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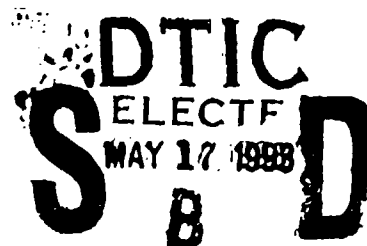
**USE OF TITANIUM CASTINGS WITHOUT A CASTING FACTOR**

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September 1992

Final Report for Sept 26 89 - Sept 30 92

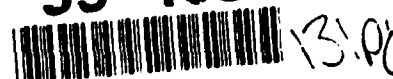
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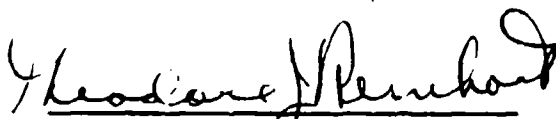
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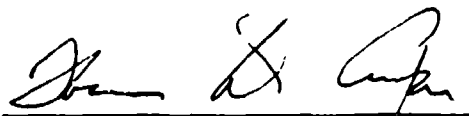


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| 13. ABSTRACT (Maximum 200 words)<br>The "Use of Titanium Castings Without a Casting Factor" program was conducted to establish "A" and "B" allowables for Ti-6Al-4V. Taguchi methods were used to develop a more restrictive chemistry and annealing condition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

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

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

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

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## SECTION 1

### INTRODUCTION AND SUMMARY

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

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

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

## 1.1 BACKGROUND

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

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

Figure 1 demonstrates this point. This figure shows the mechanical property distribution by supplier for an investment cast Ti-6Al-4V elevator housing supplied to the Boeing Corporation (Reference 8). Data from each supplier can be represented by its own population distribution. The implication is that foundry practices significantly affect the variability of mechanical properties in castings. However, the differences in properties in no way compromise the quality of the parts since mechanical properties

of the parts met the minimum values specified in the Boeing specification (BMS 7-181). Attempts to determine "A" and "B" basis design allowables from data with such a large variation in properties would result in conservative values.

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

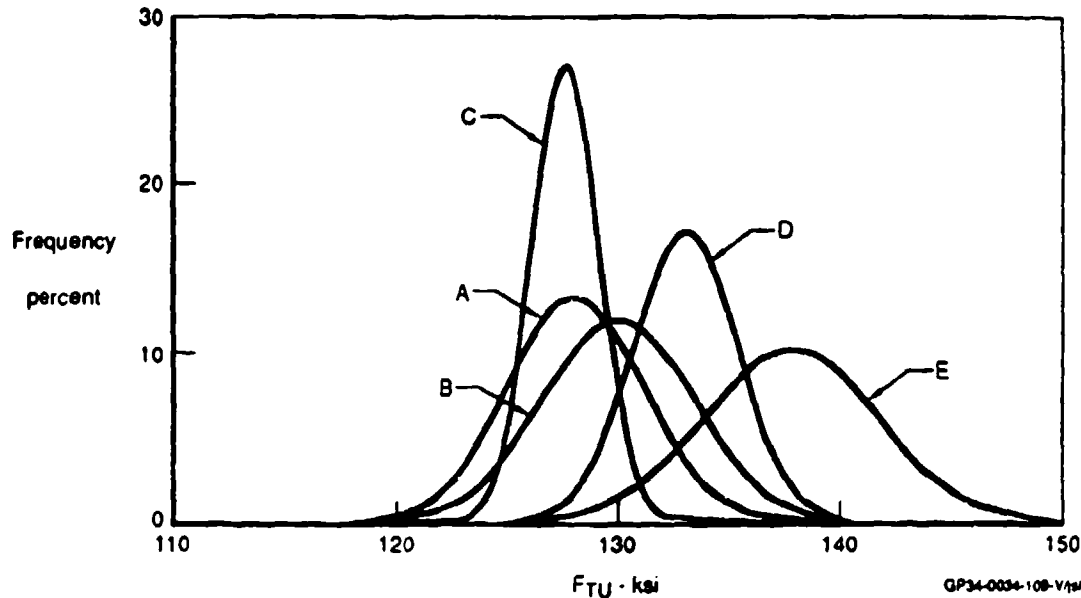


FIGURE 1. VARIATION IN MECHANICAL PROPERTIES OF TI-6AL-4V CASTINGS FROM DIFFERENT SUPPLIERS

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

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

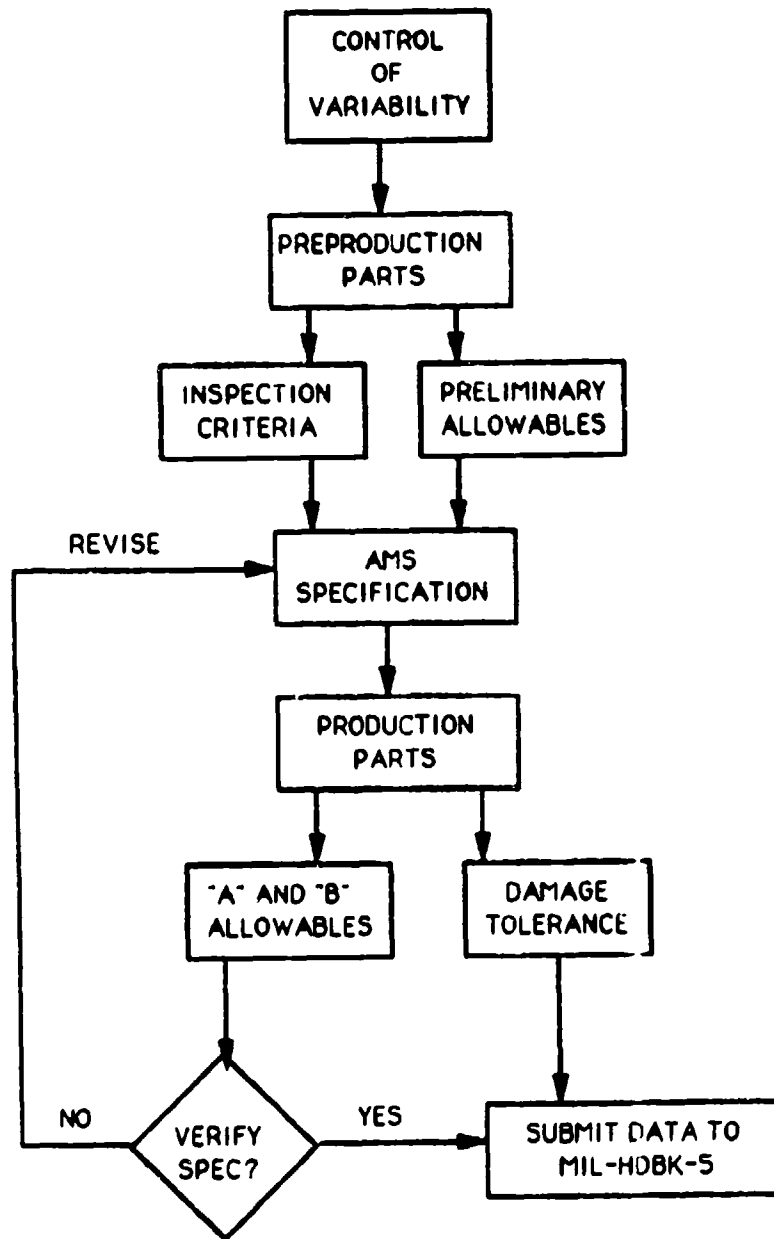


FIGURE 2. PROGRAM FLOW

## 1.2 PROGRAM PHASES

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

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

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

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

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

## SECTION 2

### CONTROL OF VARIABILITY

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

#### 2.1 COMPOSITIONAL VARIABILITY

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

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

As stated in Section 1, the intent of the program was to establish parameters to produce the most consistent properties and not necessarily the highest average properties. An example of this is shown below. Differences in chemical composition that were still within the limits of the current public specifications can produce variations in population

distributions (Figure 3). If we target a tighter chemical composition, we obtain the population labelled "minimum variance." The average strength of the parts is approximately 134 ksi. On the other hand, if our target were to be a chemistry that would produce maximum average strength, the resultant mechanical properties would show a much larger spread in values. The "A"- and "B"-basis allowables (Table 1) for each of these groups verify the influence that population distribution has upon allowable values.

