.06 to 0.375 inch were used to evaluate the effect of thickness on the tensile ultimate strength of the as-welded 6061 material. Due to the small number of tests for each condition, an indirect analysis was

Table XXI: EFFECT OF REPAIR WELDING ON STRENGTH OF AS-WELDED 6061 ALUMINUM

REPAIR METHOD	UNREPAIRED			REPAIRED			RATIO R
	WELDER	NO. TESTS	$\overline{TUS}$	WELDER	NO. TESTS	$\overline{TUS}$	
Mechanized	1	5	34.66	1	3	34.27	.989
	2	6	33.08	9	3	31.13	.941
	4	6	35.05	4	3	32.43	.925
	5	6	33.40	3	3	31.10	.931
	9	6	35.95	5	3	33.37	.928
	No. Ratios, n = 5 Avg. Ratio, $\overline{R}$ = 0.9428 Std. Dev., S = 0.0266 $t_{.95}$ = 2.132 Reduced Ratio, $R_{.95}$ = 0.9174						
Manual	1	5	34.66	9	1	29.6	.854
	2	6	33.08	1	1	27.8	.840
	4	6	35.05	1	1	26.7	.762
	5	6	33.40	1	1	27.8	.832
	6	6	33.85	9	1	30.2	.892
	6	6	33.85	11	1	26.9	.795
	7	6	35.11	11	1	28.3	.806
	8	6	35.30	11	1	30.8	.873
	8	6	35.30	3	1	31.3	.887
	9	6	35.95	3	1	34.5	.959
	9	6	35.95	4	1	33.4	.929
	9	6	35.95	4	1	33.8	.940
	10	6	35.57	3	1	32.9	.925
	10	6	35.57	4	1	34.5	.970
	No. Ratios, n = 14 Avg. Ratio, $\overline{R}$ = 0.8760 Std. Dev. S = 0.0643 $t_{.95}$ = 1.771 Reduced Ratio, $R_{.95}$ = 0.8456						

Table XXII: EFFECT OF WELD BEAD ON COUPON STRENGTH OF AS-WELDED 6061 ALUMINUM

<table>
<tr><td rowspan="8">Data Summary</td><td rowspan="3">Welder</td><td colspan="4">Tensile Ultimate Strength</td></tr>
<tr><td colspan="2">Bead Off</td><td colspan="2">Bead On</td></tr>
<tr><td>n</td><td>$\bar{X}$, ksi</td><td>n</td><td>$\bar{X}$, ksi</td></tr>
<tr><td>1</td><td>5</td><td>34.66</td><td>2</td><td>35.20</td></tr>
<tr><td>2</td><td>6</td><td>33.08</td><td>2</td><td>34.60</td></tr>
<tr><td>3</td><td>6</td><td>32.18</td><td>2</td><td>32.85</td></tr>
<tr><td>4</td><td>6</td><td>35.05</td><td>2</td><td>35.90</td></tr>
<tr><td>5</td><td>6</td><td>33.40</td><td>2</td><td>34.90</td></tr>
<tr><td rowspan="5">Sample Statistics</td><td colspan="3"></td><td>Bead off</td><td>Bead on</td></tr>
<tr><td colspan="3">No. tests, n</td><td>29</td><td>10</td></tr>
<tr><td colspan="3">Avg. TUS, ksi $\bar{X}$</td><td>33.64</td><td>34.69</td></tr>
<tr><td colspan="3">Std. Deviation, S</td><td>1.516</td><td>2.182</td></tr>
<tr><td colspan="3">Coef. of Variation, $S/\bar{X}$</td><td>4.5%</td><td>6.3%</td></tr>
<tr><td>Difference in Variance</td><td colspan="5">$F = 2.071$
$F_{.975} = 2.53$
Not Significant, $F_{.975} > F$</td></tr>
<tr><td>Difference in Mean Strength</td><td colspan="5">$D_{\bar{X}} = 1.05$
$S_p = 1.703$
$t_{.975} = 2.035$
$u = 1.27$
Not Significant, $\mu > D_{\bar{X}}$</td></tr>
</table>

indicated. Since the manual welds discussed previously illustrated that the results were normalized by linear regression, an analysis using the indirect linear regression technique was accomplished. This analysis was conducted using the average coupon strength for each welder and each gage to develop ratios from the basic 0.09 thickness. These ratios were regressed against thickness, and reduced ratios were then determined for each of the test thicknesses.

Table XXIII summarizes the reduced ratio analysis for thickness effect. The test data represent the average of three test coupons from a single welded panel in each gage for each welder. The regression analysis indicates a decrease in strength with increased thickness. The regressed average ratios show a decrease of approximately 7% over the thickness range evaluated.

Direct Analysis of 0.09 Thickness Data---The majority of mechanized weld data was generated for the 0.09 thickness. The significance of weld repair and thickness as discussed previously required additional definition of subpopulations. One area that has not been resolved is the apparent significance of tooling. While two types of tooling were represented in the test sample, the control of tooling is not generally accomplished by weld process specifications. Tooling is usually dictated by the type and configuration of a weldment, and the inclusion of tooling requirements in a process specification of general applicability is not practical. This illustrates a point where a subjective decision is required.

The two types of tooling represented in the data sample are indicative of those used in the majority of applications. The significance of the tooling as summarized in Table XIX indicated that the mean strengths differed by an average of 1.8 ksi with no significant difference in variance. The range of test values for each case was approximately 7 ksi. Based on these considerations, it was decided that separate subpopulations for tooling would not be used, provided the resulting distribution of test values was normal.

The analysis of the 0.09 mechanized weld data was accomplished using the data summarized in Table XXIV. The 10 data points for the bead-on configuration were included since they were shown not to differ significantly from the bead-off results. The sample statistics and minimum strength calculations are included with the χ^2 test for normality in the table. The sample of 129 test results can be assumed to represent a normally distributed population. The sample distribution is graphically illustrated in Figure 27. The resulting minimum tensile ultimate strength at 95% confidence and 99% probability is 29.0 ksi.

Minimum Coupon Strengths for Mechanized Welds---The previous discussion illustrates an analysis that results in separation of the basic sample into several subsamples representing the effect of several parameters. For unrepaired 0.09 thickness welds, minimum strengths were computed directly; but in other cases, indirect analysis techniques resulted in determination of reduced ratios that must be applied to the directly calculated minimum to arrive at the desired minimum strengths. Table XXV summarizes the resulting reduced ratios and minimum strengths.

Table XXIII: EFFECT OF MATERIAL THICKNESS ON STRENGTH OF AS-WELDED 6061 ALUMINUM

Data Summary

Welder	Thickness 0.06 TUS	0.06 R	0.09 TUS	0.09 R	0.125 TUS	0.125 R	0.25 TUS	0.25 R	0.375 TUS	0.375 R
1	35.47	1.0242	34.63	1.000	39.07	1.1282	31.20	0.9010	30.70	0.8865
2	31.43	0.9271	33.90	1.000	31.40	0.9262	31.23	0.9212	31.60	0.9322
3	32.77	1.0337	31.70	1.000	29.60	0.9338	30.43	0.9599	32.77	1.0337

Regression Calculations

$n = 15$ $\quad R = \text{Ratio } \frac{TUS}{TUS_{.090}}$ $\quad Y = \text{thickness}$

$\Sigma R = 14.6078$ $\quad \Sigma Y = 2.700$

$\Sigma R^2 = 14.285267$ $\quad \Sigma Y^2 = 0.6876$

$(\Sigma R)^2 = 213.389574$ $\quad (\Sigma Y)^2 = 7.290$

$\Sigma RY = 2.5878$

$(\Sigma R)(\Sigma Y) = 39.4411$

Regression Constants

$b = -0.2063$

$a = 1.0110$

$S = 0.06246$

$$c^2 = 0.06667 + \frac{(Y_o - 0.180)^2}{0.2016}$$

$t_{.95} = 1.771$

Regression Equations

$\bar{R} = 1.0110 - 0.2063\, Y_o$

$R_{.95} = \bar{R} - t_{.95}\, cS$

Reduced Ratios

Thickness Y_o	Regressed Avg. Ratio $\bar{R}$	Regression Factor c	Reduced Ratio $R_{.95}$
0.06	1.000	0.371	0.959
0.125	0.985	0.286	0.954
0.25	0.959	0.301	0.926
0.375	0.933	0.505	0.878

Table XXIV: STATISTICAL SUMMARY OF 0.09-INCH MECHANIZED WELD DATA FOR 6061 ALUMINUM

Data Summary

Tooling	Weld Bead	No. Tests n	Avg TUS $\bar{X}$ ksi	TUS Data Range
Insulated	Off	60	32.60	29.8 - 36.6
Chill	Off	59	34.41	30.2 - 37.6
Chill	On	10	34.69	31.6 - 37.7

Sample Statistics

No. Tests, $n = 129$
Avg. TUS, $\bar{X} = 33.59$ ksi
Std. Dev., $S = 1.755$ ksi
Coef. of Variation, $S/\bar{X} = 5.2\%$
$k_{.99} = 2.636$

Minimum Strength

$F_{.99} = \bar{X} - k_{.99} S = 28.96$ ksi or 29.0 Ksi

Form of Distribution

Strength Interval	$\frac{TUS-\bar{X}}{S}$	Area Under Normal Curve	Frequency f_e	Frequency f_o	χ^2
30	-2.045	0.0205	2.64	2	0.155
30-31	-1.476	0.0496	6.40	7	0.056
31-32	-0.906	0.1126	14.53	19	1.375
32-33	-0.336	0.1857	23.95	25	0.046
33-34	0.234	0.2242	28.92	24	0.837
34-35	0.803	0.1964	25.34	23	0.216
35-36	1.373	0.1262	16.28	20	0.850
36-37	1.943	0.0588	7.59	6	0.333
37		0.0260	3.35	3	0.036
				129	3.904

$\Sigma \chi^2 = 3.90 < \chi^2_{.95} = 15.51$, data is normal

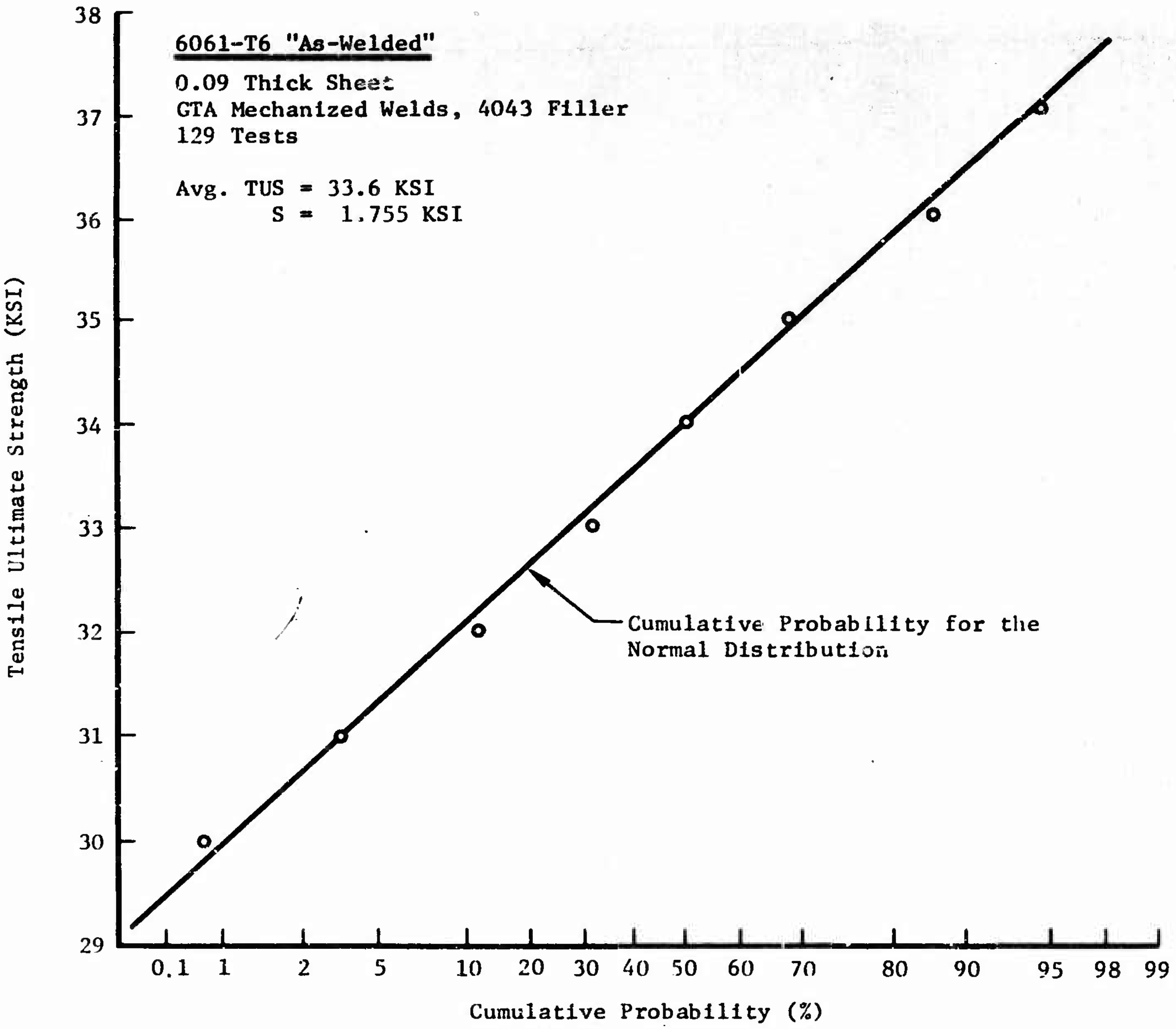


Figure 27: DISTRIBUTION OF DATA SAMPLE FOR 0.09-INCH MECHANIZED WELDED 6061 ALUMINUM SHEET

Table XXV: SUMMARY OF REDUCED RATIOS AND MINIMUM STRENGTHS FOR MECHANIZED WELDS IN 6061 ALUMINUM

Material Thickness	Type of Repair	Reduced Ratio $R_{0.95}$	Minimum Strength $F_{0.99}$, ksi	Comment
0.09	None		28.96	Basic Direct Analysis See Table XXIV
0.06	None	0.959	27.77	Effect of Thickness See Table XXIII
0.125		0.954	27.63	
0.25		0.926	26.81	
0.375		0.878	25.42	
0.09	Mechanized	0.917	26.55	Effect of Repair See Table XX
	Manual	0.845	24.47	

Table XXVI: STRENGTH COMPARISON OF TENSION TUBES AND PRESSURE VESSELS OF 6061 ALUMINUM

Data Summary	Structure Type	No. Tests n	Ultimate Strength, ksi		Std. Dev. S
			$\bar{X}$	Range	
	Tension Tubes	10	28.35	24.9-30.0	1.735
	Pressure Vessels	8	32.22	29.1-34.5	1.947
Difference in Variance	$F = 1.26$ $F_{.975} = 4.20$ Not Significant, $F_{.975} > F$				
Difference in Mean Strength	$D_{\bar{X}} = 3.87$ $S = 1.830$ $t_{.975} = 2.120$ $u = 1.84$ Significant, $u < D_{\bar{X}}$				

Determination of Coupon-Structure Correlations

Two sets of test data were generated for analysis of the correlation of test coupon ultimate strengths with the fracture strengths of typical structural joints. The two simulated structural applications involved tension tests of welded tubes and burst tests of small pressure vessels, both mechanized welded from 0.09-inch-thick 6061-T6 using 4043 filler.