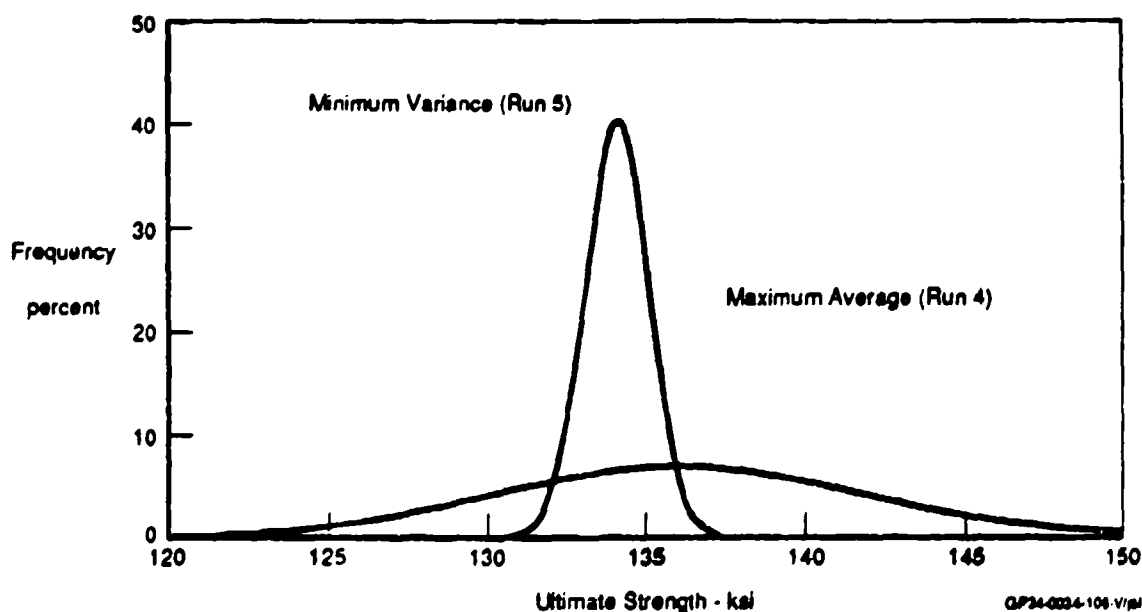


FIGURE 3. DIFFERENT CHEMISTRIES PRODUCE DIFFERENT STRENGTH LEVELS AND DISTRIBUTION OF POPULATION

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

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

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

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

| ELEMENTS         | MIL-T-81918 | MMSC PROGRAM                        | PM                                  | SUPPLIER 1                          | SUPPLIER 2                          | SUPPLIER 3                          | SUPPLIER 4                          |
|------------------|-------------|-------------------------------------|-------------------------------------|-------------------------------------|-------------------------------------|-------------------------------------|-------------------------------------|
| TI               | BALANCE     | BALANCE                             | BALANCE                             | BALANCE                             | BALANCE                             | BALANCE                             | BALANCE                             |
| Al               | 6.5 - 8.75  | 6.0 - 6.3                           | 6.0 - 6.5 or<br>5.9 - 6.4           | 6.0 - 6.4                           | 5.75 - 6.5                          | 5.8 - 6.3                           | 5.8 - 6.3                           |
| V                | 3.5 - 4.5   | 3.6 - 4.4                           | 3.6 - 4.3                           | 3.6 - 4.4                           | 3.5 - 4.5                           | 3.6 - 4.3                           | 3.6 - 4.4                           |
| Fe               | 0.30 MAX    | 0.11 - 0.21                         | 0.11 - 0.21                         | 0.10 - 0.21                         | 0.25 MAX                            | 0.25 MAX                            | 0.11 - 0.21                         |
| C                | 0.08 MAX    | 0.02 - 0.03                         | 0.03 MAX                            | 0.01 - 0.03                         | 0.07 MAX                            | 0.04 MAX                            | 0.015 - 0.035                       |
| H                | 0.015 MAX   | 0.0013 MAX                          | 0.01 MAX                            | 0.0035 MAX                          | 0.01 MAX                            | 0.01 MAX                            | 0.003 MAX                           |
| O                | 0.20 MAX    | 0.13 - 0.16                         | 0.12 - 0.16 or<br>0.13 - 0.17       | 0.13 - 0.16                         | 0.13 - 0.17                         | 0.17 - 0.20                         | 0.18 - 0.20                         |
| N                | 0.05 MAX    | 0.005 - 0.017                       | 0.017 MAX                           | 0.005 - 0.017                       | 0.01 - 0.03                         | 0.005 - 0.015                       | 0.005 - 0.017                       |
| Y                | -           | 0.005                               | 0.005 MAX                           | 0.005 MAX                           | 0.005 MAX                           | -                                   | 0.005                               |
| OTHER IMPURITIES | 0.40 MAX    | 0.40 MAX (NO ONE ELEMENT OVER 0.10) | 0.40 MAX (NO ONE ELEMENT OVER 0.10) | 0.40 MAX (NO ONE ELEMENT OVER 0.10) | 0.40 MAX (NO ONE ELEMENT OVER 0.10) | 0.40 MAX (NO ONE ELEMENT OVER 0.10) | 0.40 MAX (NO ONE ELEMENT OVER 0.10) |

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

TABLE 3. CONTRIBUTION OF ALLOYING ELEMENTS TO MECHANICAL PROPERTY VARIABILITY

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

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

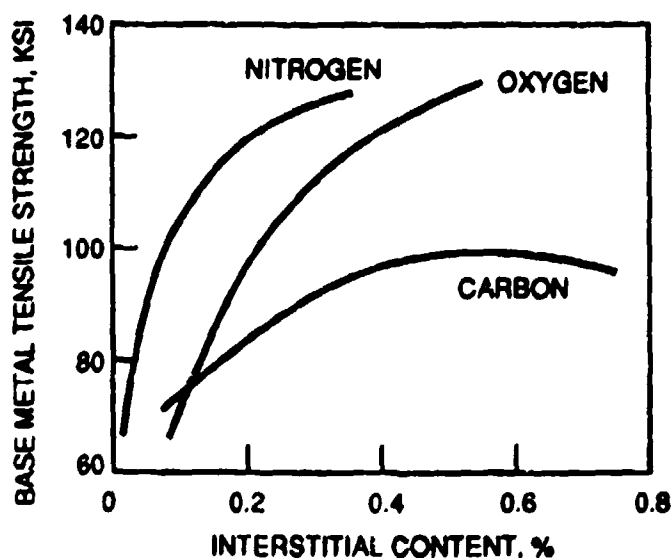


FIGURE 4. EFFECTS OF INTERSTITIAL ALLOYING ELEMENTS ON UNALLOYED TITANIUM (REFERENCE 9)

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

**TABLE 4. PROGRAM CHEMISTRY**

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

## **2.2 POST-CASTING TREATMENT**

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

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

alpha is undesirable because it has been found to cause premature fatigue crack initiation (Reference 14).

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

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

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

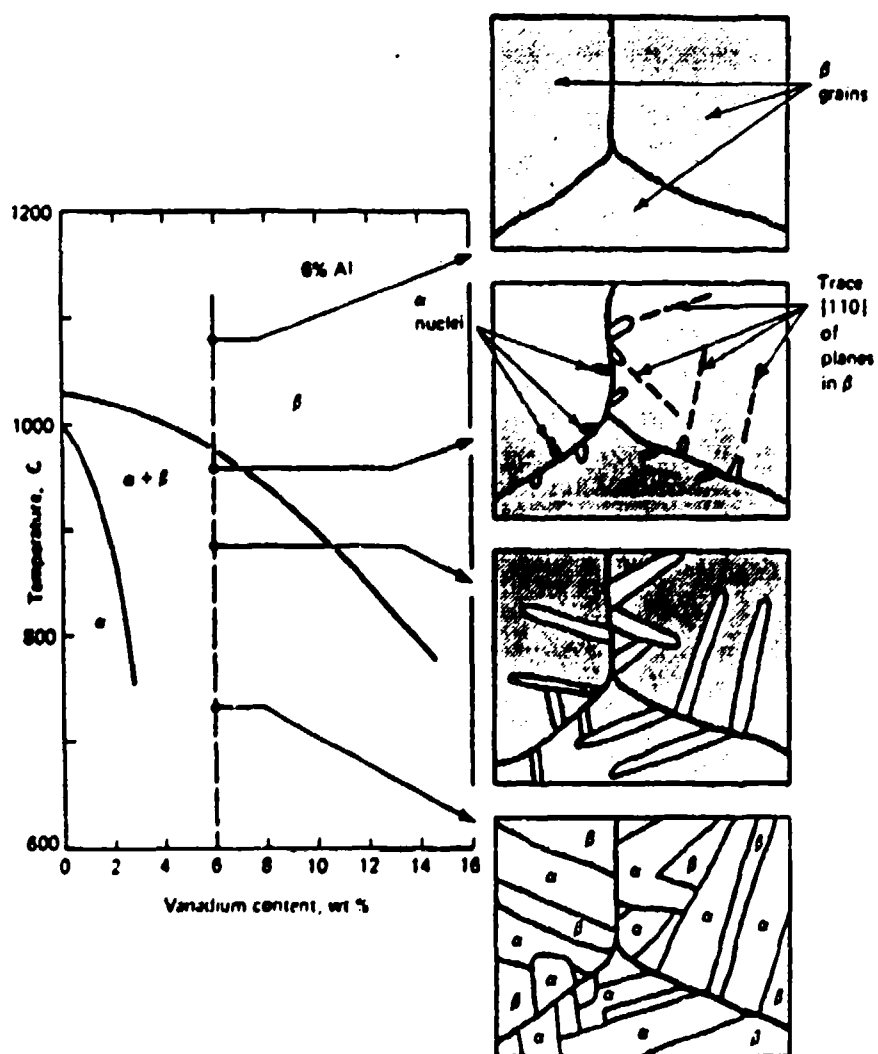


FIGURE 5. THE Ti-6Al-V PHASE DIAGRAM (REFERENCE 9)

## SECTION 3

### PREPRODUCTION PART ANALYSIS

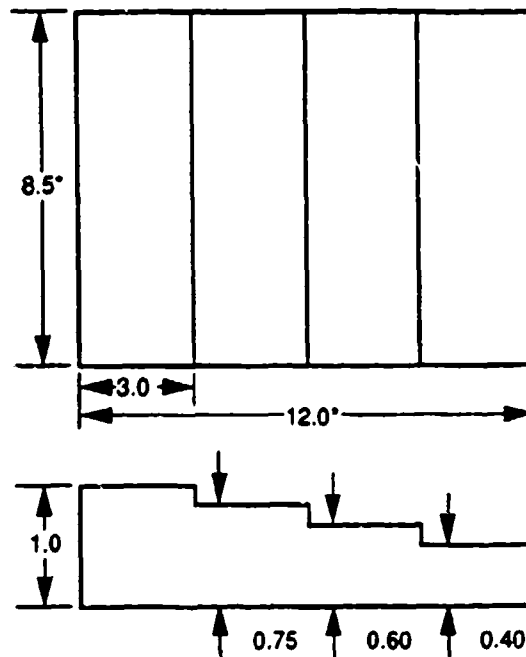
In Phase II of the program, we performed mechanical property testing and microstructural nondestructive inspection of cast step plates (Figure 6) and preproduction missile fins (Figure 7) produced using the 2 chemistries shown in Table 4. Parts were to be supplied by two foundries (Supplier 1 = Wyman-Gordon;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

#### 3.1 MECHANICAL PROPERTY TESTING

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

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

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



NOTE: ALL DIMENSIONS IN INCHES  
 \*MINIMUM DIMENSIONS

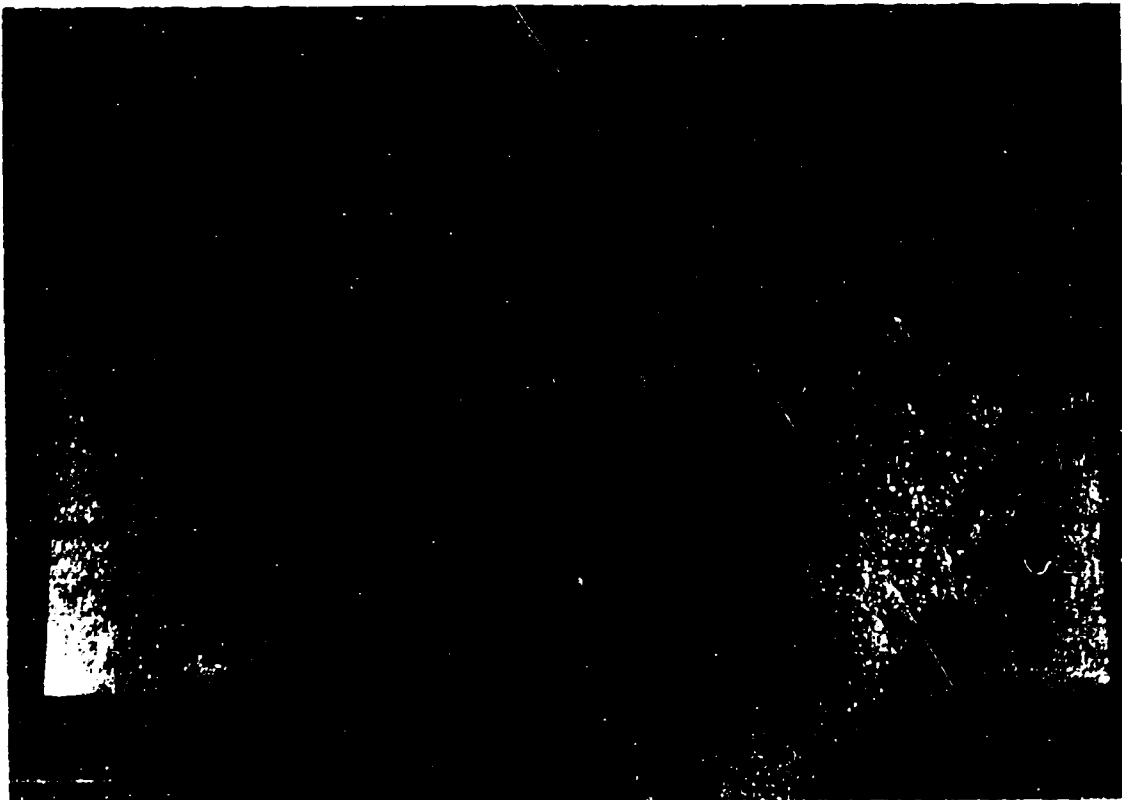


FIGURE 6. CAST TI-6AL-4V STEP PLATES

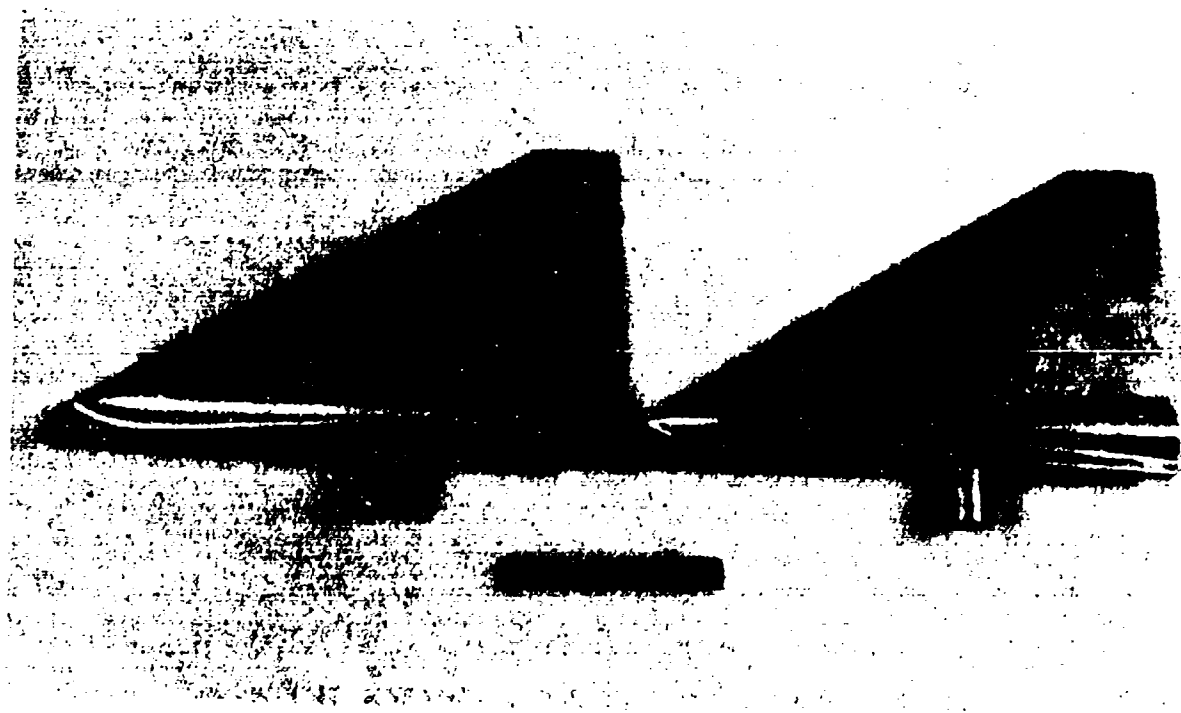
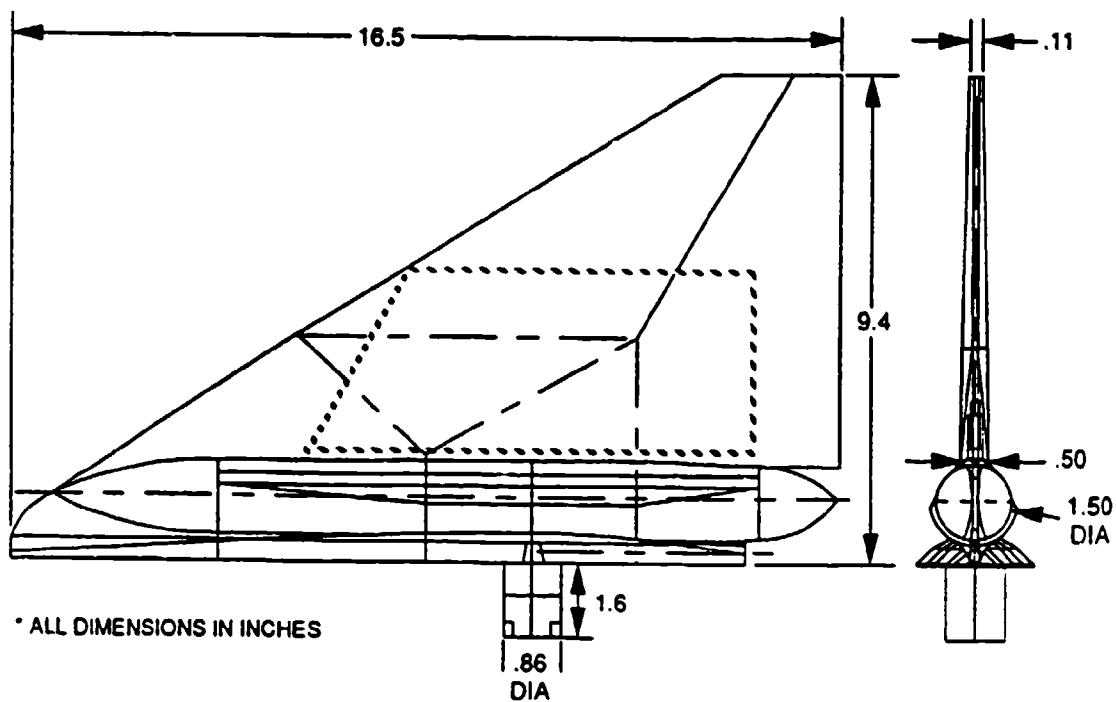
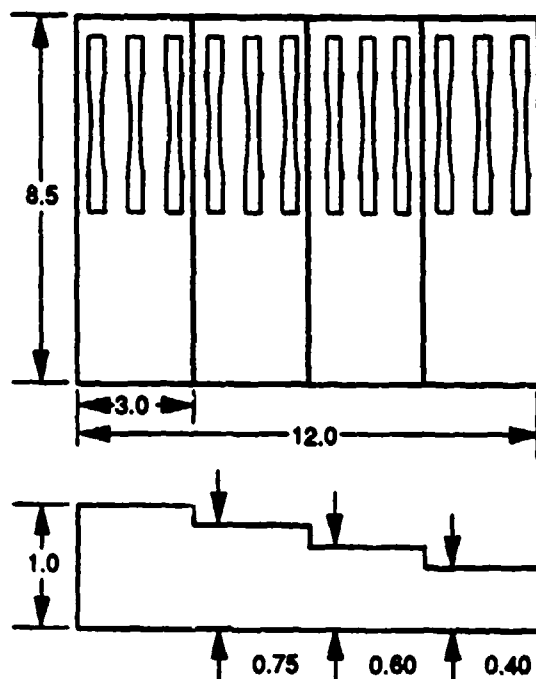


FIGURE 7. CAST TI-6AL-4V MISSILE FINS



NOTE: ALL DIMENSIONS IN INCHES

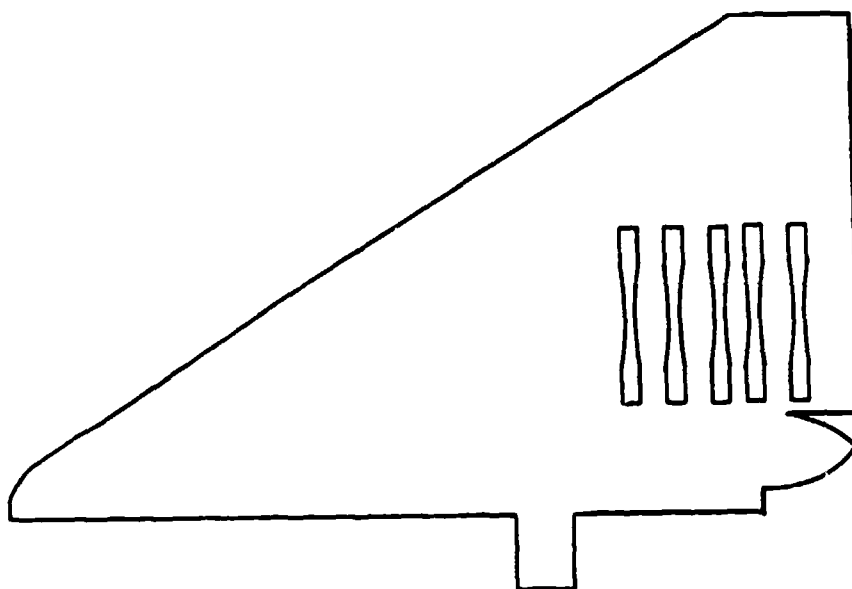


**FIGURE 8. LOCATION AND ORIENTATION OF TENSILE SPECIMENS EXCISED FROM PREPRODUCTION FINS AND STEP PLATES**

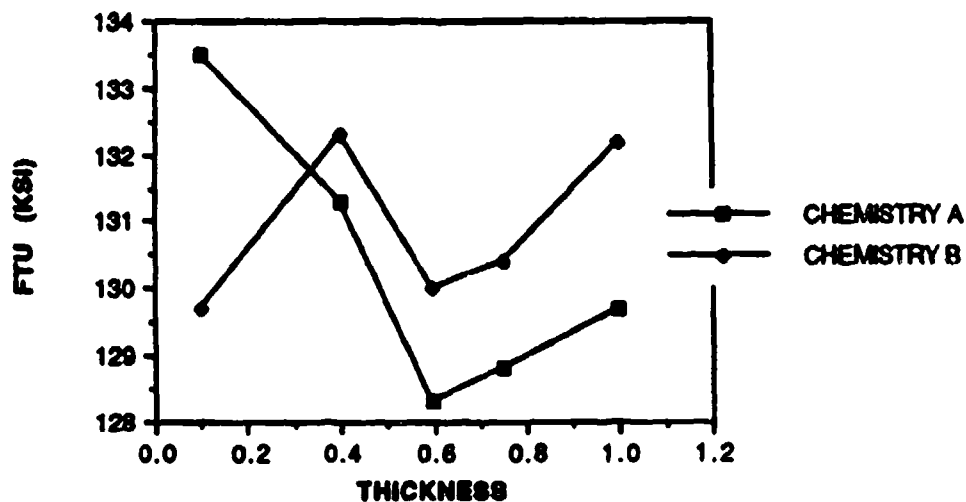


FIGURE 9. RELATIONSHIP OF CHEMISTRY TO STRENGTH

TABLE 5. ACTUAL CHEMISTRIES OF PREPRODUCTION PARTS

| ELEMENT | CHEMISTRY "A" |        | CHEMISTRY "B" |        |
|---------|---------------|--------|---------------|--------|
|         | PLATE         | FIN    | PLATE         | FIN    |
| Al      | 2.33          | 6.0    | 6.2           | 6.2    |
| V       | 3.9           | 4.2    | 3.9           | 4.1    |
| Fe      | 0.17          | 0.2    | 0.18          | 0.2    |
| C       | 0.03          | 0.02   | 0.02          | 0.02   |
| H       | 0.0009        | 0.0008 | 0.004         | 0.0028 |
| O       | 0.17          | 0.16   | 0.18          | 0.15   |
| N       | 0.008         | 0.008  | 0.007         | 0.006  |
| Y       | 0.001         | 0.001  | 0.001         | 0.001  |