The apparent failure strengths of the simulated structure were compared to the tensile coupon strengths determined from welds produced by the same welders. The influence of weld bead and manual repair was evaluated for the tube tension tests. The pressure vessel tests included data for evaluation of the effect of manual repair and mismatch. Figure 28 shows a flow diagram of the path of the analysis of the coupon-structure correlation.

Significance of Structure Type---The basic test results for the unrepaired tension tubes and pressure vessels meeting the weld quality requirements established for the coupon evaluations were compared to determine if the type of structure significantly influenced the apparent failure strengths. A statistical summary of the test results and the tests for significance are given in Table XXVI.

The analysis of these test results indicates a significant difference in mean strength between the tension tubes and pressure vessels. The variance of the two samples did not differ significantly. The average apparent stress for the pressure vessel configuration was approximately 13% greater than for the tension tubes. It is important to recognize the influence that the method of determining structure stresses may have. The tension tube strengths were determined using a simple load divided by area calculation; pressure vessel strengths were based on an analysis of the apparent membrane stress across the weld joint without regard to any biaxial strengthening. A basic welding difference should be recognized in that the tubes involved a tailout or reweld area in contrast to the single-pass longitudinal weld in the pressure vessel.

The pressure vessels were of constant thickness, which results in a 2-to-1 biaxial stress field in the shell of the cylinder. A biaxial factor based on the maximum strain energy theory would suggest an increase in the failure stress for a 2-to-1 biaxial field over that for the uniaxial case. The apparent differences between the tube and pressure vessel results may be influenced by this effect, but the influence of biaxiality is beyond the scope of this investigation. The development of coupon-structure correlations must recognize these factors, and the results should be duly noted. In further analysis, the tension tubes and pressure vessel tests are treated separately.

Significance of Weld-Bead to Tube Tension Strength---Five tension tubes were tested with the weld beads left on, and the results were compared to the 10 basic results obtained using the weld-bead-off configuration. The data is summarized in Table XXVII along with the tests for significance. The analysis indicates no significant differences in either mean strength or variance between the bead-off and bead-on samples. This is

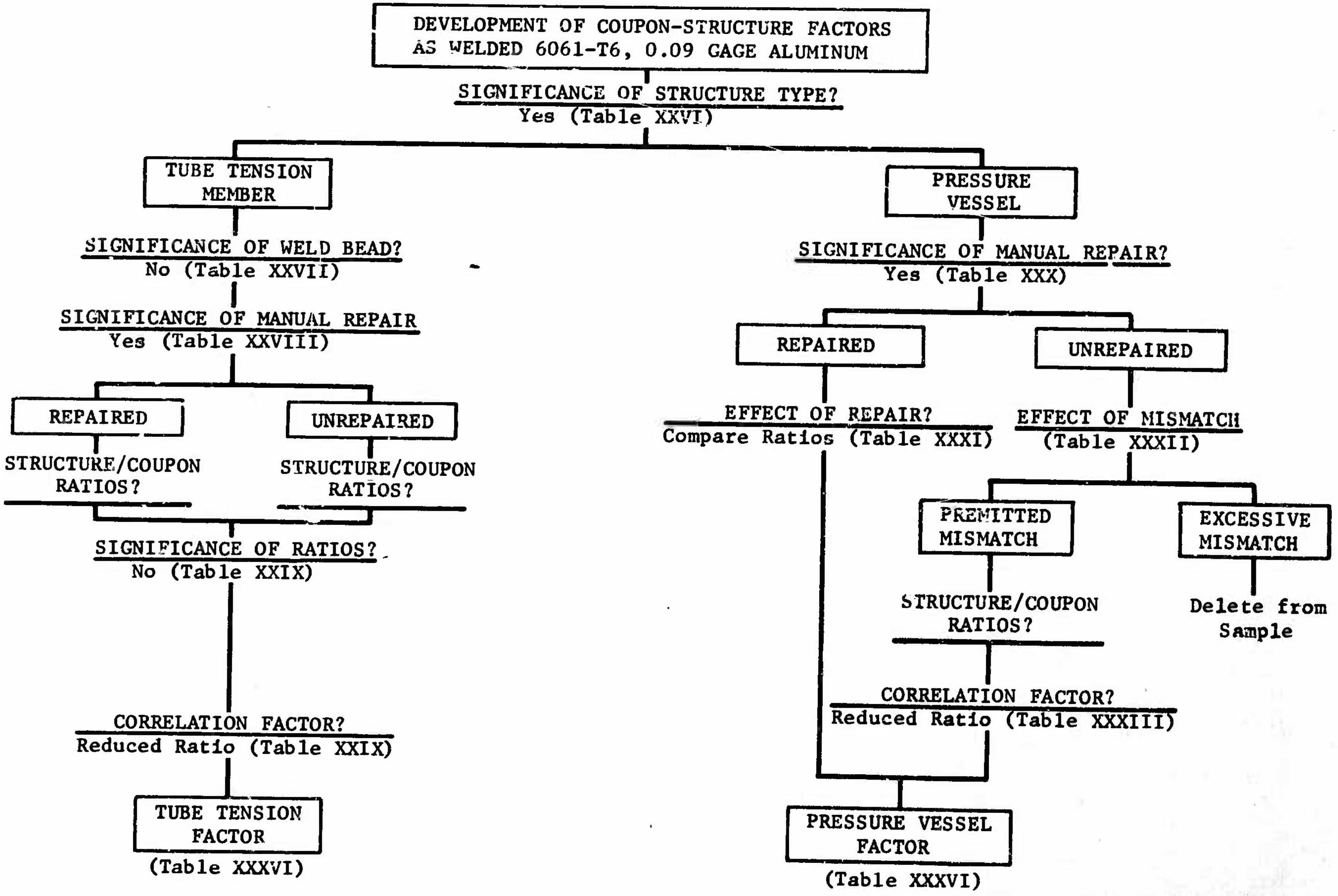


Figure 28: FLOW DIAGRAM FOR ANALYSIS OF COUPON-STRUCTURE CORRELATIONS

Table XXVII: SIGNIFICANCE OF WELD BEAD ON STRENGTH OF 6061 ALUMINUM TUBES

Data Summary	Weld Bead	No. Tests n	Ultimate Strength, ksi		Std. Dev. S
			$\bar{X}$	Range	
	Off	10	28.35	24.9-30.0	1.735
	On	5	28.60	27.0-30.2	1.161
Difference in Variance	$F = 0.448$ $1/F_{.975} = 0.212$ Not Significant, $F > 1/F_{.975}$				
Difference in Mean Strength	$D_{\bar{X}} = 0.25$ $Sp = 1.581$ $t_{.975} = 2.160$ $u = 1.87$ Not Significant, $u > D_{\bar{X}}$				

Table XXVIII: SIGNIFICANCE OF REPAIR ON TUBE STRENGTH

Data Summary	Repair	No. Tests n	Ultimate Strength, ksi		Std. Dev. S
			$\bar{X}$	Range	
	None	15	28.43	24.9-30.2	1.529
	Manual	5	25.80	24.6-27.3	0.982
Difference in Variance	$F = 0.412$ $1/F_{.975} = 0.257$ Not Significant, $F > 1/F_{.975}$				
Difference in Mean Strength	$D_{\bar{X}} = 2.63$ $Sp = 1.425$ $t_{.975} = 2.101$ $u = 1.55$ Significant, $D_{\bar{X}} > u$				

the same conclusion reached previously for the welded coupon tests. Further analysis, therefore, does not distinguish between bead-on and bead-off tests.

Effect of Repair on Tube Tension Strength---Five tube specimens containing manually repaired welds were tested to evaluate the effect of repair welding. The results are compared to the unrepaired results in Table XXVIII. The tests for significance indicate a significant difference in mean strengths but not in variance. As discussed previously, the coupon tests also indicated a significant difference in strength due to manual repair.

The effect of repair was evaluated by comparing the ratios of coupon to tube strength for the two subsamples of manually repaired and unrepaired welds. Ratios of the unrepaired tube strength to the unrepaired coupon strength were determined for each of the five welders who prepared unrepaired tubes. Similarly, ratios of the repaired tube strength to the repaired coupon strength were calculated for each of the welders making tube repairs. These data are shown in Table XXIX. Tests of significance indicate that the tube/coupon ratios obtained for the repaired tubes do not differ significantly from those obtained for the unrepaired tubes. This suggests that the effect of repair on the tubes was the same as the effect of repair on coupon strength.

Correlation of Coupon and Tension Tube Strengths---The ratios of tube to coupon strengths for both unrepaired and manually repaired welds were combined into a sample, which was used to evaluate the correlation of the tube test results and tensile coupon test results. This was accomplished using the reduced ratioing procedure. The resulting reduced ratio calculations are included in Table XXIX. At the 95% confidence level, the tube tension strength is shown to be approximately 83% of the tensile coupon strength. This ratio includes the previously mentioned state-of-stress differences as well as the tailout influence and the sheet/extrusion differences between coupon and structure.

Significance of Manual Repair on Pressure Vessel Strength---A limited number of manually repaired vessels were tested to provide an indication of the significance of repair on the strength. The results of the eight basic unrepaired pressure vessels were compared with the results for the three manually repaired vessels. These results are summarized in Table XXX. The statistical tests for significance indicate that there is a real difference in strength due to repair. This was also shown previously for both the test coupons and tension tube results.

A further analysis was conducted to see if the amount of reduction in strength was similar to that for the tension coupon tests. The three repaired vessels represented three different welders. The results for each one were ratioed to the average unrepaired pressure vessel strength for the same welder. The resulting ratios were compared to the similar ratios determined previously for the tensile coupon tests. These data are summarized in Table XXXI. The tests for significance indicate the differences between pressure vessel ratios and coupon ratios are not significant. A consistent trend is seen in that coupon tests, tube

Table XXIX: REPAIRED AND UNREPAIRED---CORRELATION OF TUBE AND COUPON STRENGTHS

Item	Unrepaired Welds				Manual Repair Welds			
	Welder	Ultimate Stress		Ratio R	Repair Welder	Ultimate Stress		Ratio R
		Tube	Coupon			Tube	Coupon	
Data Summary	1	28.87	34.75	0.831	1	24.6	27.43	0.896
	2	29.00	32.27	0.899	3	25.5	32.90	0.775
	3	25.55	31.23	0.818	4	27.3	33.90	0.805
	4	28.13	33.05	0.851	9	26.0	29.90	0.869
	7	29.28	33.32	0.879	11	25.6	28.67	0.892
	n = 5 $\bar{R}$ = 0.855 S = 0.0335				n = 5 $\bar{R}$ = 0.847 S = 0.0543			
Difference in Variance	F = 2.62 $F_{.975}$ = 9.60 Not Significant, $F < F_{.975}$							
Difference in Means	$D_{\bar{X}}$ = 0.008 Sp = 0.0451 $t_{.975}$ = 2.306 u = 0.066 Not Significant, $D_{\bar{X}} < u$							
Reduced Ratio	n = 10 $\bar{R}$ = 0.851 S = 0.0428 c = 0.3162 $t_{.95}$ = 1.833 $R_{.95}$ = 0.827							

Table XXX: SIGNIFICANCE OF REPAIR ON PRESSURE VESSELS

Item	n	Ultimate Burst Stress, Ksi		S
		$\bar{X}$	Range	
Unrepaired Data	8	32.22	29.1-34.5	1.947
Repair Data	3	27.43	24.4-30.8	3.209
Difference in Variance	$F = 2.72$ $F_{.975} = 6.54$ Not Significant, $F < F_{.975}$			
Difference in Means	$D_{\bar{X}} = 4.79$ $Sp = 2.289$ $t_{.975} = 2.262$ $u = 3.51$ Significant, $D_{\bar{X}} > u$			

Table XXXI: EFFECT OF REPAIR ON PRESSURE VESSELS

Ratio $R = \frac{\text{Repaired}}{\text{Unrepaired}}$

Data Summary	Pressure Vessel Tests			Tensile Coupon Tests		
	n	$\bar{R}$	S	n	$\bar{R}$	S
	3	0.867	0.0617	14	0.876	0.0643
Difference in Variance	$F = 0.921$ $1/F_{.975} = 0.201$ Not Significant					
Difference in Means	$D_{\bar{X}} = 0.009$ $Sp = 0.0638$ $t_{.975} = 2.131$ $u = 0.086$ Not Significant					

tension tests, and pressure vessel tests all indicate a reduction in strength due to manual repair. The reduction in strength for the two simulated structures does not differ significantly from that indicated from the tensile coupon results.

Effect of Mismatch on Pressure Vessel Strength---The original test program included three pressure vessels in which mismatch amounting to over 10% of the thickness was to be achieved. This was to evaluate the effect of a discontinuity on the apparent strength of a simulated structural weld. Inspection of all pressure vessels prior to test indicated that six rather than three of the 11 unrepaired vessels had mismatch in localized areas exceeding the 0.009 inch specified. The 11 vessels could be separated into three distinct groups representing three levels of mismatch: the first group of five vessels fell within the specified limit of less than 0.009 inch; a second group of five with maximum mismatch fell within the 0.02- to 0.03-inch range; and the third represented a single vessel with 0.08-inch mismatch.

The sample statistics for each of the three groups are shown in Table XXXII. Obviously, the 0.08-inch mismatch severely reduced the failure strength. Since the 0.02- to 0.03-inch mismatch appeared to represent what might occur even though a lesser amount was specified, a test for significance was used to compare these results with those of the acceptable pressure vessels. The tests, as shown in Table XXXII, indicate no significant differences between the two samples.

The above illustrates a situation in which subjective decisions sometimes are made in establishing specification limits or the applicability of a design strength for conditions exceeding specified limits. This need not be the case if data is treated using consistent analytical procedures as suggested by the guidelines established in this program.

Correlation of Pressure Vessel and Tensile Coupon Strengths---The pressure vessel-coupon correlation was established using the ratios of the average pressure vessel strength to coupon strength for each of the four welders producing unrepaired pressure vessels. A summary of the data and the resulting ratios are given in Table XXXIII. A reduced ratio was calculated from these data indicating, at 95% confidence level, the pressure vessel strength to be 90% of the coupon strength.

DATA PRESENTATION AND USE

The requirement to provide meaningful and useful data for design use involves description of pertinent material and processing conditions to be associated with the property values given. The previous data analysis produced property values presented to illustrate how this may be accomplished. It is important that all significant information available be presented so that the user may make an adequate assessment of its applicability.

As detailed in the guidelines, a tabular presentation of properties is desirable, but adequate notes must accompany the table to properly qualify the data presented. Use of the guidelines concept of presenting coupon-derived properties results in the additional requirement of providing proper reference to precautionary information regarding its use.