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

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

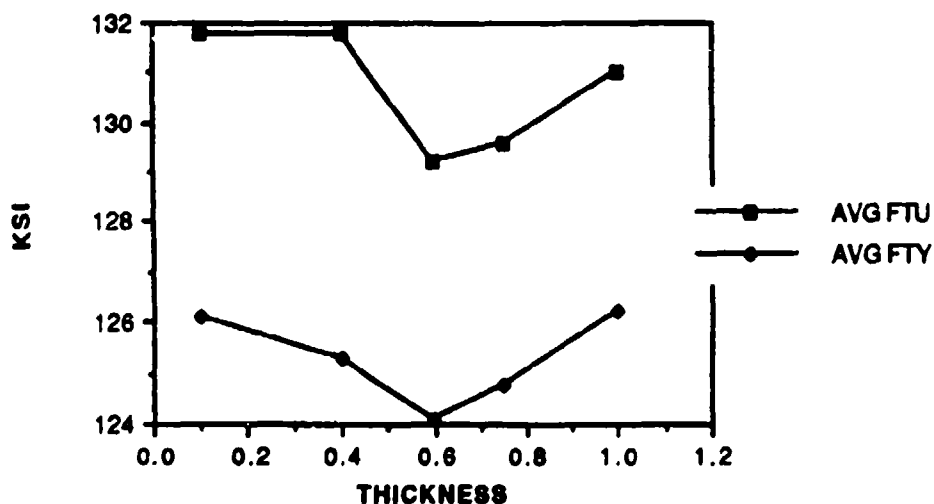


FIGURE 10. RELATIONSHIP OF THICKNESS TO TENSILE STRENGTH

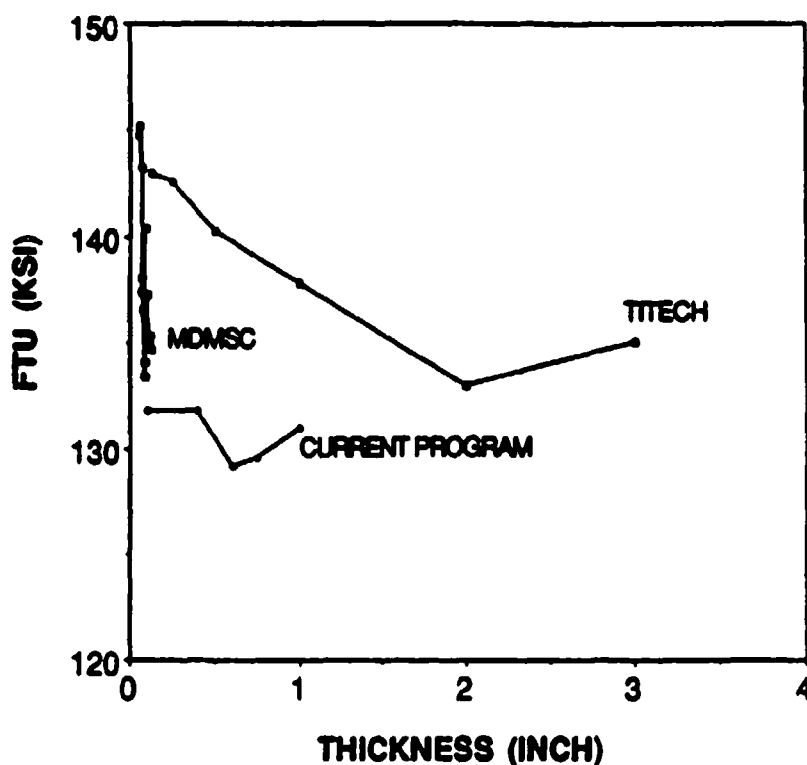


FIGURE 11. DATA GENERATED FROM PARTS CAST TO MORE RESTRICTIVE CHEMISTRY AND POST-CASTING TREATMENT SHOW LESS VARIABILITY THAN DATA GENERATED FROM PARTS CAST TO CURRENT PUBLIC SPECIFICATIONS

### 3.2 NONDESTRUCTIVE INSPECTION

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

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

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

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

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

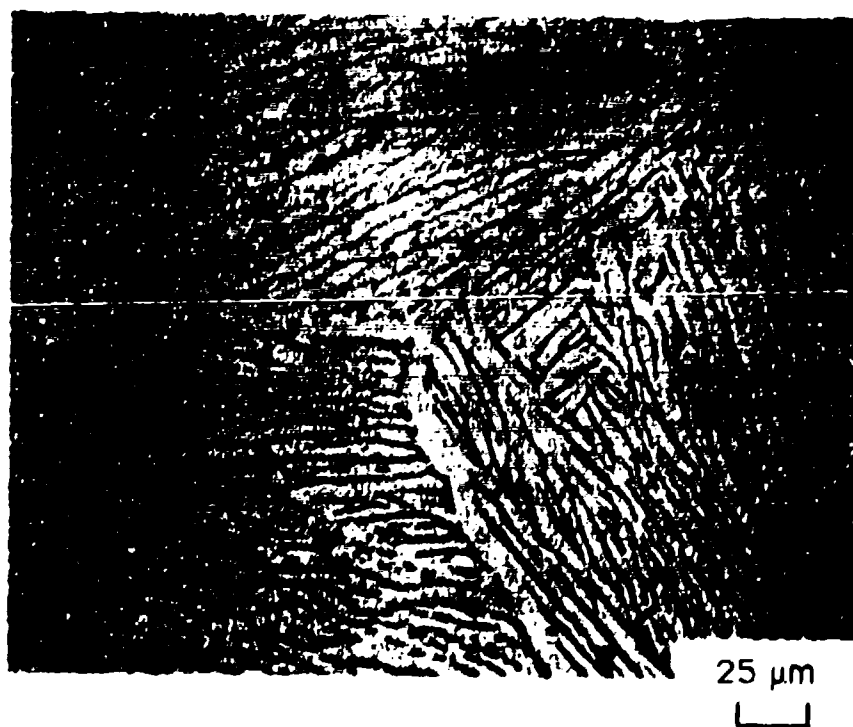
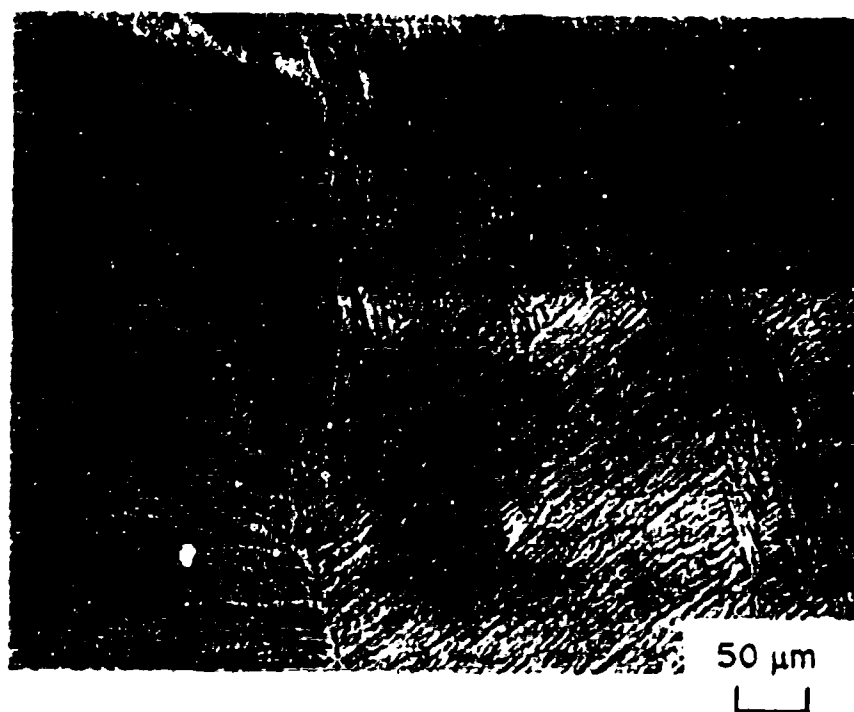


FIGURE 12. TYPICAL PHOTOMICROGRAPHS OF REPLICAS TAKEN FROM TI-6AL-4V CASTINGS

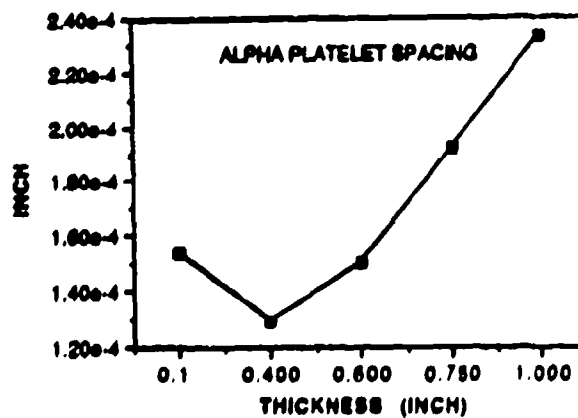
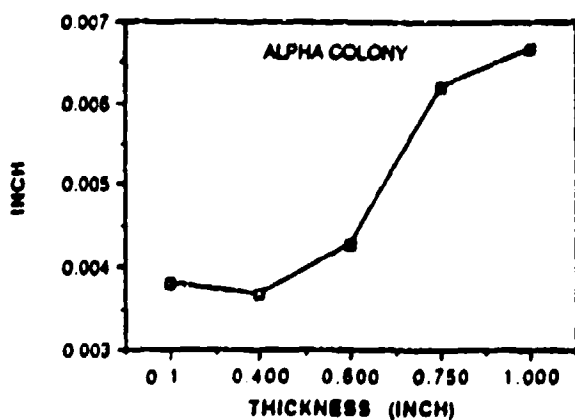
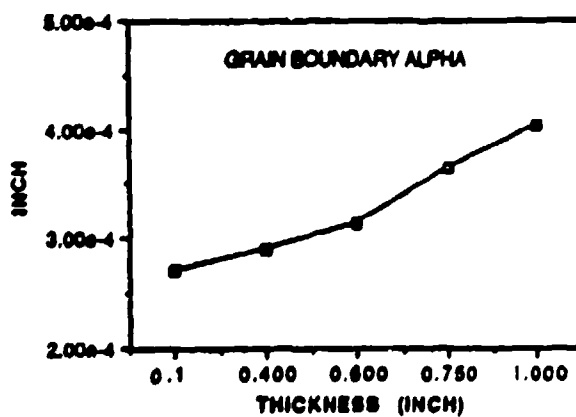
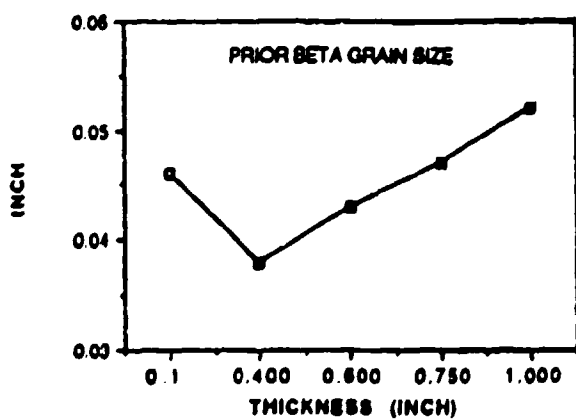


FIGURE 13. VARIATION OF MICROSTRUCTURAL FEATURE WITH PART THICKNESS

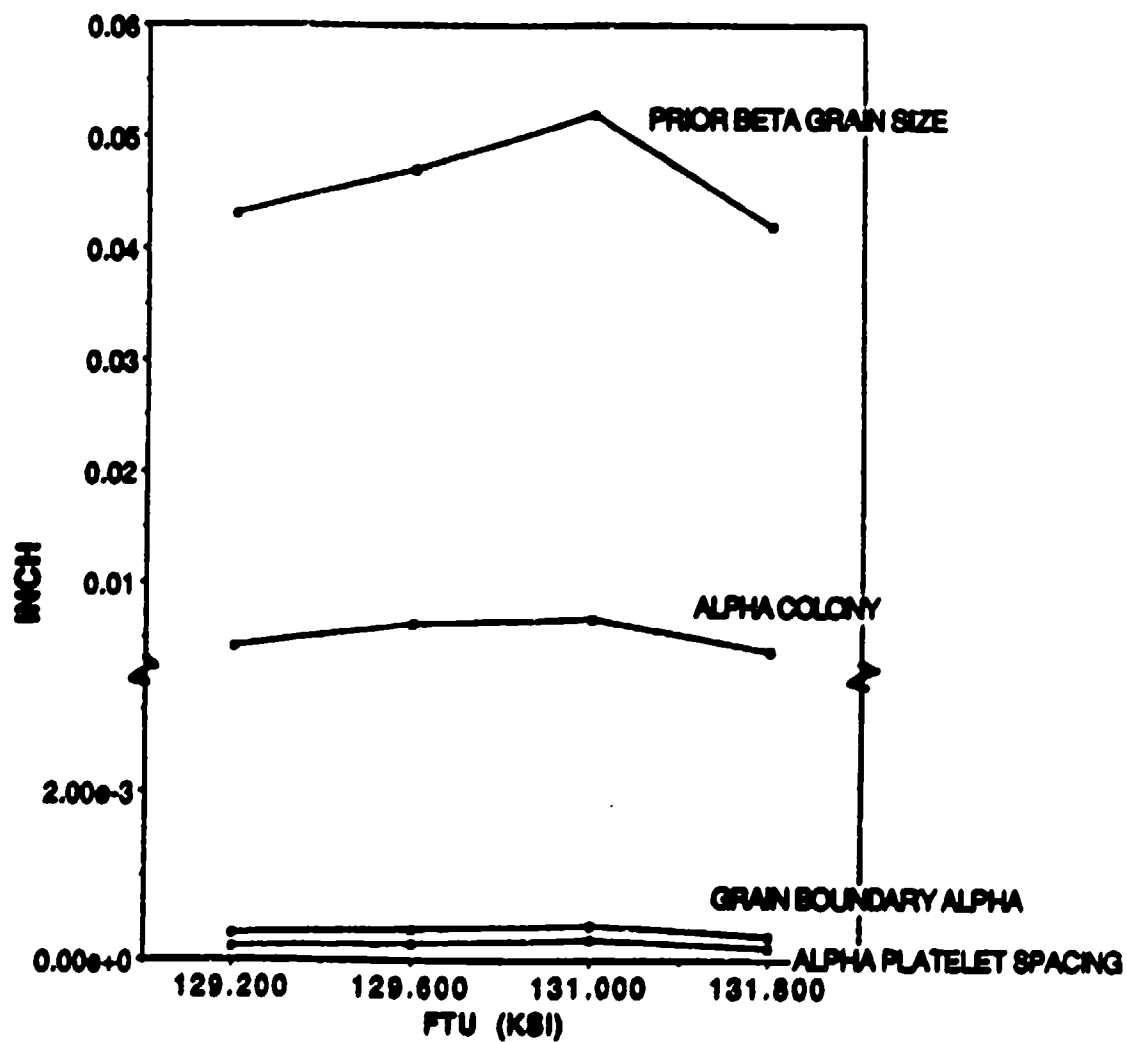


FIGURE 14. SIZES OF THE MICROSTRUCTURAL FEATURES VARY LITTLE OVER THE NARROW PROPERTY RANGE SEEN IN THESE CASTINGS

TABLE 6. MICROSTRUCTURAL FEATURES - MAXIMUM LIMITS

| MICROSTRUCTURAL FEATURE | MAXIMUM SIZE (INCH) |
|-------------------------|---------------------|
| PRIOR BETA GRAIN SIZE   | 0.057               |
| GRAIN BOUNDARY ALPHA    | 0.000825            |
| ALPHA COLONY            | 0.001               |
| ALPHA PLATELET SPACING  | 0.000357            |

## SECTION 4

### ESTABLISHMENT OF SPECIFICATION

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

Under this phase of the proposed program, we prepared a more comprehensive and stringent specification for Ti-6Al-4V castings using chemical limits and post-casting treatment established in our Taguchi analysis and NDI criteria. The specification was drafted in accordance with AMS guidelines (Reference 28). We performed both "F" ratio of variance analysis and "t" test for comparison of means (Reference 18) on data sets representing both chemistries "A" and "B".

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

may not resemble the final copy. Features of the new specification are compared with corresponding items in the current public specifications in Table 7.

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

| FEATURE                | MIL-T-81915                               | AMS 4985                                | AMS 4981                                   | PROGRAM SPECIFICATION                           |
|------------------------|-------------------------------------------|-----------------------------------------|--------------------------------------------|-------------------------------------------------|
| CHEMISTRY              | CURRENT BASELINE (CARBON = 0.08)          | SAME AS MIL-T-81915 EXCEPT CARBON = 0.1 | SAME AS MIL-T-81915 EXCEPT CARBON = 0.1    | MORE RESTRICTIVE THAN BASELINE FOR ALL ELEMENTS |
| HEAT TREATMENT         | PER MIL-H-81260                           | ANNEAL 1550°-1650°F/2-4 HR              | ANNEAL 1550°-1650°F/2-4 HR                 | ANNEAL 1550°F/2 HR                              |
| HOT ISOSTATIC PRESSING | NO CALL-OUT                               | NO CALL-OUT                             | NO CALL-OUT                                | HIP 1650°F/15 KSI/2 HR                          |
| QUALITY                | RADIOGRAPHIC PER ASTM E155 (GRADES A,B,C) | RADIOGRAPHIC PER AMS 2635               | RADIOGRAPHIC PER AMS 2635 (GRADES A,B,C,D) | MICROSTRUCTURAL INSPECTION                      |
| 5' BASIS FTU           |                                           |                                         |                                            |                                                 |
| - SEP. CAST BARS       | N/A                                       | 130 KSI                                 | 130 KSI                                    | N/A                                             |
| - PROLONGATIONS        | N/A                                       | 130 KSI                                 | 130 KSI                                    | N/A                                             |
| - PARTS                |                                           |                                         |                                            |                                                 |
| DESIGNATED             | 125 KSI                                   | 130 KSI                                 | 130 KSI                                    | 125 KSI                                         |
| NONDESIGNATED          | 125 KSI                                   | 125 KSI                                 | 127 KSI                                    | 125 KSI                                         |

## SECTION 5

### "A" AND "B" ALLOWABLES

#### 5.1 ALLOWABLES DETERMINATION

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

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

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

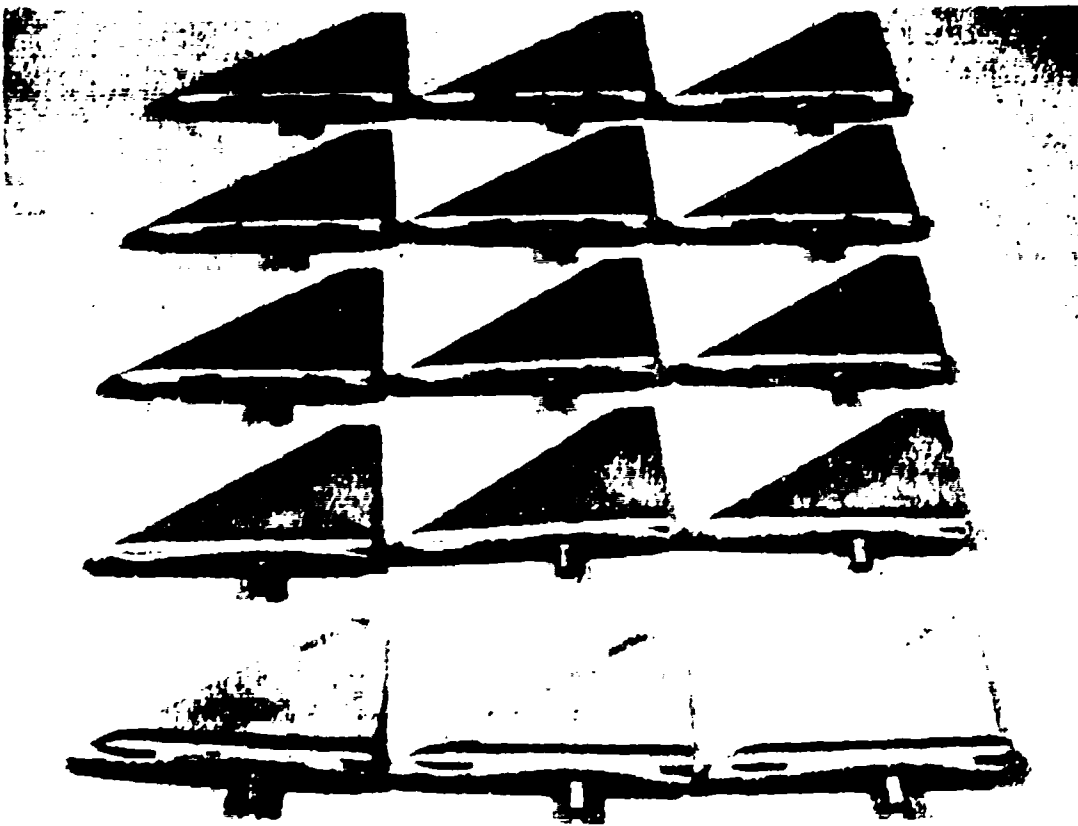


FIGURE 15. PRODUCTION FINS FROM SUPPLIER 2

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

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

**TABLE 8. "A" AND "B" ALLOWABLES**

| <b>BASIS</b> | <b>SOURCE</b>      | <b>F<sub>ty</sub> (KSI)</b> | <b>F<sub>tu</sub> (KSI)</b> |
|--------------|--------------------|-----------------------------|-----------------------------|
| <b>A</b>     | <b>WEIBULL</b>     | <b>120</b>                  | <b>125</b>                  |
|              | <b>NORMAL</b>      | <b>121</b>                  | <b>126</b>                  |
|              | <b>DAC</b>         | <b>109</b>                  | <b>123</b>                  |
| <b>B</b>     | <b>WEIBULL</b>     | <b>123</b>                  | <b>128</b>                  |
|              | <b>NORMAL</b>      | <b>123</b>                  | <b>128</b>                  |
|              | <b>DAC</b>         | <b>116</b>                  | <b>128</b>                  |
| <b>S</b>     | <b>MDMSC</b>       | <b>120</b>                  | <b>125</b>                  |
|              | <b>MIL-T-81915</b> | <b>115</b>                  | <b>125</b>                  |