Table XXXII: EFFECT OF MISMATCH ON PRESSURE VESSEL STRENGTH

Data Summary	Mismatch	n	Ultimate Strength		S
			$\bar{X}$	Range	
	<0.009	5	32.66	30.4-34.5	1.766
	0.02-0.03	5	32.18	29.1-33.9	1.979
	0.080	1	20.0	–	–
Difference in Variance	$\frac{0.02-0.03}{<0.009}$	$F = 1.25$ $F_{.975} = 9.60$ Not Significant			
Difference in Means	$\frac{0.02-0.03}{<0.009}$	$D_{\bar{X}} = 0.48$ $S_p = 1.876$ $t_{.975} = 2.306$ $u = 2.73$ Not Significant			

Table XXXIII: CORRELATION OF PRESSURE VESSEL AND COUPON STRENGTHS

Data Summary	Welder	Avg. Pressure Vessel Burst Stress	Avg. Coupon Ultimate Stress	Ratio
	1	34.07	34.66	0.983
	2	29.75	33.08	0.899
	3	32.27	32.18	1.002
	4	32.85	35.05	0.937
Reduced Ratio	$n = 4$ $\bar{R} = 0.9552$ $S = 0.0464$ $c = 0.500$ $t_{.95} = 2.353$ $R_{.95} = 0.900$			

The previous analysis generated coupon-derived tensile ultimate strengths for selected weldments in 6061 aluminum and Ti-6Al-4V. These data are presented in Tables XXXIV and XXXV according to the guidelines requirements. It is obvious that data is not available for all of the conditions listed. For instance, the effect of repair is not available for manual welded 6061. Presentation of data in the manner shown points out where data is lacking and where information is sufficient to permit the user to interpret it correctly.

The minimum properties shown in Tables XXXIV and XXXV are for the exact conditions described in the analysis discussion. The practice used in Mil-Hdbk-5 where minimum properties are presented as whole numbers (increments less than 0.75 are rounded down) would decrease the number of values required to be shown. For instance, a single value of 23 ksi would suffice for manually welded 6061 for a thickness range of 0.03 to 0.06 inch in Table XXXIV. The use of guidelines procedures in developing additional data makes this practical while not increasing the complexity of this type of presentation.

An advantage of this type of presentation is that the effect of significant process variables can be assessed by the user. The presentation of a single-strength value for the broad category of as-welded 6061-T6 would require the selection of a minumum strength value based on the weakest combination of process parameters (i.e., manual welds). Presentation of the data in a form similar to Table XXXIV permits the user to properly evaluate the process requirements for his particular application. Stipulation of an additional requirement such as mechanized welding would permit the use of a minimum strength of 29 ksi for unrepaired 0.09-inch welds as opposed to 22 ksi for manual welds. An assessment of the desirability of the additional requirement with respect to the gained strength may then be made on a more knowledgeable basis.

The data presented in Tables XXXIV and XXXV are minimum coupon strengths. According to guidelines procedures, structure-coupon ratios are also required for application of these properties to structural design. The appropriate structure-coupon ratios developed in this program are shown in Table XXXVI.

The tensile ultimate strength to be used for design of an as-welded 0.09-inch thick 6061-T6 tube, mechanized GTA welded without repair using 4043 filler metal, is determined in the following manner. The minimum coupon strength for the above stated conditions is 28.9 ksi per Table XXXIV. The applicable structure ratio as shown in Table XXXVI is 0.827. The resulting strength to be used for design is therefore 28.9 x 0.827 = 23.9 ksi. If a manual repair is to be permitted, the coupon-derived strength of 24.4 ksi is multiplied by the structure ratio of 0.827 ksi, and the resulting strength to be used for design is 20.2 ksi.

SUMMARY OF VERIFICATION TESTING PROGRAM

The verification testing program successfully illustrated and verified the use of the recommended guidelines established in Phase 1 of this contract. Following the guidelines procedures, meaningful weldment design strengths for 6061 aluminum alloy and Ti-6Al-4V alloy were

Table XXXIV: COUPON-DERIVED MINIMUM STRENGTHS OF 6061-T6 ALUMINUM WELDMENTS

Base Material	Filler Wire	Weld Joint Type	Postweld Treatment	Weld Method	Weld Bead	Thickness, In.	Minimum Tensile Ultimate Strength [1]		
							Unrepaired [2]	Mechanized Repaired [3]	Manual Repaired [3]
6061-T6	4043	Square Butt	As-Welded	Manual GTA	Off	0.03	23.3		
						0.04	23.1		
						0.05	23.0		
						0.06	22.8		
						0.07	22.6		
						0.09	22.2		
						0.125	21.5		
				Mechanized GTA	off	0.06	27.8		
					on & off	0.09	28.9	26.5	24.4
					off	0.125	27.6		
					off	0.250	26.8		
					off	0.375	25.4		

[1] Based on 99% probability with 95% confidence limits. Use of these values for design is subject to the limitations of Table XXXVI.

[2] Meeting weld character requirements of Table VIII.

[3] Based on single repair meeting quality requirements of [2]

Table XXXV: COUPON-DERIVED MINIMUM STRENGTHS OF Ti-6Al-4V WELDMENTS

Base Material	Filler Wire	Weld Joint	Postweld Treatment	Weld Method	Weld Bead	Thickness, In.	Minimum Tensile Ultimate Strength, ksi [1]	
							Unrepaired [2]	Manual Repaired [3]
Ti-6Al-4V STA 1000	Com. Pure	Square Butt	1000° F -2 Hrs	Mechanized GTA	Off	.0.600	129.6	96.9

[1] Based of 99% probability with 95% confidence limit. Coupon strengths may differ significantly from structural strengths. Use of these valued for design requires development of adequate coupon-structure correlations.

[2] Meeting weld character requirements of Table IX.

[3] Based of single manual repair, meeting quality requirements of [2]

Table XXXVI: STRUCTURE-COUPON RATIOS FOR WELDMENT APPLICATIONS

Structural Applications	Material	Structure - Coupons
Uniaxial Tension in Tubes	6061-T6 As-Welded With 4043 Filler	0.827 [1]
Longitudinal Welds in Pressure Vessel	6061-T6 As-Welded With 4043 Filler	0.900 [2]

[1] Based on square butt joint mechanized welds in 0.09-inch thick wall tubes loaded transverse to the weld. Weld bead off or on. With or without repair.

[2] Based on square butt joint mechanized welds in 0.09-inch uniform thickness pressure vessels with weld bead removed. Analysis based on membrane stress. No biaxial increase factor allowed.

determined for various welding conditions. Data was generated for coupons obtained from welded panels and for simulated structure. Statistical concepts were satisfactorily applied in the analysis of the weldment data. Specific results of the verification program are as follows:

Significance of Welding Method---There was a significant difference in tensile ultimate strengths between manual and mechanized as-welded 6061 aluminum alloy weld strengths. The analysis techniques using the guidelines procedures resulted in the recognition of two distinct subpopulations representing the mechanized and manual weldments.

Significance of Tooling---Tooling was not a significant parameter for re-heat-treated 6061-T6 aluminum welds. For the as-welded condition, chill and insulated tooling showed a significant difference in mean strength.

Significance of Weld Repair---Repair welding was the most significant variable that affected weldment design strength. As-welded 6061 aluminum alloy weld strength was reduced by approximately 8% due to mechanized repair and approximately 15% due to manual repair. In the case of Ti-6Al-4V, weld strength was reduced from 129.6 ksi to 96.9 ksi by manual repair welding. The statistical tests for significance indicated that two distinct subpopulations representing repaired and unrepaired welds were involved.

Significance of Weld-Bead on Coupon Strength---No significant differences were noted in the variance between bead-on samples of as-welded 0.09-inch-thick 6061 aluminum alloy. The average strength for the bead-on configuration was approximately 1 ksi higher than for the bead-off configuration.

Effect of Thickness on Strength---There was a decrease in strength with increased thickness in as-welded 6061 material. The decrease amounted to approximately 7% over the thickness range evaluated (0.06 to 0.375 inch).

Coupon-Structure Correlations---The ultimate strengths exhibited in the tube and pressure vessel structures were significantly different than those exhibited by simple test coupons. The as-welded 6061-T6 tubes in tension and uniform wall thickness pressure vessels exhibited strengths of 83% and 90%, respectively, of the coupon strengths. Tests of significance indicated that the effect of weld repair on the tubes and pressure vessels was not significantly different from that indicated from the tensile coupon results.

Presentation of Data---The data presentation was made according to the recommended guidelines. The method makes it obvious where data is lacking and presents sufficient information for the data that is given to permit the user to interpret it correctly.

The verification testing program effectively demonstrated the use of recommended guidelines for establishing adequate engineering weld design data and their applicability to different materials and welding conditions.

SECTION VIII

CONCLUSIONS

Analysis of the literature and industrial surveys resulted in the following conclusions:

1) Presently used weldment design data generation, analysis, and presentation procedures are not sufficiently standardized to be useful to design engineers on an industry-wide basis. There is, however, considerable interest and desire within the aerospace industry to establish standardized methods for development of weldment design data.

2) The three major factors contributing to the lack of weldment design data for industry-wide usage are (1) insufficient standards for describing the welding conditions contained in a given population definition, (2) nonuniformity in the definition of weldment design strength; and (3) lack of established standards on specimen configurations and test procedures.

3) Presentation of the welding conditions represented by the weldment design data will continue to limit industry-wide generation and usage of the data until adequate government or industry-wide welding specifications are available. The only alternative to the current lack of these specifications is the difficult task of presenting all specific weld characterization data in association with the design property data.

4) Each of the weld characterization variables shown in Table XXXVII must be considered to determine their significance in all phases of weldment design data generation.

5) Definition of weldment design strength based only on coupon-derived data has the general consensus of industry as being the preferred approach in establishing and presenting these properties for industry-wide usage. Determination and presentation of weldment design properties from varying combinations of coupon-derived data and structural hardware considerations has created considerable and unnecessary confusion within industry because of the differences in the resulting design values.

6) In using coupon-derived weldment design data, the potential differences between coupon and structure must be recognized and a correlation established for each structural component being analyzed.

7) Transverse-weld tensile ultimate strength is the most significant weld joint property that can be effectively developed and analyzed by reproducible industry-wide accepted methods. The transverse test is the test most widely used by industry to determine the over-

Table XXXVII: WELD CHARACTERIZATION VARIABLES

BASE MATERIALS	WELDING PROCESS VARIABLES	WELD CHARACTER
● ALLOY ● COMPOSITION ● FORM ● PRE- AND POST-WELD HEAT-TREAT CONDITION ● THICKNESS ● FILLER MATERIAL	● JOINT PREPARATION Joint Type Edge Preparation Cleaning ● TOOLING Alignment Restraint Thermal Control ● WELDING CONDITIONS Process (e.g., GTA) Method (e.g., Manual) Position (e.g., Flat) Sequence (e.g., No. of Passes) Heat Input Control (e.g. KJ/in or setting) Pre- and Postheat Interpass Temperature Shielding Gas ● WELD REPAIR Number of Repairs Type of Repair	● ACCEPTANCE LEVELS External Quality Pores Reinforcement Cracks Undercut Internal Quality Cracks Pores Inclusions Lack of Fusion Tensile Properties Specification Minimum & Minimum Average ● INSPECTION METHODS NDT Visual Radiographic Penetrant Magnetic Particle Ultrasonic DT Tensile Test

all strength of weldments. In addition, the test techniques are established by ASTM and federal test method standards. Other joint properties are less frequently used and are more difficult to standardize.

8) A better correlation is required between weld discontinuities and probability of failure in order to establish industry-wide nondestructive testing acceptance criteria.

Efforts to develop standardized procedures and the analysis of the model testing program resulted in the following conclusions:

1) The validity of the recommended guidelines that were developed was effectively demonstrated by the model test program.

2) Meaningful weldment design strengths were determined using the developed transverse-weld tensile coupon configuration requirements and testing procedures.

3) The established guideline procedures applied equally well to the different types of materials and welding conditions investigated, as demonstrated by the as-welded and welded-plus-heat-treated 6061 aluminum alloy and welded-plus-stress-relieved Ti-6Al-4V titanium alloy sequences.

4) The influence of welding variables can be analyzed and related to design strength when the recommended guideline procedures are used.

5) Manual repair welding was the most significant variable which affected weldment design strength. The reduction in weld strength due to repair welding (mechanized or manual) should be considered in any design allowables program.

6) The welding variables of most frequent concern and the minimum that should be specified with published weldment design strengths are: (1) alloys, (2) weld heat-treat conditions, (3) filler materials, (4) joint thicknesses, (5) joint types, (6) welding processes, (7) welding methods, i.e., manual or mechanized, (8) weld quality levels, and (9) weld repairs.

7) Standardized transverse-weld tensile coupon configuration requirements and testing procedures were developed for obtaining weldment design strength.

SECTION IX

RECOMMENDATIONS

1. The recommended guidelines should be coordinated with the aerospace industry for critical review and comment. Industry recommendations should be reviewed and resolved. The guidelines should then be considered for inclusion in Mil-Hdbk-5 *Guidelines for the Presentation of Data.*

2. Weldment design data that can meet the requirements of the recommended guidelines should be included in Mil-Hdbk-5 as soon as possible. New programs should be recommended for development of design data for selected welding processes, materials, and heat-treatment conditions for Mil-Hdbk-5.

3. An industry-wide survey should be conducted to recommend changes to military welding specifications applicable to the aerospace industry. The main objective of this survey should be the development of effective controls for establishing useful weld characterization. The specifications should ultimately specify minimum joint strength properties in order to better control parameters affecting thermal input to the joint. Requirements and procedures for repairing of weldments should also be defined.

4. Nondestructive testing and weld character (internal and external quality levels) requirements in present government specifications should be reviewed and more firmly developed to establish improved and realistic requirements.

5. Specimen configurations and testing procedures should be standardized and included in the guidelines for establishing firm criteria for generating design data on: (1) fatigue strength; (2) fracture toughness; and (3) creep and stress rupture properties.

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APPENDIX A

LITERATURE SOURCES AND ABSTRACTS

APPENDIX A

LITERATURE SOURCES AND ABSTRACTS

The literature review consisted of a computerized search of NASA and DDC files as well as manual searching of the sources shown below. Those references, which contained information pertinent to the program, were reviewed in detail and abstracted for uture use. The abstracts obtained are presented on the following pages.

INDEXES AND ABSTRACTS	DATES COVERED	SUBJECT HEADINGS SEARCHED
MECCA (Boeing Aerospace Library Mechanized Catalog)	1964 - May 12, 1967	Battelle; Rensselaer; M.I.T., Fusion Welding; Design, Handbook and Manual; Standard, Welded Joint
Engineering Index	1958 - March 1967	Welding and Subheadings; Welds; Welds, Mechanical Properties
Applied Science and Technology Index	1958 - April 1967	Welding and Subheadings to Welding Research
ASM Review of Metal Literature	1962 - May 1967	Welding Joints, Mechanical Property; Weldments, -Design, -Mechanical Property
Applied Mechanics Review	1966 - March 1967	Joining
Welding Research Council, Research Reports	1962 - 1966	Titles
Welding Research Council, Reports of Progress	1963 - 1964	Titles
Welding Research Council, Bulletin	April 1967	Titles
Welding Research Abroad	1964 - 1967	Table of Contents
British Welding Journal	1957 - 1967	Titles

Metal Progress	June 1967	Table of Contents
Welding Journal	1957 - 1967	Titles, -Regular and Research Supplement

1. F. C. Smith, "The True Design Strength of Materials and Joints," *Machine Design*, December 1966, pp. 181-189.

   A detailed method for establishment of base metal and welded design allowables is presented. This is based on a statistical approach resulting in values with known confidence level and conformance. This approach was successfully used by LTV Aerospace Corporation for missile-type applications. Included in the discussion are methods of: selecting the desired reliability, gathering test data, analyzing data, normality testing, calculating design allowable strength, and rejecting suspicious data. The 2014 aluminum alloy is used as an example.