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

## 5.2 REDUCED RATIOS

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

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

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

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

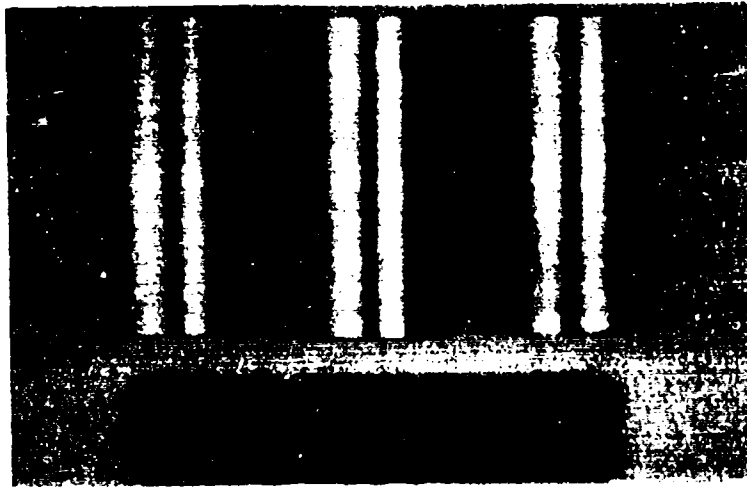
| PROPERTY           | MDMSC         |             | DAC           |             | MIL-HDBK-5    |              |
|--------------------|---------------|-------------|---------------|-------------|---------------|--------------|
|                    | REDUCED RATIO | VALUE (KSI) | REDUCED RATIO | VALUE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

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

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

### 5.3 NONDESTRUCTIVE INSPECTION

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



COMPRESSION



BEARING



SHEAR

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

**Mechanical & Physical Properties For  
TI-64, Investment Cast**

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

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

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

## SECTION 6

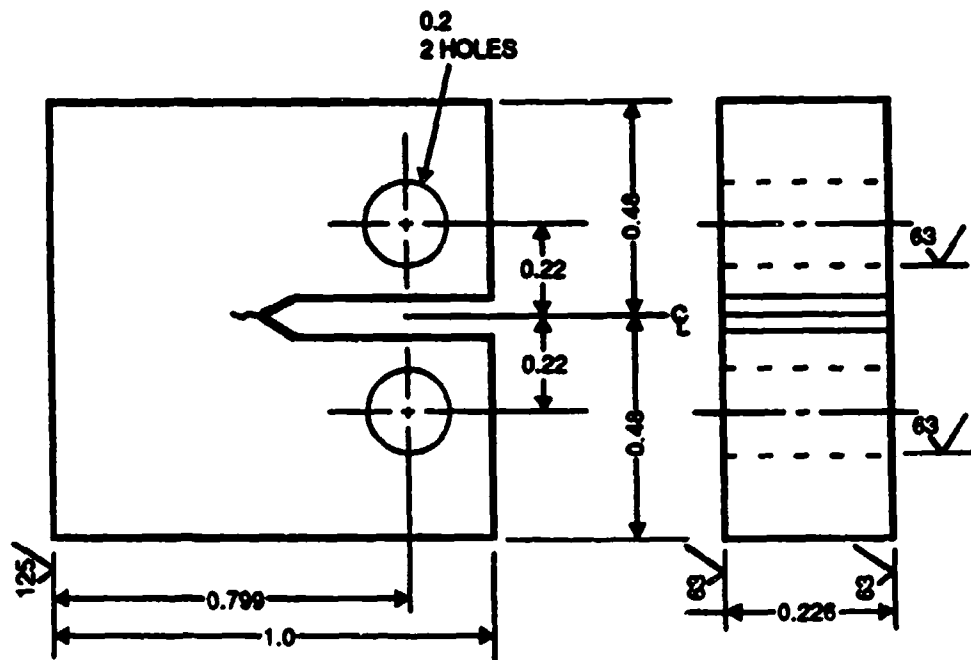
### DAMAGE TOLERANCE

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

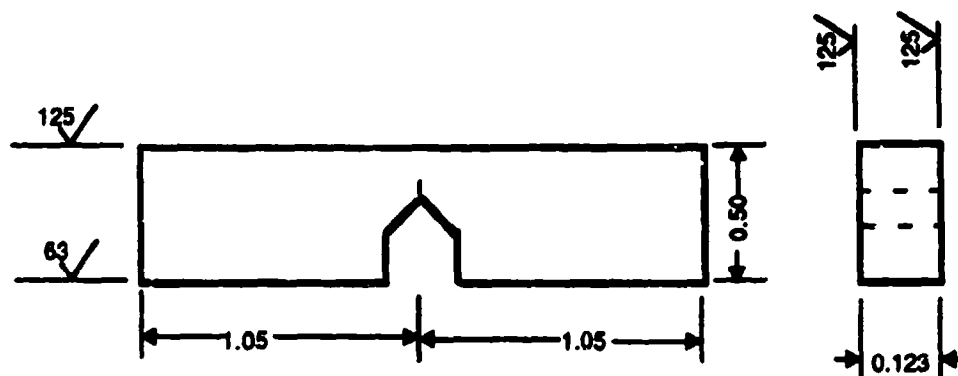
MIL-A-87221 defines durability and damage tolerance analysis requirements for aircraft structures (Reference 27). In the damage tolerance analysis of wrought alloys, the presence of a flaw is assumed to account for defects that may arise in critical areas of parts during manufacturing. In castings there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

#### 6.1 FRACTURE TOUGHNESS

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



**COMPACT TENSION SPECIMEN**



**BEND SPECIMEN**

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

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

TABLE 10. FRACTURE TOUGHNESS TESTS

| SAMPLE | SPECIMEN TYPE   | R   | K <sub>MAX</sub><br>(KSI√IN) | PRECRACK CYCLES | K <sub>Q</sub><br>(KSI√IN) | VALIDITY |
|--------|-----------------|-----|------------------------------|-----------------|----------------------------|----------|
| 4AA-01 | COMPACT TENSION | 0.1 | 13.6                         | 133080          | 70.6                       | INVALID  |
| 4AC-01 | COMPACT TENSION | 0.1 | 13.8                         | 276730          | 66.8                       | INVALID  |
| 4G-02  | COMPACT TENSION | 0.1 | 12.2                         | 181460          | 70.0                       | INVALID  |
| 4T-01  | BEND            | 0.1 | 18.0                         | 947000          | 48.3                       | INVALID  |
| 4P-02  | BEND            | 0.1 | 17.1                         | 300000          | 48.3                       | INVALID  |
| 4G-07  | BEND            | 0.1 | 17.1                         | 351000          | 46.6                       | INVALID  |

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

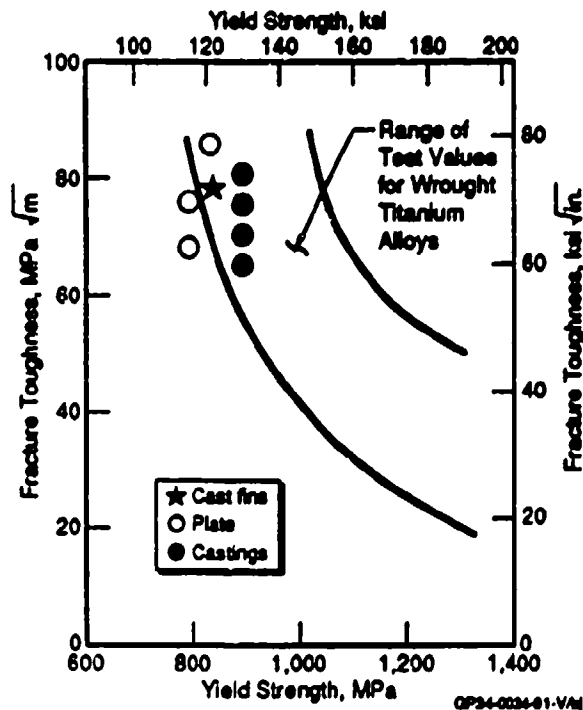


FIGURE 19. FRACTURE TOUGHNESS DATA FROM THE COMPACT TENSION SPECIMENS ARE COMPARABLE TO LITERATURE VALUES (REFERENCE 9)

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

TABLE 11. R-CURVE MEASUREMENTS

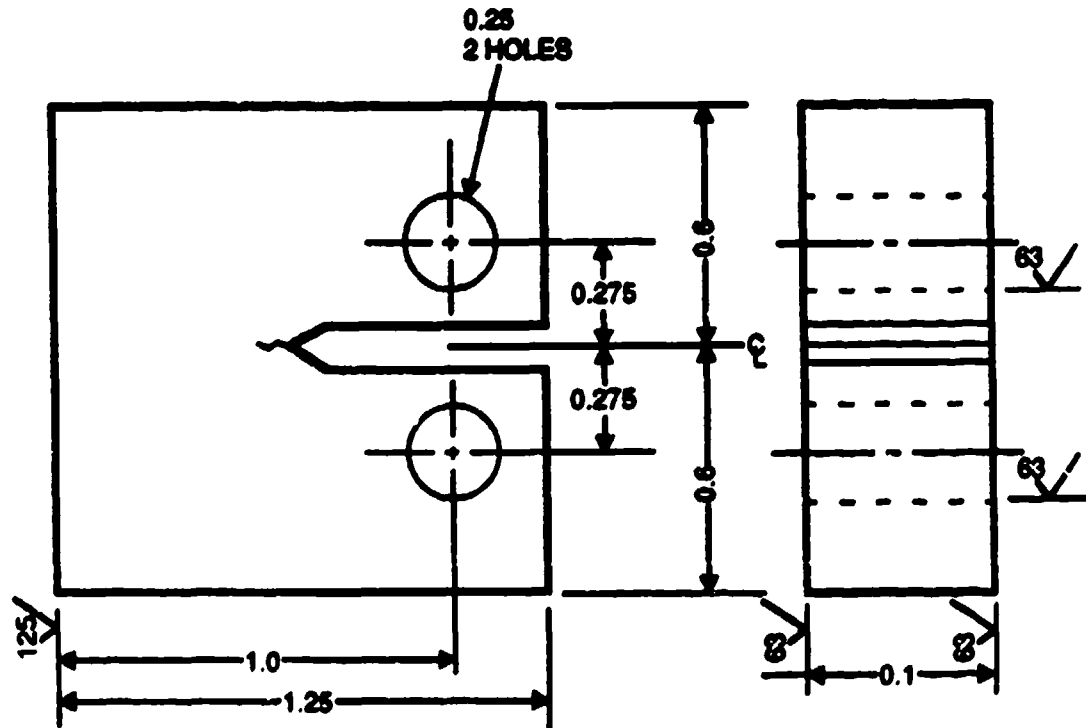
| SAMPLE | $K_R$<br>(KSI) | $K_{MAX}$<br>(KSI/IN) | UNCRAKED<br>LIGAMENT<br>LENGTH (IN) | $(4/P)(K_{MAX}/F_{TY})^2$ | VALIDITY |
|--------|----------------|-----------------------|-------------------------------------|---------------------------|----------|
| 4AA-01 | 122.7          | 140.9                 | 0.3957                              | 1.7652                    | INVALID  |
| 4AC-01 |                | 112.7                 | 0.4118                              | 1.1230                    | INVALID  |
| 4G-02  | 118.6          | 125.0                 | 0.3989                              | 1.3815                    | INVALID  |