2. F. G. Nelson and R. L. Rolf, "Shear Strength of Aluminum Alloy Fillet Welds," *The Welding Journal*, February 1966, pp. 82-s - 84-s.

   Average and minimum longitudinal and transverse shear strength are determined for fillet welds from results of about 550 tests of longitudinal and transverse shear specimens made with nine filler metals in a wide range of sizes. The filler metals evaluated were 1100, 2319, 4043, 5052, 5154, 5356, 5554, and 5556 using fillets from 1/8 through 3/4 inch and the appropriate base metal.

3. *Mil-Hdbk-5 Meeting Minutes*, 1962, 1963, 24th, 26th, 27th, and 28th Meetings.

   At the request of Mr. Shinn, Air Force, weld allowables were examined by ARTC Committee per the 24th Meeting. A report was given at the 26th Meeting summarizing the ARTC work---Project 23-62 dated 10 September 1963 (replies to questionnaire covering aluminum alloys). At the 27th Meeting a proposed draft of Mil-Hdbk-5 *Section of Fusion Welding of Aluminum Alloys* was presented. At the 28th Meeting the item was dropped by ARTC and Mil-Hdbk-5 due to the complexity of the problem and that there were too many variables, done differently by each company, little data on methods available, and difficult to consolidate.

4. D. P. Moon and W. S. Hyler, *Mil-Hdbk-5 Guidelines for the Presentation of Data*, AFML-TR-66-386, February 1967.

   Procedures to be used for the development of Mil-Hdbk-5 design data are presented. The section on welding has not been written. Methods and standards for testing are referred to federal and ASTM specifications. Details of the statistical techniques to be used in analysis of data are presented.

5. G. E. Martin, "Design and Fabrication of Welded Titanium Wing Leading Edge," *Joining of Materials for Aerospace Systems*, SAMPE 9th National Symposium, Dayton, Ohio, November 1965.

A summary of welding development and production of a Ti-5Al-2.5Sn leading edge is presented. Typical test results in conjunction with simulated joint tests were used in detailed weldment sizing. This assembly was subjected to fatigue loading in service, and subscale tests were conducted to verify performance.

6. V. L. Young, "Design and Quality Requirements for Weldments in Liquid Rocket Propulsion Systems," *Joining of Materials for Aerospace Systems*, SAMPE 9th National Symposium, Dayton, Ohio, November 1965.

   A summary of an overall approach to design and fabrication of critical welded structure is presented. Emphasis is placed on the need for standardized requirements, which can be interpreted by large complements of personnel. This is implemented through design manuals, process specifications, and inspection procedures. Weld classes are defined based upon load-carrying capacity rather than criticalness of the structure as is often done. A maximum joint efficiency is established for a particular alloy, welding procedure, heat treatment, condition, discontinuity level, etc., and used at the best weld class. Lower class welds are then percentages of this number.

7. E. F. Condon, "The Design and Fabrication of Welded Titanium Spacecraft Structures," *Joining of Materials for Aerospace Systems*, SAMPE 9th National Symposium, Dayton, Ohio, November 1965.

   A summary of the design and construction of the Gemini and Mercury spacecraft with respect to welding is presented. Details of weld land dimensions and welding procedures for a specific case are not presented. Fusion welding applications included the joining of magnesium alloy, HM31A, titanium Ti-6Al-4V, and commercially pure alloys.

8. J. F. Rudy, "The Design and Fabrication of Welded Aluminum Alloy Boosters," *Joining of Materials for Aerospace Systems*, SAMPE 9th National Symposium, Dayton, Ohio, November 1965.

   A comprehensive description of the methods used in design and fabrication of the Titan launch vehicle is presented. The common ground between engineering and manufacturing is shown to be the design allowable, which in this case is the transverse static tensile ultimate strength of the weldment. The basic allowable is initially statistically derived from typical test data. This allowable is then further reduced by considerations for internal defects (i.e., porosity, tungsten inclusions, slag, oxides) mismatch, and repair. Subsequent repair decisions are based on discontinuity and repair versus joint strength data on an individual basis. This technique allows acceptance of fairly severe discontinuities on a quantitative basis.

9. R. A. Davis, *Evaluation of Welded 2219-T87 Aluminum Alloy*, George C. Marshall Space Flight Center, Engineering Materials Branch, P and V Engineering Division Report MTP-P & VE-M-62-16, December 1962.

   A program to determine weld strength design allowables for aluminum alloy 2219-T87 was conducted in support of the Saturn S-1C. Gas metal-arc (GMA) and gas tungsten-arc (GTA) weld data were evaluated in plate thicknesses of 1/4, 1/2, 3/4, and 1 inch. Welds of each process and thickness combination were produced in flat, vertical, and horizontal welding positions. Studies were also conducted to determine the extent of weld heat affected zone in the base metal.

The ultimate strength data of welds were statistically analyzed by the students' "t" test, assuming the data conforms to a normal distribution. Both 95 and 99% confidence levels were determined for GTA, GMA, and combined GMA and GTA welds.

10. R. F. Breyer, R. K. Akiyama, R. [illegible]. Cutrell, and G. F. Herbst, *Weld Repair and Inspection Procedure*, Martin Co., Materials Engineering Section, Materials Engineering Report ME 688, DSR S11050; X65-12087.

The total report is comprised of four related papers:

- Review of Weld Defects Causing Leaks
- Inspection and Control Techniques for Aluminum Welds and Weld Repairs
- Repair Welding Study
- Weld Defect Repair by Localized Mechanical Removal

The last paper contains design allowable information. The feasibility of repairing weld bead areas containing localized crack-like defects by mechanical removal (i.e., grinding and drilling) of the defect with no rewelding were determined. The strength reduction trends with respect to alloy, thickness, method of removal, depth of removal, length of removal, location of removal, bead shaving, and specimen geometry induced notch effects are determined in general.

A detailed statistical evaluation of the weld strength reduction caused by the significant defect removal parameters is given. Applicable design allowables are determined by analysis of the data. Static tensile strength, low cycle fatigue strength, and properties under biaxial loading are evaluated 2014-T6 and 6061-T6 are the alloys tested using both 2014-T6 to 2014-T6 and 2014-T6 to 6061-T6 combinations.

11. R. Weck, "A Rational Approach to Standards for Welding Construction," *British Welding Journal*, Vol. 13, No. 11, pp. 658-668, November 1966.

A very general discussion of the problems involved in standards for welded construction is presented. The topics discussed pertain to structures such as boilers and pressure vessels. It is stated that, presently, steel specifications are given major consideration; whereas weldability is hardly considered. Mechanical properties and their relation to weld defects are discussed. One graph, fatigue S-N diagrams for butt welds, is given, on which the permissible stress levels of the British Standards for Steel Girder Bridges are superimposed.

12. S. A. Greenberg, "What Engineers Should Know in Designing Welded Structures," *Metal Progress*, pp. 93-99, June 1967.

A historical development of welding codes and specifications for welded buildings and bridges is presented. The applicability of shielded metal arc, submerged arc, and gas metal arc welding was discussed. Economy of automation is pointed out. ASTM requirements for weldable structural steels are given in terms of thickness, composition, tensile strength, yield strength, elongation, reduction in area, and weldability. Weld design allowables are not specifically mentioned. However, the factors governing design allowables are discussed in detail.

13. W. E. Cooper, "The Significance of the Tensile Test to Pressure Vessel Design," *The Welding Journal*, pp. 49-56, January 1957.

A discussion is given of why it is not possible to relate the maximum pressure which a cylindrical or spherical vessel can withstand directly to the ultimate tensile strength of the material from which it is constructed in all cases. It is concluded that whereas initial yielding may be related to the properties usually reported from a tensile test, it is not possible to relate the maximum pressure which a cylindrical or spherical vessel can withstand directly to ultimate tensile strength of the material from which it is constructed. Yield pressure, maximum pressure, strain at maximum pressure, and the localization of deformation at rupture in terms of the initial dimensions of thin-walled cylindrical and spherical shells and the material properties of pressure vessels are discussed in detail. A mathematical analysis of the failure mechanics is included.

14. R. P. Newman and T. R. Gurney, "Fatigue Tests on 1/2 Inch Thick Transverse Butt Welds Containing Slag Inclusions: 1st Interim Report," *British Welding Journal*, Vol. 11, No. 7, pp. 341-352, July 1964.

A series of butt welds with slag inclusions ranging from a continuous line of slag over the whole specimen width to a single 1/16-inch inclusion were fatigue tested. The results are compared with the design stresses specified for fatigue loading conditions in British Standard 153: 1958, British design allowables. It was found that there are acceptable defect levels for specified fatigue lives. Their results also indicate that for a given size of defect, a greater strength could be attained with low hydrogen than with rutile welding rods.

15. A. Matting and M. Neitzel, "The Evaluation of Weld Defects in Fatigue Testing," *Welding Research Abroad*, pp. 34-60, August-September 1966.

An attempt to establish standard values with respect to reduction of fatigue strength caused by weld defects is given. The primary aim of the paper is to provide designers and inspection authorities with a basis for evaluating such defects. However weld allowables, as such, are not discussed.

16. W. L. Burch, "The Effect of Welding Speed on Strength of 6061-T4 Aluminum Joints," *The Welding Journal*, pp. 361-s - 367-s, August 1958.

The factors affecting tensile strength of welded-and-aged 6061-T4 aluminum joints are studied. Welding by gas tungsten arc (GTA) is used on joints, which upon aging have nearly the strength of 6061-T6. Welds are single pass in 1/16, 1/8, and 1/4 inch thicknesses. It is found that joint strength increases rapidly up to 15 ipm with increasing welding speeds. Whereupon, the tensile strength is uniformly high at 90 to 95% of -T6 strength. Optimum welding speeds for 1/8 and 1/4 inch thicknesses are given; but weld design allowables are not discussed. This technique was developed for large airborne tanks to avoid solution heat treatment of the finished structure with attendant quenching and distortion problems.

17. "Welded Boilers and Pressure Vessels," *The Engineer*, Volume 211, pp. 122-125, January-June 1961.

The article presents extracts from B. Lancaster's paper "A Comparison of United States, European and British Commonwealth Codes for the Construction of Welded Boilers and Pressure Vessels." There is also given *in extenso* the paper, "Pressure Vessel Design Requirements in the Near Future," by W. B. Carlson.

Lancaster discusses the wide range of codes used in these nations, and points out that both France and Britain have no single code which is either officially recognized or universally accepted. There is a wide difference in the degree of local authority given to codes. Broad agreement is found as to the essentials required for sound design. On this comparison basis the author appraises possible future lines of development of British codes. Carlson states his views in detail for revising of both mandatory and recommended codes based on results of authenticated research.

18. R. P. Newman, "Fatigue Strength of Butt Welds in Mild Steel," *British Welding Journal*, Vol. 7, No. 3, pp. 169-178, 1960.

A review is given of the methods used for determining fatigue properties of welded joints which relates these properties to the factors that influence butt welds in mild steel. In general transverse, transverse-welded from one side, longitudinal, and discontinuous longitudinal butt welds are the weldments considered. It is pointed out that there can be a wide range of variations in fatigue strength, depending on joint form. The permissible fatigue stresses for butt welds is B.S. 15 steel under axial loading (based on B.S. 153:1958, British design rule) are compared with experimental data.

19. J. L. Wood, "Flexural Fatigue Strength of Butt Welds in N.P. 5/6 Type Aluminum Alloy," *British Welding Journal*, Vol. 7, No. 3, pp. 365-380, 1960.

A series of fatigue strength tests of butt welded N.P. 5/6 type aluminum alloy taken transverse to that of welding are presented. It is found that 50% loss of fatigue strength exists from the plate in as-received condition as compared to the as-welded condition, which is mostly attributed to an annealed condition of the heat-affected zone and the stress concentration effects at the weld bead edges. It is pointed out that a thermal treatment and removal of the bead raises the welded fatigue strength almost to that of the parent plate. Various mechanical treatments for correcting distortion after welding are also considered. In comparison with butt welded steel, a general similarity in behavior under fatigue conditions is indicated. Some general design considerations are briefly discussed.

20. *Strength of As-Welded Longitudinal Weld Joints in 2219-T87 Pressure Vessels*, The Boeing Company, D2-125092-1.

    A development of strength allowables for longitudinal welds of 2219 aluminum alloy in the as-welded condition at both room temperature and -320°F is presented. Both 17- and 70-inch-diameter pressure vessels were burst tested and studied. Uniaxial tensile test results were obtained by the evaluation of specimens cut from weld areas of test tanks after failure. A statistical analysis was used to determine the distribution of weldment strengths and their relation to pressure vessel failure stresses.

21. B. L. Baird, "Biaxial Stress-Strain Properties of Welds in High Strength Alloys," *The Welding Journal*, pp. 571-s - 576-s, December 1963.

    Experimentally derived biaxial stress-strain data are presented for weldments of B120-VCA titanium alloy and 5CrMoV, D6AC, PH15-7 Mo, and AISI 4340 steels. The test results show that the often stated general rule that all welds are weaker than base metal is not true. Stress-strain characteristics of three test materials, after heat treatment, are shown to be identical to those of the base metal. Due to inherent metallurgical deficiencies, the titanium biaxial yield stress values were totally unacceptable. In the PH15-7 Mo stainless steel, they were only slightly reduced from base metal biaxial yield stress values due to imperfect heat-treat response.

22. J. R. Dyar and N. F. Bratkovich, "Reliable Weld Joint Design for High Strength Rocket Motor Cases," *The Welding Journal*, pp. 126-s - 133-s, March 1963.

    A statistical analysis, by use of variance of welded joint, joint geometry, and filler metal, is presented. The details of this analytical method are not given. This paper was employed in developing weld joint design for the first-stage Minuteman ICBM rocket motor case. A detailed discussion of the parameters effecting weld quality is given. To limit process variables, a statistical design experiment was developed. However, there is no mention of a statistical analysis made of the experimental data. The alloy treated was Ladish D6AC.

23. W. H. Munse, "Fatigue of Welded Steel Structures," *Welding Research Council*, 1964.

The Welding Research Council has presented this monograph to provide structural and other engineers and code-writing bodies, in readily usable form, available charts and tables summarizing structural fatigue data coming from several different countries. The University of Illinois undertook this task. Several sections pertain to weld design allowables: Section 3.5, "Statistical Evaluation," pp. 33-35; and Section 7.1-7.4, "Fatigue Strength of Welded Butt Joints," pp. 70-115.

24. *Requirements Analysis of Welding Specifications*, National Aeronautics and Space Administration, Marshall Space Flight Center, Saturn V Report SMPR 100-11-1, May 31, 1967.

A study is presented of the welding specifications used on the Saturn V program. The extent and nature of specification coverage initially available is given. An attempt is made to establish guidelines that will ensure adequate welding procedures for the metals or alloys in future space programs.

25. *Welding Research Council Yearbook*, pp. 60-61, 1966.