## 6.2 FATIGUE CRACK GROWTH

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

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

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



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

FIGURE 20. FATIGUE CRACK GROWTH SPECIMEN

TABLE. 12 FATIGUE CRACK GROWTH CONDITIONS

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

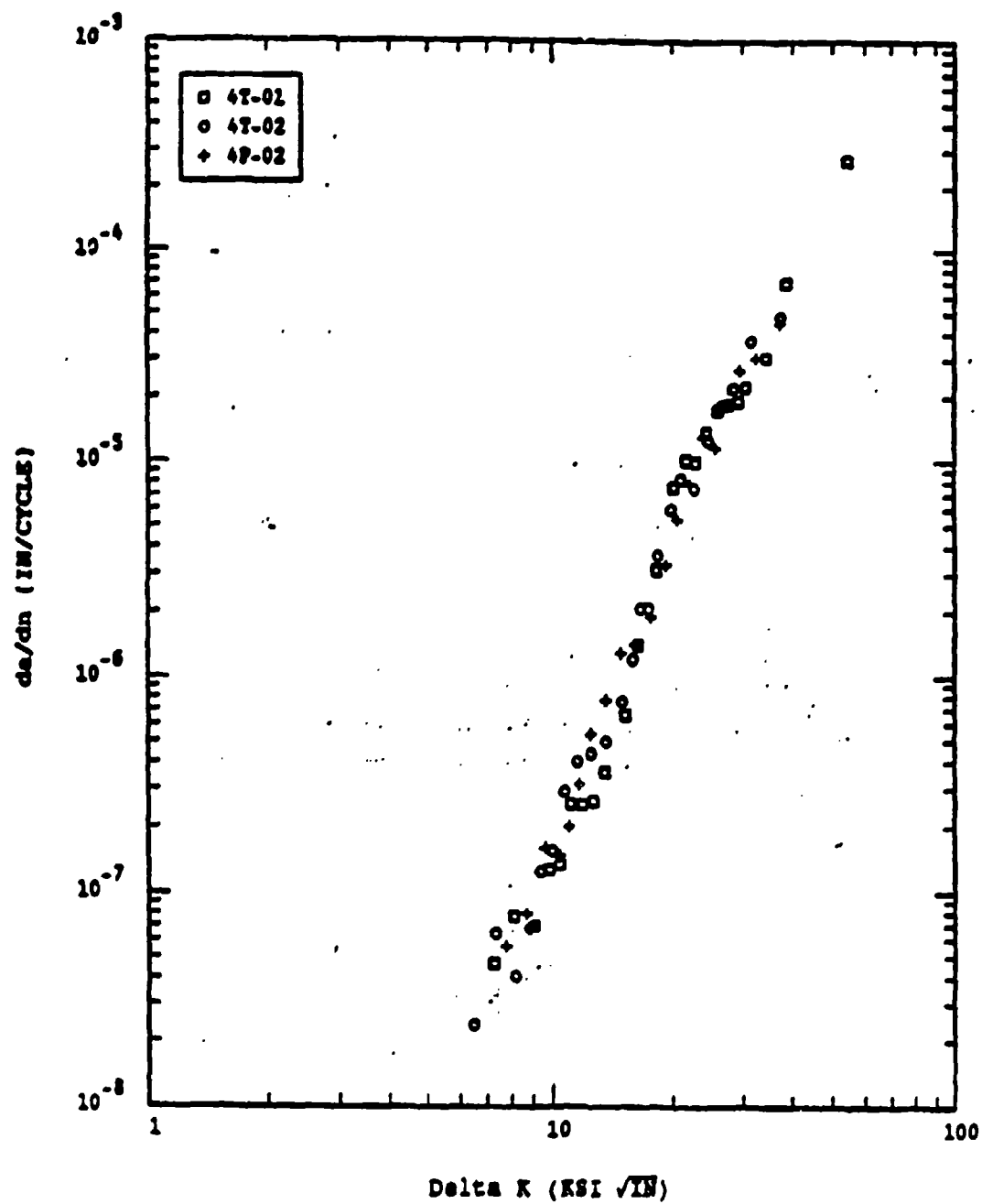
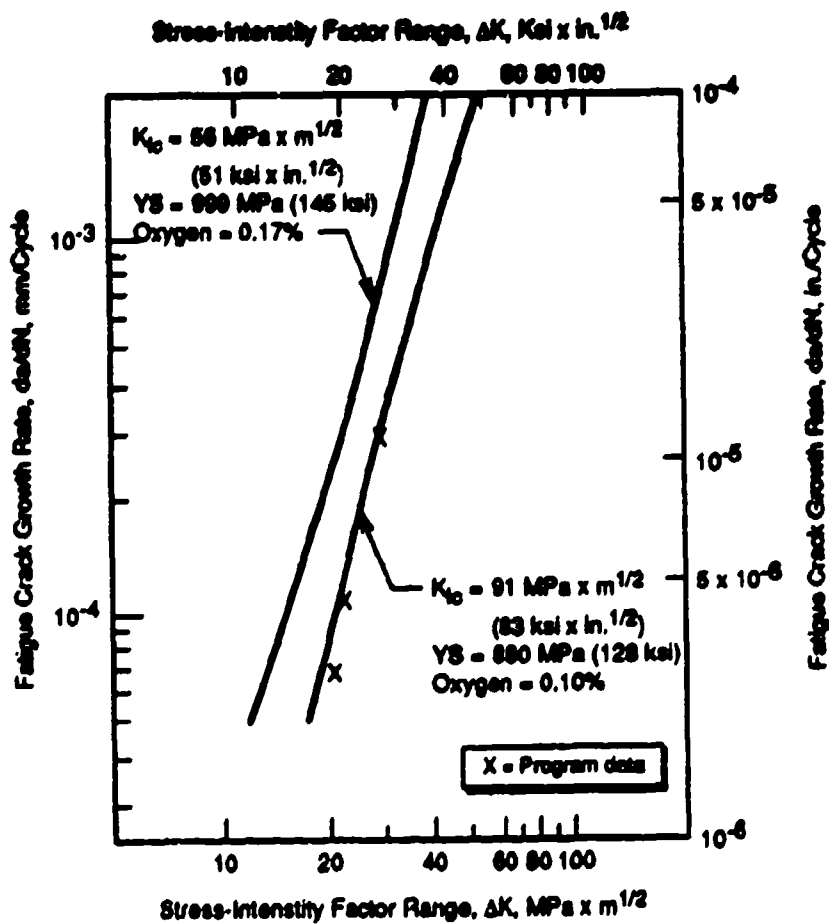