The Aerospace Advisory Committee has presented ten important problems and their order of priority. The problem of weld strength design allowables is not considered. On April 19, 1966 a subcommittee meeting was held to review the work being done and to discuss compiling a new problem-priority list. No discussion is given on the subcommittee meeting review.

26. E. R. Scay and R. C. Stewart, "New Concepts for the Design, Control, and Evaluation of Test Welding," *Minutes of Aluminum Welding Symposium*, July 7, 8, 9, 1964, October 13, 1964, pp. 25-41, George C. Marshall Space Flight Center, Huntsville, Alabama.

A very complete listing and discussion of welding variables treated statistically is presented. Classical experiment design is compared with statistical experiment design. Percent confidence, analysis of variance, regression analysis, replication, confounding, randomization, and interaction are discussed with respect to welding variables. Specific topics for statistical analysis are suggested. Erratic welding variables, previously thought to be constant, are given.

27. B. G. Bandelin, "Evaluation of the Combined Effects of Porosity and Mismatch on the Weld Strengths of 6061-T6 and 2014-T6 (As-Welded) Aluminum Alloys," *Minutes of Aluminum Welding Symposium*, July 7, 8, 9, 1964, October 13, 1964, pp. 290-322, George C. Marshall Space Flight Center, Huntsville, Alabama.

The combined effects of mismatch and porosity on the as-welded strength of 2014-T6 and 6061-T6 aluminum alloys is presented. Graphs representing the combined effects show that 2014-T6 strength loss is more dependent on mismatch than porosity as the level of each increases in magnitude; whereas, in 6061-T6 both porosity and mismatch contribute similarly to strength lowering as the level of each increases in magnitude.

28. *Materials Data Handbooks*, March through June 1966, Edited by J. Sessler and V. Weiss, Department of Chemical Engineering and Metallurgy, Syracuse University, Syracuse, New York.

A detailed summary of the materials property information presently available on Type 301 stainless steel and Types 5456, 2219, and 2014 aluminum alloy is presented. Weldment design allowables, as such, are not discussed but rather typical values for various welding conditions are given. The publications present physical and mechanical property data at cryogenic, ambient, and elevated temperatures, supplemented with useful information in such areas as material procurement, metallurgy of the alloy, corrosion, environmental effects, fabrication, and joining techniques.

29. R. J. Runck, *Review of Alloys and Fabricating Methods*, DMIC Memorandum 224, August 1967, Defense Metals Information Center, Battelle Memorial Institute, Columbus, Ohio.

A discussion is given of the alloys used for motor cases for 21 solid-propellant and liquid-propellant missiles of the tactical type. A history of alloy development for solid-propellant missile motor cases is given as background information. Consideration is given to the abilities of NDT methods for the recent higher-strength motor cases. A detailed listing of data on missiles and missile motor cases is appendicized.

30. M. D. Randall, *Methods of Evaluating Welded Joints*, DMIC Report 165, 1961.

A summary of the test methods used within the defense industry for evaluation of welded joints is presented. This is based upon the results of an extensive industrial survey. It was determined that 10 types of tests are used for evaluating weldments and approximately 80 types of specimens. However, relatively few specimens and tests are most frequently used.

31. ARTC Project 28-58, "Standardization of Welded Joint Specimens," *Minutes of Specialists Meeting*, 20 February 1961.

The four most universally used specimens for evaluation of weldments as determined by industry questionnaire were recommended for adoption by the industry as standards. These include: (1) weld transverse tensile, (2) weld parallel (longitudinal) tensile, (3) all-weld-metal tensile, and (4) weld parallel face and root bend specimens.

32. ARTC Project 1-61, *Effect of Discontinuities on Fusion Welded Butt Joints*, Final Report, August 1965.

The Aerospace Research and Testing Committee (ARTC) sponsored a test program, Project 1-61, to evaluate the fatigue life of fusion welded butt joints of 5456 aluminum alloy specimens containing internal weld discontinuities. The work of specimen manufacture and testing was shared by five ARTC member companies.

The fusion welded specimens were subjected to tension-tension fatigue testing after being radiographically inspected and identified as Class I, III, or V in accordance with NAS1514. Specimens were loaded for fatigue testing so as to cause failure at 10^4 or 10^6 cycles. The stress ratio used was +0.1. Supplementary examinations performed included tensile testing, microhardness traverses, and metallographic examination.

A large overlap of fatigue test results was obtained for the three classes. Results indicated that there was no significant difference in the fatigue life of weld specimens containing the different classes of discontinuities.

33. W. P. Goepfert, *Statistical Aspects of Mechanical Property Assurance*, communication from the Aluminum Company of America, December 1965.

A presentation is made of statistical aspects of the nature of variability of the tensile properties of aluminum alloys, its effect on establishing guaranteed properties, and the problem of determining sampling plans that would provide guaranteed properties. Within-piece, piece-to-piece, among-pieces-within-lot, and lot-to-lot variability are considered. The 7075-T6, 2024-T86, and alclad 2024-T3 aluminum alloys are treated.

34. K. F. Thornton and J. F. Faulkner, *Upgrading Via Specification*, communication from the Aluminum Company of America, October 1958.

Several types of upgrading via specification are discussed. The case of dimensional tolerances can often be successfully upgraded, whereas higher-than-normal mechanical property specification values cannot be obtained by upgrading specifications. It is shown that mechanical properties can be justified by rigorous analysis of data from first tests only with no retests. The alclad aluminun alloy 7075-T6 was chosen as the example for the discussion.

35. R. A. Kelsey, *Strength of Welded Panels of 2014 and 2219 Sheet as Determined by Tension and Bulge Tests*, Alcoa Research Laboratories Report 12-61-37, June 6, 1961.

Tensile test data from wide, slotted sheet specimens is presented for 2014 and 2219 aluminum alloys, heat treated and aged after welding. A comparison is made of these results with tensile tests on wide and narrow, plain and welded specimens without slots, and with bulge test results on plain and welded specimens. No significant difference was found in the strength of plain and transversely welded 0.5- and 12-inch-wide tensile specimens; longitudinal welds in both narrow and wide specimens show a slight decrease in tensile strength. Note: The ductility properties stated in this paper are deceptive as presented because both plain and welded specimen elongation is based on a 10-inch extensometer separation distance and does not give an accurate evaluation of elongation in the weld.

36. A. G. Pickett, S. C. Grigory, and A. R. Whiting, *Studies of the Fatigue Strength of Pressure Vessels*, Southwest Research Institute, San Antonio, Texas, N66-13074, July 18, 1965.

A discussion of fatigue properties of various types of welds in A302B steel pressure vessels is presented. Graphic comparison is made of the fatigue properties of various weld types and plain sheet. Specimen configurations of different weld designs for A302B steel are also given.

37. R. S. Gill, *Comparative Tensile and Fatigue Properties at Room Temperature and at Minus 423 Deg F of Some Welded Centaur Tank Joint Configurations*, General Dynamics/Convair, N66-18481, October 1963.

Ten welded 301 and 310 alloy stainless steel joint design configurations are treated. Tensile and fatigue data are both tabulated and graphed for each alloy joint configuration combination. Detailed machine drawings are presented of the specimen configurations tested during the program. The research discussed was in support of a Centaur lightweight tank development program. A detailed chemical analysis is given of each of three different thicknesses used for the testing program.

38. O. T. Ritchie, Editor, *Strength Evaluation of Fusion Welded Rene 41 Nickel Alloy*, The Boeing Company, D2-81283, August 15, 1964.

A study has been conducted to determine allowable stresses for fusion-welded Rene 41 nickel base superalloy joints for use in the design and development of the X-20 reentry vehicle. Mil-Hdbk-5 was complied with, where possible, to determine allowable shear ultimate, tensile ultimate, tensile yield, stress rupture, and typical fatigue properties in the weld-metal and heat-affected zones of original and repaired welds. A detailed graphic treatment is given of all experimental results.

39. J. L. Christian, *Physical and Mechanical Properties of Pressure Vessel Materials for Application in a Cryogenic Environment*, General Dynamics, Astronautics, San Diego, California, March 1962.

Both tabular and graphic presentations are made of test data to aid metallurgical and design engineers in the selection of materials for structural applications at cryogenic temperatures. Data is statistically analyzed per the A and B values as discussed in Mil-Hdbk-5, March 1959. However, the statistically determined values are not intended as design allowables for the materials but are probability values based upon tests from one coil or one heat of each material. Various alloys are treated: 301, 304ELC, and AM-355 stainless steels; 5052, 5456, and 2014 aluminum alloys; and 5Al-2.5Sn titanium alloy.

APPENDIX B

INDUSTRIAL SURVEY SOURCES AND QUESTIONNAIRE

INDUSTRIAL SURVEY QUESTIONNAIRE

1. Tensile Coupon Configuration

As a result of the Aerospace Research and Testing Committee Survey (ARTC Project 28-58) on methods of evaluating welds, four specimens were recommended for standardization within the industry*. These were; transverse tensile, longitudinal tensile, all weld metal tensile and guided bend. The guided bend test is not used for determination of weld design strengths. Therefore, only the tensile specimens are of interest to the subject contract. The tensile specimen configurations are shown in Figures 1, 2 and 3 for reference in this questionnaire.

A. For the purposes of room temperature transverse butt weld design strength (allowable) determination, what flat specimen (see Figure 1) width would be recommended for the following thicknesses (t)? Assume that weld reinforcements would be removed in all cases.

Weld Joint Thickness - Inches (t)	Specimen-Test Section Width - Inches (w)				
	.5	.75	1.0	1.5	Other
<.18					
.18 - .25					
.25 - .5					
>.5					

B. What minimum ratio between test section width and length is normally used in design allowables testing of flat transverse weld specimens?

a. 1/3 b. 1/4 c. 1/5 d. Other______ e. None______

C. Are longitudinal design strengths determined for butt welds, Yes____ No____?
If yes, is the configuration shown in Figure 2 normally used, Yes____ No____.

Exceptions____

D. Above what weld joint thickness are transverse round rather than flat specimens generally used for steel ______ inches and aluminum ________ inches?

---

*M.D. Randall, "Methods of Evaluating Welded Joints", DMIC Report 165, Dec. 1961.

E. When all weld metal tensile tests are performed for design strength determinations, which specimen diameter or diameters are used? .125, .252, .357, .505, Other ________ inches (see Figure 3). Do the dimensions and notes in Figure 3 adequately describe the specimen used? Yes______ No______, Exceptions ____.

F. When design strengths are determined from transverse round specimens are the dimensions and notes shown in Figure 3 adequate? Yes______ No______ Exceptions ____

II. Tensile Testing Methods

A. Are tensile tests of weld specimens conducted in accordance with Federal Test Method 151? Yes________ No ________. Other Specification ___________. Specific exception or additions to the above specification ______________________________.

B. Are design allowables determined for the 0.2% yield strength of transverse welds? Yes________ No ________. If yes, over what gage length is the yield strength measured for round specimens__________ inches and flat specimens____________inches.

III. Fracture Toughness Values

Are fracture toughness values (K_{IC}) determined for weldments? Yes______ No______. If yes, are the ASTM - "Special Committee on Fracture Testing of High Strength Materials" procedures followed? Yes ______ No ________ Exceptions ____.

Are design strengths determined for K_{IC} properties of weldments? Yes________ No________.

IV. Welding Variables

In establishing design strengths for weldments, a decision must be made concerning the disposition of the many variables. When design properties are determined for general application, which of the following variables are specified or not specified? Check appropriate column.

Potential Variables	Specified	Not Specified
Base Metal		
Alloy		
Form - Sheet, Forging, etc.		
Heat Treat Condition		
Thickness		
Welding Process		
GTA, GMA, EB, etc.		
Manual, Mechanized, etc.		
Position, - Vertical, Downhand, etc.		
Welding Sequence - Tacking, etc.		
Heat Input		
Preheat		
Interpass Temperature		
Joint Preparation		
Joint Type		
Edge Preparation		
Cleaning		
Tooling		
Alignment		
Restraint		
Thermal Control		
Filler Material		
Post Weld Heat Treatment		
Weld Repair		
Internal Quality		
Porosity, Inclusions, etc.		
External Quality		
Mismatch, Undercut, etc.		
Weld Reinforcement - On, Off		
Inspection Methods		
Visual		
Radiographic		
Ultrasonic		
Penetrant		
Minimum Strength Requirements		

V. Design Allowable Establishment

The translation of weldment test results into design allowables is a major factor in the establishment of an approach to development and utilization of engineering data on weldments. Since this procedure is normally quite involved and difficult to describe briefly, the following test data will be used as an illustrative example:

EXAMPLE DATA

Number of Tests	391
Sample Mean	28.2 KSI
Coefficient of Variation	7.4%
Standard Deviation	2.099 KSI
Data Range (Min.-Max.)	21.8 - 34.3
Statistical Minimum	
99% Probability, 95% Confidence	22.9 KSI
90% Probability, 95% Confidence	25.2 KSI

This data represents results from twenty-three welders at five different companies and was obtained over a two year period of time. Welding was conducted under the following conditions in accordance with a common specification.

Base Metal - 6061 Aluminum T4 or T6

Sheet Material Gage - .05 to .125 inches

Welding Process - Manual GTA downhand position, single pass. No heat input or weld setting controls.

Joint Preparation - Square groove butt welds, deoxidized and manually scraped prior to welding.

Tooling - None specified.

Filler Material - 4043 alloy

Post Weld Heat Treatment - None

Weld Repair - None

Internal Quality - Specified level does not affect F_{tu} results*

External Quality - Specified level does not affect F_{tu} results*

Weld Reinforcements - Removed flush

Inspection - Visual, radiographic and penetrant

The room temperature tensile tests were conducted on three-quarter inch wide specimens in accordance with the requirements of Federal Test Method 151. Panels from which the specimens were removed were nominally 6" x 12" containing a 6" long weld.

*These levels are controlled by specification.

A. Assuming that the conditions specified in the example would be prescribed by drawing and specification control, what tensile ultimate strength design allowable would be selected for the following applications? (Circle number selected).

Type of Application	99 Prob. [1] 95 Conf.	90 Prob. [1] 95 Conf.	85% of Mean	85% of Low Value	85% of 99/95 [1]	Other
General Aircraft & Aerospace	22.9	25.2	24	18.5	19.5	
Extremely Weight Critical	22.9	25.2	24	18.5	19.5	
Non-Critical	22.9	25.2	24	18.5	19.5	

B. Assume that repair welding was evaluated by similar tensile testing and that the mean ultimate strength was 4 KSI lower for specimens with two repairs. What design allowable would be selected for general aircraft and aerospace usage which permitted two repairs? ________KSI.

How was this allowable derived?

C. When the above selected design allowable or allowables are used in calculating weld joint thicknesses of a structure, with a known state of stress across the joint, are additional reduction factors (other than those used for base metal) normally applied to the allowable? Yes______ No.______. If yes, what is the general magnitude of this factor and what considerations does it include for the three types of applications? Indicate percentages of each in the following table.

Considerations	Percent		
	General Aircraft & Aerospace	Extremely Weight Critical	Non-Critical
1. Residual Stress			
2. Excess or Undetected Internal Flaws			
3. Excess or Undetected External Flaws			
4. Potential Difference in Welding Between Test Panels and Structures			
5. The Welding Conditions in the Allowables Program may not have been Totally Representative			
6. Because it is a Weld			
7. Other			
8. Total Reduction Factor			

[1] Statistically derived with stated probability and confidence.

VI. Personal Information

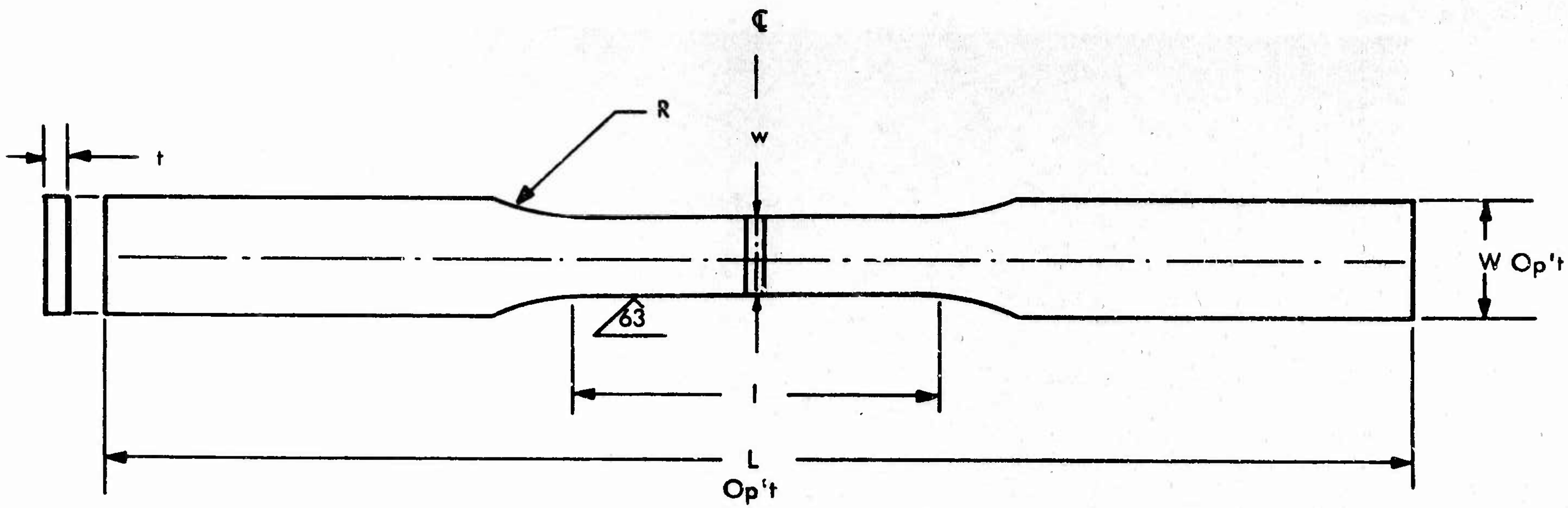
Name of person completing questionnaire ______________________________

Organization Represented ______________________________

Position ______________________________

Telephone ____________________

VII. Additional Comments:

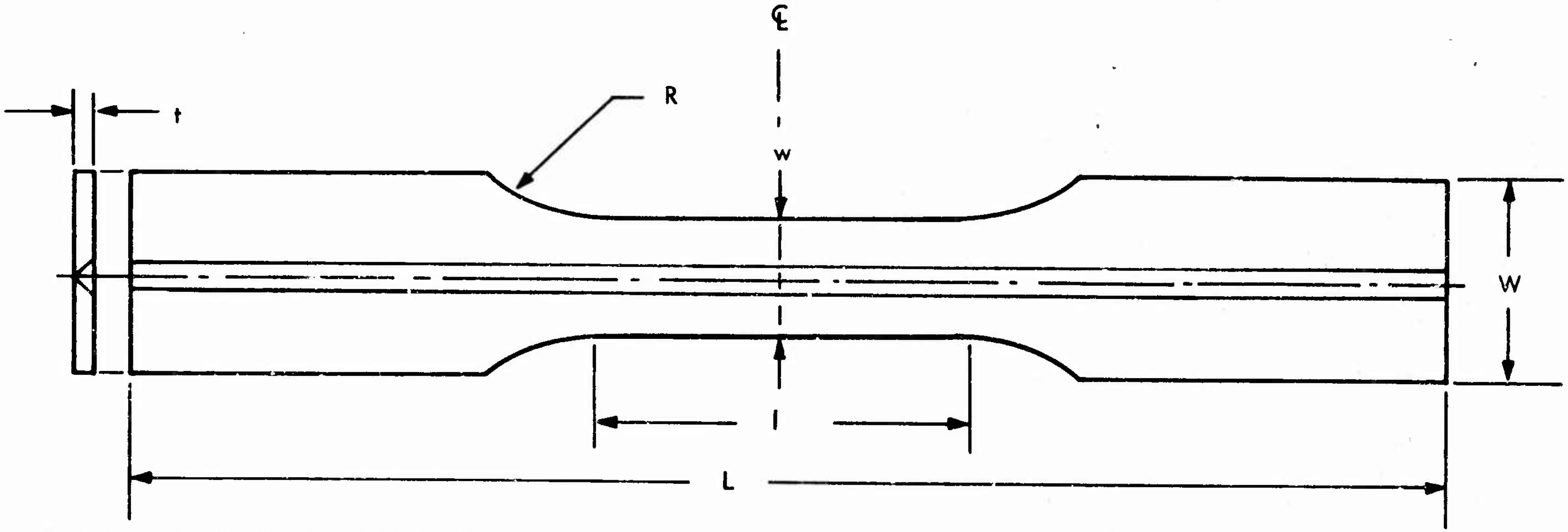


t	w	l	R
.001	.250	1.25	1 min.
to	.500	2.25	1 min.
.250	1.00	4.00	2 min.
	2.00	8.00	2 min.

NOTES:

1. Dimension "W" and "L" optional.
2. Weld bead on or off optional.
3. Fillet radii must fair smoothly into reduced section.
4. Material and grain direction per test requirements.
5. Specimens warped from welding or heat treatment shall not be straightened.
6. Reduced section machined surfaces 63.
7. The reduced section and grip ends must be symmetrical about the longitudinal ℄ within ±.01.
8. Tolerances except otherwise noted: Linear ±.03, Angular +1°.

FIGURE 1 TRANSVERSE WELD TENSILE SPECIMEN

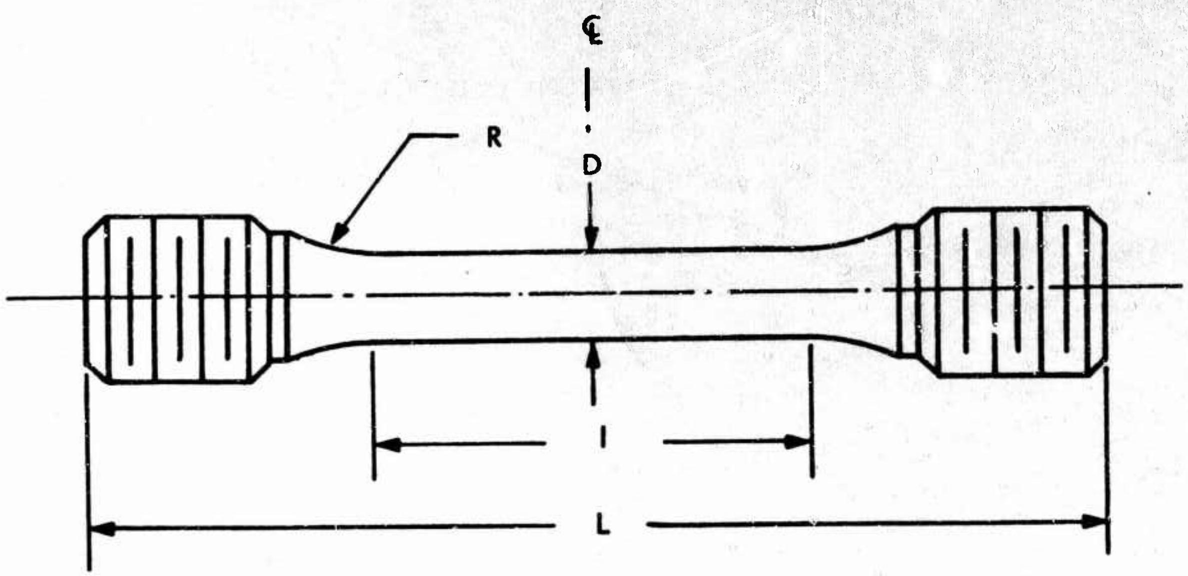


t	w	l	R
.001 to .060	.50	2.25	1.00 Min.
.061 to .125	1.00	3.00	1.00 Min.
.1251 to .250	1.50	5.00	2.00

NOTES:

1. Dimension "W" and "L" optional.
2. Weld bead on or off optional.
3. Fillet radii must fair smoothly into reduced section.
4. Material and grain direction per test requirements.
5. Specimens warped from welding or heat treatment shall not be straightened.
6. Reduced section machined surfaces 63.
7. The reduced section and grip ends must be symmetrical about the longitudinal ℄ within ±.01.
8. Tolerances except otherwise noted: Linear ±.03, Angular ±1°.

FIGURE 2 LONGITUDINAL WELD TENSILE SPECIMEN



D	I	R
.125	.75	.12
.252	1.25	.250
.357	1.4	.350
.505	2.0	.500

NOTES:

1. Dimension "L" and thread size optional.
2. Fillet radii must fair smoothly into reduced section.
3. Reduced section machined surface 32
4. Heat treatment to be performed prior to finish machining.
5. The reduced section and grip ends must be symmetrical about the longitudinal ℄ within ± 0.01.
6. Tolerances except otherwise noted: Linear ± 0.03, Angular +1°.

FIGURE 3 ALL WELD METAL TENSILE SPECIMEN

INDUSTRIAL TOUR SOURCES

First Industrial Tour:

Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio

Battelle Memorial Institute, Columbus, Ohio

North American Aviation, Columbus, Ohio

The Boeing Company, Huntsville, Alabama

NASA-Marshall Space Flight Center, Huntsville, Alabama

The Boeing Company, New Orleans, Louisiana

Lockheed Aircraft, Marietta, Georgia

Bell Aeronautics, Buffalo, New York

McDonnell-Douglas, St. Louis, Missouri

Martin Marietta, Denver, Colorado

Second Industrial Tour:

Aerojet-General Corporation, Sacramento, California

Northrop-Norair, Hawthorne, California

McDonnell-Douglas, Santa Monica, California

Lockheed California Corporation, Burbank, California

North American Aviation, Inc., Los Angeles Division and Space Division, Los Angeles, California

General Dynamics Corporation, Fort Worth, Texas

ORGANIZATIONS ACKNOWLEDGING OR REPLYING TO THE SURVEY

Naval Air Systems Command, Washington, D.C.

U.S. Naval Research Laboratory, Washington, D.C.

Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio

Aero Structures Department, Naval Air Development Center, Johnsville, Warminster, Pennsylvania

Lockheed-Georgia Company, Marietta, Georgia

Northrop-Norair, Hawthorne, California

McDonnell-Douglas Corporation, Missile and Space Division, Santa Monica, California

Aerojet-General Corporation, Sacramento, California

The Martin Company, Denver, Colorado

National Aeronautics and Space Administration, George C. Marshall Space Flight Center, Huntsville, Alabama

McDonnell-Douglas Corporation, St. Louis, Missouri

North American Rockwell Corporation, Columbus, Ohio

Lockheed California Corporation, Burbank, California

North American Rockwell Corporation, Downey, California

Garrett Corporation, AiResearch Manufacturing Company, Phoenix, Arizona

General Dynamics Corporation, Convair Division, San Diego, California

Grumman Aircraft Engineering Corporation, Bethpage, Long Island, New York

Hughes Aircraft Company, Culver City, California

Goodyear Aerospace Corporation, Akron, Ohio

Ling-Temco-Vought, Inc., Development Center, West Long Branch, New Jersey

Rohr Corporation, Chula Vista, California

Ryan Aeronautical Company, San Diego, California

TRW, Inc., Cleveland, Ohio

United Aircraft Corporation, Pratt & Whitney Aircraft Division, East Hartford, Connecticut

Martin Marietta Corporation, Baltimore Division, Baltimore, Maryland

Alcoa Research Laboratories, New Kensington, Pennsylvania

Kaiser Aluminum and Chemical Corporation, DMR Trentwood Works, Spokane, Washington

Reynolds Metals Company, Richmond, Virginia

The Dow Chemical Company, Metal Products Department, Midland, Michigan

Republic Steel Corporation, Electrochemical Research Center, Cleveland, Ohio

Armco Steel Corporation, Baltimore Works, Baltimore, Maryland

Titanium Metals Corporation of America, W. Caldwell, New Jersey

Reactive Metals, Niles, Ohio

Bendix Corporation Energy Controls Division, South Bend, Indiana

Southwest Research Institute, San Antonio, Texas

Sciaky Brothers, Inc., Chicago, Illinois

Newark Laboratories, Linde Division, Union Carbide Corporation, Newark, New Jersey

Frankford Arsenal, Philadelphia, Pennsylvania

APPENDIX C

TEST PROGRAM DATA AND STATISTICAL PROCEDURES

APPENDIX C

TEST PROGRAM DATA AND STATISTICAL PROCEDURES

TEST PROGRAM DATA

Summary tables of the test data generated during Phase II of the program are presented in Tables C-1 through C-10.

STATISTICAL PROCEDURES

The following discussion gives the computational expressions with appropriate definitions of terms used throughout the illustrative examples treated in the "Verification Testing Program" section. These procedures are consistent with those presented in AFML-TR-66-386 for the development of design data for Mil-Hdbk-5.

Direct Computation for the Normal Distribution

The minimum property determined through direct analysis of a normally distributed sample is the lower tolerance limit corresponding to the assurance of the selected statistical basis. The lower tolerance limits were calculated using the following expressions:

$$F = \bar{X} - k\,S$$

where:

F = lower tolerance limit

k = statistical factor

(k factors are a function of sample size and statistical assurance level. They were taken from Table 6.4.1 in AFML-TR-66-386.)

$\bar{X}$ and S = sample statistics

The form of $\bar{X}$ and S depend on whether the total sample is normally distributed or whether it has been normalized through regression. For the normally distributed total sample:

$\bar{X}$ = average of test results = $(\Sigma X)/n$

S = standard deviation = $\sqrt{\frac{\Sigma X^2 - \text{[illegible]}}{n - \text{[illegible]}}}$

X = individual observed test result

n = number of observed test results

Σ = summation of all values of the indicated quantity

For a sample that is normally distributed about a regression line, the sample statistics take the following form:

$\bar{X} = a + bY_o$ = regressed value of X for the particular value of the independent variable Y

$S = S_X \sqrt{1 + \frac{1}{n} + \frac{(Y_o - \Sigma Y/n)^2}{\Sigma Y^2 - (\Sigma Y)^2/n}}$ = corrected standard deviation of the dependent variable X about the regression line at Y_o

$a = \frac{\Sigma X - b\Sigma Y}{n}$ = regression constant

$b = \frac{\Sigma(YX) - (\Sigma Y)(\Sigma X)/n}{\Sigma Y^2 - (\Sigma Y)^2/n}$ = regression coefficient

X = individual observed property value (i.e., UTS)

Y = individual value of the characteristic against which the property is regressed (i.e., thickness)

n = total number of observed test values

$S_X = \sqrt{\frac{[\Sigma X^2 - (\Sigma X)^2/n] - b^2[\Sigma Y - (\Sigma Y)^2/n]}{n - 2}}$ = gross standard deviation of X

The procedure described for the regressed case above assumes that lower tolerance limits will be determined only for specific values of Y (i.e., $Y = Y_o$). When it is desired that a single limit cover a range of values for Y, Y_o is selected at the extreme of the range that will result in the lowest value for $\bar{X}$.

Indirect Computation of Property Values

This procedure assumes that the mean ratio of paired observations, representing two related properties, provides an estimate of the ratio of the corresponding population means. This requires that an unknown property be ratioed to an established or known property and that these properties are related in some manner. The basis for properties derived in this manner is assumed to be the same as the basis for the known property.

The individual values used in these computations are the ratios obtained from two paired observations. The ratio is obtained by dividing the observed value for the unknown property by the observed value for the known property. Sample statistics are computed from these observed ratios, from which confidence limits are determined, to provide a reduced ratio which, when applied to the known property limit, gives the required limit for the unknown property.

Computations for the reduced ratio were accomplished using the following relationships:

$$R_{.95} = \bar{R} - t_{.95}\, c\, S$$

where:

$R_{.95}$ = reduced ratio at 95% confidence level

n = number of observed ratios

$c = 1/\sqrt{n}$ = correction factor

$t_{.95}$ = statistical factor

$\bar{R}$ and S = sample statistics

The appropriate values for the statistical factor $t_{.95}$ were taken from Table 6.4.5 of AFML-TR-66-386.

The sample statistics $\bar{R}$ and S take different forms depending on whether or not a regression analysis is involved. For the direct calculation of a reduced ratio:

$\bar{R} = (\Sigma R)/n$ = average observed ratio

$S = \sqrt{\dfrac{\Sigma R^2 - (\Sigma R)^2/n}{n - 1}}$ = standard deviation of the ratios

R = individual observed ratio

n = number of observed ratios

When the reduced ratio determination was made for a sample that had been regressed against some dimensional characteristic, the computations for $\bar{R}$ and S used the following expressions:

$\bar{R} = a + bY_o$ = regressed ratio for the particular value of the dimensional characteristic Y_o.

$S = \sqrt{\dfrac{[\Sigma R^2 - (\Sigma R)^2/n] - b^2\, [\Sigma Y^2 - (\Sigma Y)^2/n]}{n - 2}}$ = gross standard deviation of R

$c = \sqrt{\dfrac{1}{n} + \dfrac{(Y_o - \Sigma Y/n)^2}{\Sigma Y^2 - (\Sigma Y)^2/n}}$ = correction factor

$a = \dfrac{\Sigma R - b\, \Sigma Y}{n}$ = regression constant

$b = \dfrac{\Sigma(YR) - (\Sigma Y)(\Sigma R)/n}{\Sigma Y^2 - (\Sigma Y)^2/n}$ = regression coefficient

R = individual observed value of the ratio

Y = individual value of the dimensional characteristic

n = total number of observed ratios

The required minimum value for the unknown property is determined by application of the reduced ratio to the minimum value for the known property:

$$F_{derived} = R_{.95} F_{known}$$

Tests for Significant Differences

Tests for significance were employed to evaluate the influence of several parameters represented in the weldment samples. Two statistical tests were used: the F test to determine if sample variances differ significantly; and the t test to evaluate whether two sample means differ significantly. These tests were performed at a confidence level of 0.95 to be consistent with Mil-Hdbk-5.

The F test compares the variance of two samples, A and B, such that:

$$F = S_A^2/S_B^2$$

where:

S_A = standard deviation of Sample A

S_B = standard deviation of Sample B

If this calculated value for F meets the following criterion, one can conclude that the two samples do not differ with regard to their variability.

$$F_{.975} > F > \frac{1}{F_{.975}}$$

where:

$F_{.975}$ = statistical factor from Table 6.4.4 of AFML-TR-66-386.

The t test compares the mean values for two samples, A and B. It can be concluded that the two sample means do not differ significantly if the following criterion is met:

$$u > D_{\bar{X}}$$

where:

$$D_{\bar{X}} = |\bar{X}_A - \bar{X}_B|$$

$$u = t_{.975}\ Sp\sqrt{\frac{nA + nB}{nA\ nB}}$$

$$Sp = \sqrt{\frac{(nA - 1)\ S_A^2 + (nB - 1)\ S_B^2}{nA + nB - 2}}$$

$t_{.975}$ = statistical factor from Table 6.4.5 of AFML-TR-66-386

$\bar{X}$, S, and n are sample statistics for Samples A and B as defined previously.

Tests for Normality

The procedure used to establish design strength values by statistical techniques usually is based on the assumption that the data distribution is normal. The chi-squared test is used to evaluate whether the assumption of a normal distribution should be rejected. This test compares the frequencies of the normal curve and that of the data sample within several intervals of the measured property:

$$\chi^2 = \sum_{1}^{m} \frac{(f_o - f_e)^2}{f_e}$$

where:

m = number of intervals

f_o = observed number of measurements falling within the interval

f_e = expected number of measurements falling within the interval based on an assumed normal distribution

If chi-squared (χ^2) is larger than the value of $\chi^2_{.95}$ determined from standard statistical tables, it may be concluded that the population distribution is not normal. Values for $\chi^2_{.95}$ were taken from Table 6.4.3 of AFML-TR-66-386.

Table C-1: TENSILE COUPON RESULTS, 0.09-INCH 6061-T6 ALUMINUM AS-WELDED WITH CONVENTIONAL TOOLING

Coupon * No.	F_{tu}	F_{ty}	% El.		Failure Location	Coupon * No.	F_{tu}	F_{ty}	% El.		Failure Location
			.5"	2"					.5"	2"	
1-1-1	35.3	28.9	-	4	W	1-2-1	NOT AVAILABLE				
-2	35.2	29.3	14	3	W	-2	34.6	28.3	10	2.4	W
-3	33.4	28.1	-	3	W	-3	34.8	28.6	14	3.5	W
2-1-1	33.5	25.7	9	4.5	HAZ	2-2-1	33.3	24.4	8	5	HAZ
-2	34.5	25.1	18	6	HAZ	-2	31.7	23.9	-	5	HAZ
-3	33.7	25.4	14	5.5	HAZ	-3	31.8	23.8	16	4.5	HAZ
3-1-1	32.2	24.3	12	5	HAZ	3-2-1	34.1	26.1	15	4	HAZ
-2	32.7	24.9	-	4.5	HAZ	-2	32.3	24.7	10	4.5	HAZ
-3	30.2	24.6	8	2	W	-3	31.6	27.4	7	1.5	FL
4-1-1	35.7	27.4	12	3	W	4-2-1	35.0	28.6	12	3	FL
-2	33.7	26.3	12	3	W	-2	34.5	27.8	16	3.5	W
-3	36.2	25.9	16	4	W	-3	35.2	28.7	-	3.5	FL
5-1-1	34.2	26.4	10	5	HAZ	5-2-1	33.0	26.0	13	4	HAZ
-2	33.7	26.9	15	4	HAZ	-2	33.6	25.7	15	5	HAZ
-3	31.0	24.0	15	4	HAZ	-3	34.9	26.9	18	5	HAZ
6-1-1	34.6	27.9	12	3	FL	6-2-1	34.5	27.2	14	4.5	W
-2	33.5	24.7	16	5	HAZ	-2	32.2	25.3	-	5	HAZ
-3	33.8	27.8	12	3	FL	-3	34.5	27.2	12	5	FL
7-1-1	35.9	29.3	8	2	FL	7-2-1	35.1	27.8	14	4	FL
-2	33.8	26.6	-	5	HAZ	-2	34.7	26.3	15	4	HAZ
-3	35.8	30.4	6	2	FL	-3	35.4	28.4	-	3	FL
8-1-1	35.1	26.0	16	6	HAZ	8-2-1	35.9	26.7	20	5	HAZ
-2	34.6	26.4	10	5.5	HAZ	-2	34.8	26.6	10	5	HAZ
-3	36.5	26.8	12	6	HAZ	-3	34.9	27.5	18	5	HAZ
9-1-1	35.4	29.9	10	5	W	9-2-1	34.3	27.0	12	3	FL
-2	36.2	29.7	12	4	W	-2	37.6	30.2	14	4	W
-3	36.6	30.1	8	2	FL	-3	35.6	30.2	10	2	W
10-1-1	35.6	28.9	10	3.5	W	10-2-1	34.8	28.6	14	4	W
-2	35.9	29.0	12	4.5	HAZ	-2	36.1	29.0	13	4	W
-3	35.6	28.9	18	5	HAZ	-3	35.4	28.3	-	4	HAZ

Panel Number

* 1 thru 10 - 1 or 2 - 1, 2 or 3

Coupon Number

Welder Identification Number

Table C-II: TENSILE COUPON RESULTS, 0.09-INCH 6061-T6 ALUMINUM AS-WELDED WITH INSULATED TOOLING

Coupon * No.	F_{tu}	F_{ty}	% El.		Failure Location	Coupon * No.	F_{tu}	F_{ty}	% El.		Failure Location
			.5"	2"					.5"	2"	
1-1-1	34.2	26.4	12	5	HAZ	1-2-1	36.6	27.2	18	5	HAZ
-2	33.8	26.3	16	4.5	HAZ	-2	35.2	27.7	15	5	HAZ
-3	34.2	26.3	-	5	HAZ	-3	34.5	27.1	18	5	HAZ
2-1-1	34.5	24.0	-	5	HAZ	2-2-1	32.2	24.7	12	4.5	HAZ
-2	31.9	23.8	12	5	HAZ	-2	31.6	24.1	15	4.5	HAZ
-3	31.2	24.0	14	5	HAZ	-3	32.2	24.3	16	4.5	HAZ
3-1-1	30.0	22.0	14	6	HAZ	3-2-1	29.8	21.6	16	6	HAZ
-2	31.2	23.2	14	5	HAZ	-2	32.0	23.6	12	6	HAZ
-3	31.9	24.2	12	5	HAZ	-3	32.5	23.8	14	6	HAZ
4-1-1	31.8	24.8	12	5	HAZ	4-2-1	34.5	25.6	19	6	HAZ
-2	33.5	25.8	10	3	FL	-2	32.9	25.0	12	4	FL
-3	33.0	25.8	16	4	HAZ	-3	32.6	25.2	-	4	HAZ
5-1-1	32.4	24.8	15	4	HAZ	5-2-1	31.2	24.0	14	5	HAZ
-2	33.2	25.2	14	4	HAZ	-2	33.5	24.1	-	6	HAZ
-3	30.6	23.6	13	4	HAZ	-3	32.7	26.2	16	4.5	HAZ
6-1-1	32.3	24.7	-	-	HAZ	6-2-1	32.8	25.2	-	4.5	HAZ
-2	32.3	25.2	16	5	HAZ	-2	32.5	25.3	16	5.0	HAZ
-3	32.7	25.3	14	5	HAZ	-3	32.8	25.4	13	4.5	HAZ
7-1-1	33.0	25.1	14	5	HAZ	7-2-1	33.1	25.9	-	5	HAZ
-2	33.4	25.2	10	5	HAZ	-2	32.9	25.8	14	5	HAZ
-3	34.3	25.5	-	5	HAZ	-3	33.2	25.9	16	4.5	HAZ
8-1-1	31.7	24.3	15	4.5	HAZ	8-2-1	31.1	23.1	-	5.5	HAZ
-2	31.1	24.4	14	4	HAZ	-2	31.2	24.3	15	5	HAZ
-3	30.9	23.6	14	5	HAZ	-3	31.0	23.8	14	4.5	HAZ
9-1-1	33.6	26.1	15	5	HAZ	9-2-1	33.5	26.1	16	5	HAZ
-2	33.4	26.5	18	5	HAZ	-2	33.8	25.9	18	5	HAZ
-3	33.9	26.3	14	5	HAZ	-3	33.7	25.7	14	5	HAZ
10-1-1	32.6	24.6	12	5	HAZ	10-2-1	31.9	24.6	16	5	HAZ
-2	31.8	25.1	12	4.5	HAZ	-2	32.0	23.9	-	5	HAZ
-3	31.3	24.5	14	4.5	HAZ	-3	30.9	24.1	12	4	HAZ

Panel Number

* 1 thru 10 - 1 or 2 1, 2 or 3

Welder Identification Number

Coupon Number

Table C-III: TENSILE COUPON RESULTS, 0.09-INCH 6061 ALUMINUM HEAT TREATED TO T 62 CONDITION AFTER WELDING

Coupon * No.	F_{tu}	F_{ty}	% El.		Failure Location	Coupon *No.	F_{tu}	F_{ty}	% El.		Failure Location
			.5"	2"					.5"	2"	
A-1-1-1	47.0	44.9	18	8	HAZ	A-1-2-1	48.3	46.5	20	7	HAZ
-2	46.6	44.9	22	8	HAZ	-2	47.8	45.8	22	8	HAZ
-3	47.5	45.6	18	9	HAZ	-3	48.3	45.8	22	7.5	HAZ
A-2-1-1	45.1	42.6	18	7	HAZ	A-2-2-1	47.8	45.5	22	8	HAZ
-2	42.7	41.3	16	4	HAZ	-2	47.7	45.5	20	8	HAZ
-3	46.0	44.1	18	7	HAZ	-3	47.1	44.9	18	7	HAZ
A-3-1-1	47.4	45.5	20	6	HAZ	A-3-2-1	47.4	45.5	20	7.5	HAZ
-2	48.3	46.2	14	6	HAZ	-2	47.4	45.4	23	8	HAZ
-3	48.8	46.4	10	6	FL	-3	47.5	46.0	6	3.5	W
A-4-1-1	47.1	45.2	-	5	HAZ	A-4-2-1	47.0	45.0	22	9	HAZ
-2	46.9	45.0	18	6	HAZ	-2	47.8	45.4	22	9	HAZ
-3	45.1	44.4	-	5.5	HAZ	-3	48.0	45.8	22	8.5	HAZ
A-5-1-1	46.3	44.6	20	8	HAZ	A-5-2-1	51.4	49.5	18	7	HAZ
-2	46.7	43.1	20	7	HAZ	-2	48.2	46.6	18	7	HAZ
-3	43.4	42.6	16	7.5	HAZ	-3	47.5	45.7	17	6.5	HAZ
B-1-1-1	47.7	45.9	18	7	HAZ	B-2-1-1	46.6	44.9	20	7	HAZ
-2	44.5	43.5	18	6	HAZ	-2	51.0	48.8	16	5.5	HAZ
-3	47.0	45.4	18	4	HAZ	-3	47.7	45.6	22	10	HAZ
B-3-1-1	46.7	45.1	21	6	HAZ	B-4-1-1	47.9	46.1	10	4	FL
-2	48.5	46.5	20	8	HAZ	-2	48.1	46.1	18	6	HAZ
-3	47.3	45.2	-	8	HAZ	-3	45.0	43.4	12	3	FL
B-5-1-1	47.5	45.7	20	7	HAZ						
-2	46.0	45.9	20	6	HAZ						
-3	45.2	44.3	18	4	HAZ						

Welder Identification Number

Panel Number

* A or B - 1 thru 5 - 1 or 2 - 1, 2 or 3

Tooling Type

Coupon Number

A = Conventional

B = Insulated

Table C-IV: TENSILE COUPON RESULTS, AS-WELDED 6061-T6 ALUMINUM, VARIOUS JOINT THICKNESSES

Coupon *No.	F_{tu}	F_{ty}	% El.		Failure Location	Coupon * No.	F_{tu}	F_{ty}	% El.		Failure Location
			.5"	2"					.5"	2"	
6-1-1	35.5	28.5	16	4	W	2-1-1	31.7	25.3	10	2	W
-2	35.9	28.8	8	3	W	-2	35.2	25.3	-	5.5	W
-3	35.0	27.9	12	4	FL	-3	26.7	25.2	8	2	W
6-2-1	32.2	25.3	12	4	HAZ	2-2-1	31.6	23.4	22	8	HAZ
-2	31.3	24.0	10	4	HAZ	-2	31.2	22.1	-	8	HAZ
-3	30.8	22.9	16	5	HAZ	-3	30.9	22.2	26	8	HAZ
6-3-1	32.1	25.7	-	4	HAZ	2-3-1	33.5	22.9	20	8	HAZ
-2	30.9	23.3	13	4	HAZ	-2	33.2	23.3	12	4.5	W
-3	35.3	27.7	18	5	HAZ	-3	24.6	24.0	8	1	W
1-1-1	39.1	28.6	14	3.5	W	3-1-1	31.4	22.6	24	9	HAZ
-2	38.6	28.3	3	3	W	-2	31.5	21.7	24	10	HAZ
-3	39.2	28.3	14	3.5	FL	-3	29.2	22.7	16	5.5	W
1-2-1	30.7	22.6	12	6	HAZ	3-2-1	32.0	21.3	-	10	HAZ
-2	31.6	23.2	14	6	HAZ	-2	31.6	26.3	22	10	HAZ
-3	31.9	23.7	16	6	HAZ	-3	31.2	22.4	28	10	HAZ
1-3-1	30.6	22.4	16	6	HAZ	3-3-1	33.1	22.5	32	10	HAZ
-2	30.8	22.7	18	6	HAZ	-2	33.4	22.8	28	9.5	HAZ
-3	27.4	24.0	-	2.5	W	-3	31.8	22.1	16	6	W

Welder Identification

* 6, 1, 2 or 3 - 1, 2 or 3 - 1, 2 or 3

Joint Thickness

Coupon Number

6 = 0.06 Inch

1 = 0.125 Inch

2 = 0.25 Inch

3 = 0.38 Inch

Table C-V: TENSILE RESULTS, 0.09-INCH 6061-T6 ALUMINUM AS-WELDED WITH WELD REINFORCEMENTS ON

Coupon *No.	F_{tu}	F_{ty}	% El. 2"	Failure Location
1-1-1	37.7	33.6	3	HAZ
-2	32.7	27.3	3	HAZ
2-1-1	37.6	33.3	4	HAZ
-2	31.6	25.4	4	HAZ
3-1-1	32.8	26.9	4	HAZ
-2	32.9	28.2	3	HAZ
4-1-1	35.8	25.1	3	FL
-2	36.0	24.9	3	HAZ
5-1-1	35.9	24.7	4	HAZ
-2	33.9	23.5	4	HAZ

* 1 thru 5 - 1 - 1, 2 or 3

Welder Identification Number

Original Panel Number

Coupon Number

Table C-VI: TENSILE RESULTS, 0.09-INCH 6061 ALUMINUM REPAIR WELDS

Coupon ▷1 No.	F_{tu}	F_{ty}	% El.		Failure Location	Coupon ▷2 No.	F_{tu}	F_{ty}	% El.		Failure Location
			.5"	2"					.5"	2"	
1-5-3	27.8	21.1	18	5	HAZ	M-1-1-3-1	35.1	23.1	18	5	W
1-4-3	26.7	20.1	10	3	W	-2	34.0	23.0	20	7	W
1-2-3	27.8	20.1	16	4	HAZ	-3	33.7	23.3	16	5	W
2-1-3	29.6	22.1	18	5	HAZ	M-2-2-3-1	31.2	21.4	14	4.5	HAZ
2-6-1	30.2	21.6	18	6	HAZ	-2	31.3	21.9	14	5	HAZ
2-7-1	NOT AVAILABLE					-3	30.9	22.0	12	5	HAZ
3-6-2	26.9	22.6	8	3	W	M-3-5-3-1	30.3	19.9	16	6	HAZ
3-7-2	28.3	20.6	16	5	HAZ	-2	31.3	20.8	16	6	HAZ
3-8-1	30.8	21.2	16	6	HAZ	-3	31.7	21.6	16	6	HAZ
4-8-2	31.3	22.7	16	5	HAZ	M-4-4-3-1	33.3	24.8	12	3.5	HAZ
4-9-1	34.5	23.8	14	5	W	-2	33.7	23.9	18	5	HAZ
4-10-1	32.9	24.4	14	4	W	-3	30.3	22.6	16	4	HAZ
5-10-2	34.5	24.4	14	5	W	M-5-9-3-1	34.3	23.2	12	4.5	HAZ
5-9-2	33.4	24.9	12	5	W	-2	33.0	22.9	20	6	HAZ
5-9-3	33.8	25.6	16	6	HAZ	-3	32.8	22.3	18	5	HAZ

Original Panel Welder Identification

▷1 1 thru 5 - 1 thru 10 - 1, 2 or 3

Manual Repair Welder

Panel Number

Repair Welder Identification

Original Panel Number

▷2 M - 1 thru 5 - 1, 2, 4, 5 or 9 - 3 - 1, 2, or 3

Coupon Number

Mechanized Repair

Original Panel Welder Identification

Table C-VII: TENSION TUBE TEST RESULTS, 0.09-INCH 6061 ALUMINUM

Specimen Code [1]	Failure Load Kips	Failure Stress Ksi [2]	Failure Location
1-1	27.95	27.0	W
1-2	30.45	29.4	HAZ
2-1	29.5	28.5	HAZ
2-2	30.5	29.5	HAZ
3-1	25.3	24.9	W
3-2	27.1	26.2	W
4-1	30.15	29.1	HAZ
7-1	31.1	30.0	HAZ
7-2	31.1	30.0	HAZ
7-3	29.95	28.9	HAZ
R-1-3	25.5	24.6	W
R-3-4	26.4	25.5	HAZ
R-4-3	28.3	27.3	HAZ
R-9-7	26.9	26.0	W
R-11-7	26.5	25.6	W
W-1	31.25	30.2	HAZ
W-4	27.95	27.0	HAZ
W-4A	29.3	28.3	HAZ
W-7	29.5	28.5	HAZ
W-7A	30.05	29.0	HAZ

[1] As-Welded Tubes 1 to 7 - 1 or 2
Welder Identification
Tube Number

Repaired Tubes R - 1 to 11 - 3 to 7 Original Tube Welder Identification
Manually Repaired
Repair Welder Identification

Weld Reinforcements On W - 1 to 7 Tube Welder Identification
Indicates Weld Reinforcements On

[2] Failure Stresses as Calculated from Failure Load and Nominal Tube Cross Sectional Area

Table C-VIII: BURST TEST RESULTS, 0.09-INCH 6061-T6 ALUMINUM PRESSURE VESSELS

Specimen Code [1]	Burst Pressure Psi	Failure Location	Failure Stress Ksi [2]	Comments
1-1	760	HAZ	34.5	0.03" mismatch
1-2	750	FL	33.9	
2-1	645	FL	29.1	0.01" to 0.02" mismatch
2-2	675	FL	30.4	
3-1	725	FL	32.8	
3-2	695	W	31.4	
4-1	700	FL	31.5	0.03" mismatch
4-2	760	HAZ	34.2	
R-9-3	540	W	24.4	
R-3-2	600	FL	27.1	
R-1-4	680	FL	30.8	
M-1	750	FL	33.8	0.03" mismatch
M-2	445	W	20.0	0.08" mismatch
M-3	720	FL	32.6	0.03" mismatch

Welder Identification Number

[1] As-Welded 1,2,3 or 4 - 1 or 2

Pressure Vessel

Original Welder Identification

Repaired R - 9, 3 or 1 - 2, 3 or 4

Manual Repair

Repair Welder Identification

Mismatched

M - 1, 2 or 3

Mismatch

Welder Identification

[2] As Calculated From: Failure Stress = Burst Pressure X Radius / Thickness

$$\text{Failure Stress} = \frac{\text{Burst Pressure X Radius}}{\text{Thickness}}$$

Table C-IX: TENSILE COUPON RESULTS, UNREPAIRED Ti- 6Al-4V

Coupon *No.	F_{tu}	F_{ty}	% El.		Failure Location	Coupon *No.	F_{tu}	F_{ty}	% El.		Failure Location
			.5"	2"					.5"	2"	
1-1-1	140.3	133.1	10	8.5	W	1-2-1	137.3	132.7	22	8.5	HAZ
-2	141.0	136.5	13	6	W	-2	140.7	136.4	16	8.5	HAZ
-3	140.2	136.3	12	6	W	-3	140.5	135.0	20	11	HAZ
2-1-1	137.5	134.3	12	3	W	2-2-1	134.4	130.9	16	4	W
-2	139.0	136.0	10	2.5	W	-2	136.3	131.6	18	3	W
-3	134.5	132.9	12	3.5	W	-3	133.1	130.9	10	4.5	W
3-1-1	143.0	140.4	-	2	W	3-2-1	139.5	136.0	12	4	W
-2	137.7	134.8	6	4	W	-2	136.5	133.1	20	7	HAZ
-3	139.2	136.9	8	3	W	-3	140.5	138.5	8	2	W
3-1-1	138.4	135.2	10	3	W						
-2	139.7	137.4	8	2	W						
-3	139.8	135.8	10	6	W						
4-1-1	138.4	133.8	26	8	HAZ	4-2-1	136.3	132.4	22	11	HAZ
-2	134.5	131.0	30	9	HAZ	-2	139.1	133.4	-	11.5	HAZ
-3	135.6	129.7	28	10	HAZ	-3	144.4	139.4	13	5.5	W
5-1-1	138.3	129.7	12	4.5	W	5-2-1	138.4	137.5	12	4	W
-2	NOT AVAILABLE					-2	136.2	134.1	9	3	W
-3	136.2	131.7	8	6	W	-3	135.2	132.6	12	6	W
6-1-1	142.7	137.9	-	6	HAZ	6-2-1	141.9	137.0	21	9	HAZ
-2	142.8	137.8	26	9	HAZ	-2	141.4	137.1	-	5.5	W
-3	143.1	139.5	24	9	HAZ	-3	143.4	139.2	6	5	W
7-1-1	138.7	134.6	-	6.5	W	7-3-1	137.9	134.6	25	9	HAZ
-2	138.7	134.9	7	6	HAZ	-2	142.8	140.9	6.5	4	W
-3	143.0	139.9	8	6	W	-3	143.2	141.1	20	9	HAZ
8-1-1	132.6	129.9	5.5	2	W	8-2-1	1[illegible].3	130.0	8	4	W
-2	133.0	131.0	12	4	W	-2	132.8	130.4	8	2.5	W
-3	134.8	132.0	9	2.5	W	-3	133.9	132.6	10	2.5	W
9-1-1	141.9	138.5	-	8.5	HAZ	9-2-1	139.4	129.7	26	9	HAZ
-2	141.2	138.2	26	11.5	HAZ	-2	144.6	140.1	8	7	W
-3	142.5	138.7	10	6	W	-3	141.6	136.5	22	8	HAZ
10-1-1	140.2	137.1	8	3.5	W	10-2-1	138.9	137.8	8	3.5	W
-2	139.7	135.9	-	3	W	-2	138.5	135.1	8	5	W
-3	143.2	137.9	10	3.5	W	-3	139.4	138.2	6	2	W

Panel Number

* 1 thru 10 - 1, 2 or 3 - 1, 2 or 3

Welder Identification Number

Coupon Number

Table C-X: TENSILE COUPON RESULTS, Ti- 6Al-4V, MANUALLY REPAIRED

Coupon *No.	F_{tu}	F_{ty}	% El.		Failure Location	Coupon *No.	F_{tu}	F_{ty}	% El.		Failure Location
			.5"	2"					.5"	2"	
1-3-1	110.4	106.1	10	2	W	4-5-2	106.1	103.6	-	2	W
1-4-1	101.0	98.5	18	3	W	4-6-1	106.2	104.0	12	3	W
1-8-1	102.2	98.9	14	3.5	W	4-7-1	107.1	103.2	3	2	W
3-1-3	110.9	109.2	8	2	W	5-1-3	104.5	99.7	-	2	W
3-4-2	106.6	104.5	12	3	W	5-7-2	102.8	99.3	12	2.5	W
3-5-1	110.4	108.8	10	2.5	W	5-8-2	101.4	98.6	12	2.5	W
9-2-2	100.9	98.6	8	2	W	12-2-1	101.9	98.5	8	2.5	W
9-6-2	116.1	112.4	-	3	W	12-2-3	99.6	95.3	12	2.5	W
9-10-1	95.9	90.7	12	3	W	12-3-2	107.9	105.7	12	3	W
11-1-2	103.2	99.3	10	2.5	W	13-1-1	108.9	105.3	10	2.5	W
11-3A-3	100.0	100.0	-	2.5	W	13-2-3	105.1	100.7	15	3.5	W
11-3-3	101.8	99.3	10	2.5	W	13-9-1	112.9	112.2	10	2.5	W

Original Welder Identification

Panel Number

* 1, 3, 4, 5, 9, 11, 12, 13 - 1 thru 10 - 1, 2 or 3

Repair Welder Identification Number

Original Welded Panel Identification

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11. SUPPLEMENTARY NOTES

12. SPONSORING MILITARY ACTIVITY
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13. ABSTRACT

Present industry methods of obtaining engineering data on weldments were reviewed by literature and industrial surveys. Serious lack of uniformity was found within the aerospace industry in the development and utilization of engineering design data. Difficulties in defining weldment characterization, due primarily to the absence of adequate government or industry-wide welding process specifications, were the major factors limiting industry-wide generation and use of weldment design data. It was concluded from the literature and industrial surveys that properly characterized coupon-derived weldment design data was the most meaningful approach in establishing and presenting data that would have industry-wide usefulness. Guidelines for the generation and presentation of weldment design data were developed. These guidelines were used in a model test program in which design data on 6061 aluminum and Ti-6Al-4V titanium alloy weldments were obtained. Significant welding variables and conditions were identified. The correlation between coupon data and structure was demonstrated by testing welded tubes and pressure vessels. The test program effectively demonstrated the validity of the guidelines. Based on the surveys and the weldment data obtained in this program, recommendations are made to include the guidelines in Mil-Hdbk-5 *Guidelines for Presentation of Data,* AFML-TR-66-386, February, 1967.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Welding						
Weldments						
Design Properties						
Design Data						
Generation of Data						
Utilization of Data						
Weldment Characterization						
6061 Aluminum Alloy						
Ti-6Al-4V Alloy						
Welding Variables						
Simulated Structure						

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