FIGURE 21. FATIGUE CRACK GROWTH RATE AS A FUNCTION OF STRESS INTENSITY FACTOR FOR ALL THREE SPECIMENS TESTED



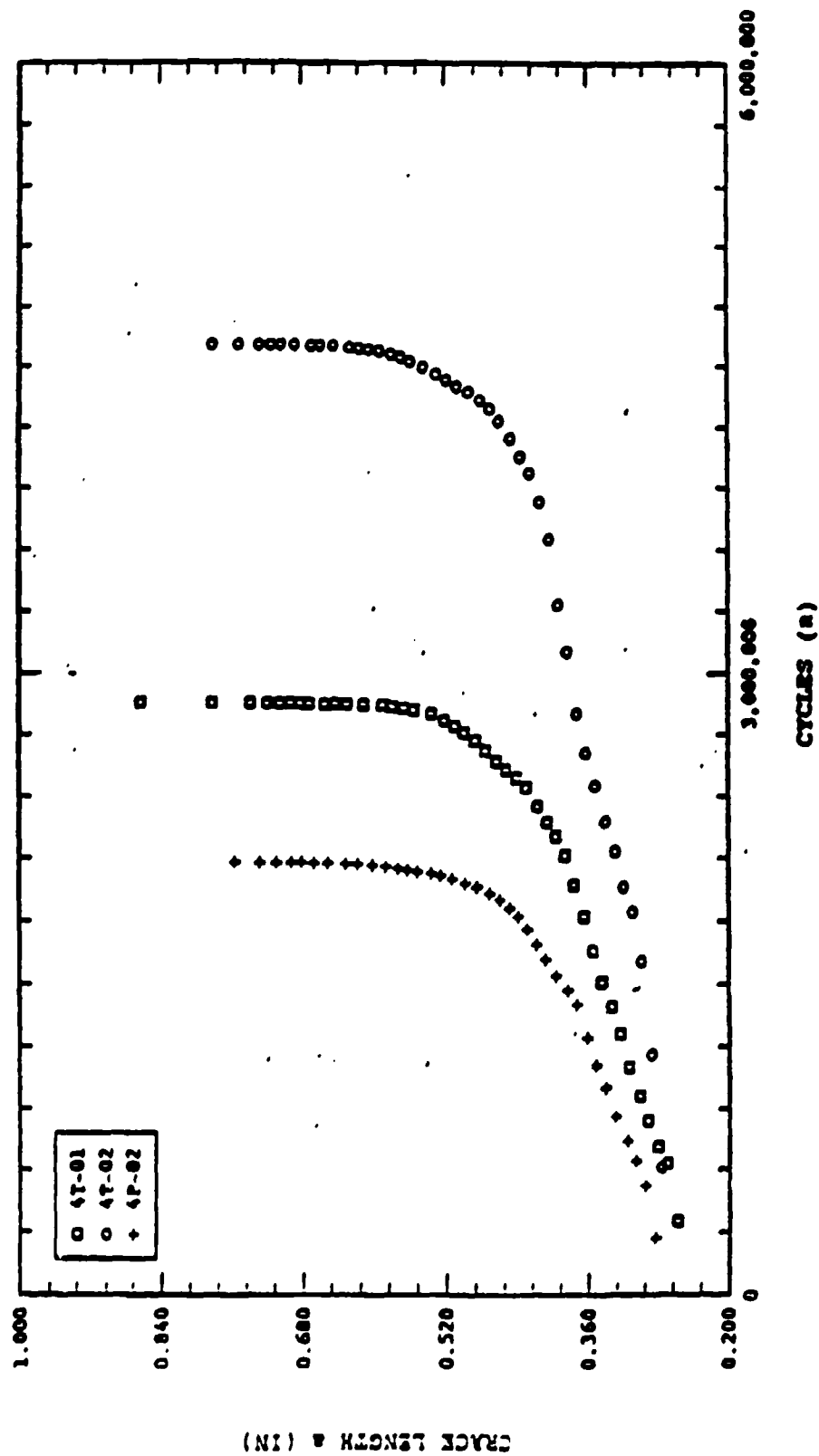


FIGURE 23. CRACK GROWTH VERSUS CONSTANT-AMPLITUDE STRESS CYCLES FOR THREE TI-6AL-4V CAST FINS

## SECTION 7

### CONCLUSIONS AND RECOMMENDATIONS

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

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

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

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

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

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

## SECTION 8

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## **APPENDIX A**

### **CONTROL OF VARIABILITY TAGUCHI ANALYSIS**

## APPENDIX A

### CONTROL OF VARIABILITY TAGUCHI ANALYSIS

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

#### A.1 CHEMICAL VARIABILITY

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

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

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

| CODE LETTER | AVERAGE FTU, KSI | AVERAGE FTV, KSI | AVERAGE ELONGATION | AVERAGE RA | Oxygen | Aluminum | Vanadium | Zinc   | Carbon | Si     | 5th    | 5th    |
|-------------|------------------|------------------|--------------------|------------|--------|----------|----------|--------|--------|--------|--------|--------|
| A           | 136050           | 123163           | 11.50              | 16.52      | 0.1750 | 0.00     | 3.00     | 0.0000 | 0.0200 | 0.1000 | 0.0000 | 0.0000 |
| B           | 134000           | 117000           | 10.00              | 10.00      | 0.1700 | 0.05     | 4.00     | 0.0000 | 0.0200 | 0.1000 | 0.0000 | 0.0000 |
| C           | 131200           | 110075           | 10.02              | 21.74      | 0.1640 | 0.10     | 4.10     | 0.0100 | 0.0210 | 0.2400 | 0.0000 | 0.0000 |
| D           | 131000           | 109400           | 10.04              | 20.10      | 0.1600 | 0.10     | 4.00     | 0.0120 | 0.0200 | 0.1300 | 0.0000 | 0.0000 |
| E           | 125720           | 116353           | 9.40               | 21.00      | 0.1620 | 0.00     | 4.20     | 0.0200 | 0.0200 | 0.1700 | 0.0000 | 0.0000 |
| F           | 129650           | 116000           | 11.30              | 21.70      | 0.1610 | 0.40     | 4.10     | 0.0040 | 0.0200 | 0.1000 | 0.0000 | 0.0000 |
| G           | 129200           | 116300           | 11.00              | 22.20      | 0.1600 | 0.00     | 4.00     | 0.0000 | 0.0200 | 0.1000 | 0.0000 | 0.0000 |
| H           | 129000           | 116200           | 11.20              | 22.75      | 0.1600 | 0.20     | 4.10     | 0.0000 | 0.0200 | 0.1000 | 0.0000 | 0.0000 |
| I           | 129000           | 116200           | 11.00              | 23.25      | 0.1700 | 0.05     | 3.70     | 0.0017 | 0.0200 | 0.1000 | 0.0000 | 0.0000 |
| J           | 122240           | 110210           | 11.70              | 19.01      | 0.1070 | 0.10     | 4.00     | 0.0140 | 0.0200 | 0.1000 | 0.0000 | 0.0000 |
| K           | 124600           | 116000           | 7.00               | 24.00      | 0.1600 | 0.00     | 4.00     | 0.0000 | 0.0200 | 0.1000 | 0.0000 | 0.0000 |
| L           | 124000           | 116000           | 9.40               | 24.00      | 0.1610 | 0.40     | 4.10     | 0.0040 | 0.0200 | 0.1000 | 0.0000 | 0.0000 |
| M           | 127000           | 117000           | 10.00              | 23.00      | 0.1620 | 0.10     | 4.20     | 0.0170 | 0.0200 | 0.2700 | 0.0000 | 0.0000 |
| N           | 127000           | 117000           | 10.00              | 23.00      | 0.1620 | 0.10     | 4.20     | 0.0170 | 0.0200 | 0.2700 | 0.0000 | 0.0000 |
| O           | 127000           | 117000           | 10.00              | 23.00      | 0.1620 | 0.10     | 4.20     | 0.0170 | 0.0200 | 0.2700 | 0.0000 | 0.0000 |
| P           | 127000           | 117000           | 10.00              | 23.00      | 0.1620 | 0.10     | 4.20     | 0.0170 | 0.0200 | 0.2700 | 0.0000 | 0.0000 |
| Q           | 127000           | 117000           | 10.00              | 23.00      | 0.1620 | 0.10     | 4.20     | 0.0170 | 0.0200 | 0.2700 | 0.0000 | 0.0000 |
| R           | 127000           | 117000           | 10.00              | 23.00      | 0.1620 | 0.10     | 4.20     | 0.0170 | 0.0200 | 0.2700 | 0.0000 | 0.0000 |
| S           | 127000           | 117000           | 10.00              | 23.00      | 0.1620 | 0.10     | 4.20     | 0.0170 | 0.0200 | 0.2700 | 0.0000 | 0.0000 |
| T           | 127000           | 117000           | 10.00              | 23.00      | 0.1620 | 0.10     | 4.20     | 0.0170 | 0.0200 | 0.2700 | 0.0000 | 0.0000 |
| U           | 127000           | 117000           | 10.00              | 23.00      | 0.1620 | 0.10     | 4.20     | 0.0170 | 0.0200 | 0.2700 | 0.0000 | 0.0000 |
| V           | 127000           | 117000           | 10.00              | 23.00      | 0.1620 | 0.10     | 4.20     | 0.0170 | 0.0200 | 0.2700 | 0.0000 | 0.0000 |
| W           | 127000           | 117000           | 10.00              | 23.00      | 0.1620 | 0.10     | 4.20     | 0.0170 | 0.0200 | 0.2700 | 0.0000 | 0.0000 |
| X           | 127000           | 117000           | 10.00              | 23.00      | 0.1620 | 0.10     | 4.20     | 0.0170 | 0.0200 | 0.2700 | 0.0000 | 0.0000 |
| Y           | 127000           | 117000           | 10.00              | 23.00      | 0.1620 | 0.10     | 4.20     | 0.0170 | 0.0200 | 0.2700 | 0.0000 | 0.0000 |
| Z           | 127000           | 117000           | 10.00              | 23.00      | 0.1620 | 0.10     | 4.20     | 0.0170 | 0.0200 | 0.2700 | 0.0000 | 0.0000 |
| AA          | 127000           | 117000           | 10.00              | 23.00      | 0.1620 | 0.10     | 4.20     | 0.0170 | 0.0200 | 0.2700 | 0.0000 | 0.0000 |
| BB          | 127000           | 117000           | 10.00              | 23.00      | 0.1620 | 0.10     | 4.20     | 0.0170 | 0.0200 | 0.2700 | 0.0000 | 0.0000 |
| CC          | 127000           | 117000           | 10.00              | 23.00      | 0.1620 | 0.10     | 4.20     | 0.0170 | 0.0200 | 0.2700 | 0.0000 | 0.0000 |
| DD          | 127000           | 117000           | 10.00              | 23.00      | 0.1620 | 0.10     | 4.20     | 0.0170 | 0.0200 | 0.2700 | 0.0000 | 0.0000 |
| EE          | 127000           | 117000           | 10.00              | 23.00      | 0.1620 | 0.10     | 4.20     | 0.0170 | 0.0200 | 0.2700 | 0.0000 | 0.0000 |
| FF          | 127000           | 117000           | 10.00              | 23.00      | 0.1620 | 0.10     | 4.20     | 0.0170 | 0.0200 | 0.2700 | 0.0000 | 0.0000 |
| GG          | 127000           | 117000           | 10.00              | 23.00      | 0.1620 | 0.10     | 4.20     | 0.0170 | 0.0200 | 0.2700 | 0.0000 | 0.0000 |
| HH          | 127000           | 117000           | 10.00              | 23.00      | 0.1620 | 0.10     | 4.20     | 0.0170 | 0.0200 | 0.2700 | 0.0000 | 0.0000 |
| II          | 127000           | 117000           | 10.00              | 23.00      | 0.1620 | 0.10     | 4.20     | 0.0170 | 0.0200 | 0.2700 | 0.0000 | 0.0000 |
| JJ          | 127000           | 117000           | 10.00              | 23.00      | 0.1620 | 0.10     | 4.20     | 0.0170 | 0.0200 | 0.2700 | 0.0000 | 0.0000 |
| KK          | 127000           | 117000           | 10.00              | 23.00      | 0.1620 | 0.10     | 4.20     | 0.0170 | 0.0200 | 0.2700 | 0.0000 | 0.0000 |
| LL          | 127000           | 117000           | 10.00              | 23.00      | 0.1620 | 0.10     | 4.20     | 0.0170 | 0.0200 | 0.2700 | 0.0000 | 0.0000 |
| MM          | 127000           | 117000           | 10.00              | 23.00      | 0.1620 | 0.10     | 4.20     | 0.0170 | 0.0200 | 0.2700 | 0.0000 | 0.0000 |
| NN          | 127000           | 117000           | 10.00              | 23.00      | 0.1620 | 0.10     | 4.20     | 0.0170 | 0.0200 | 0.2700 | 0.0000 | 0.0000 |
| OO          | 127000           | 117000           | 10.00              | 23.00      | 0.1620 | 0.10     | 4.20     | 0.0170 | 0.0200 | 0.2700 | 0.0000 | 0.0000 |
| PP          | 127000           | 117000           | 10.00              | 23.00      | 0.1620 | 0.10     | 4.20     | 0.0170 | 0.0200 | 0.2700 | 0.0000 | 0.0000 |
| QQ          | 127000           | 117000           | 10.00              | 23.00      | 0.1620 | 0.10     | 4.20     | 0.0170 | 0.0200 | 0.2700 | 0.0000 | 0.0000 |
| RR          | 127000           | 117000           | 10.00              | 23.00      | 0.1620 | 0.10     | 4.20     | 0.0170 | 0.0200 | 0.2700 | 0.0000 | 0.0000 |
| SS          | 127000           | 117000           | 10.00              | 23.00      | 0.1620 | 0.10     | 4.20     | 0.0170 | 0.0200 | 0.2700 | 0.0000 | 0.0000 |
| TT          | 127000           | 117000           | 10.00              | 23.00      | 0.1620 | 0.10     | 4.20     | 0.0170 | 0.0200 | 0.2700 | 0.0000 | 0.0000 |
| UU          | 127000           | 117000           | 10.00              | 23.00      | 0.1620 | 0.10     | 4.20     | 0.0170 | 0.0200 | 0.2700 | 0.0000 | 0.0000 |
| VV          | 127000           | 117000           | 10.00              | 23.00      | 0.1620 | 0.10     | 4.20     | 0.0170 | 0.0200 | 0.2700 | 0.0000 | 0.0000 |
| WW          | 127000           | 117000           | 10.00              | 23.00      | 0.1620 | 0.10     | 4.20     | 0.0170 | 0.0200 | 0.2700 | 0.0000 | 0.0000 |
| XX          | 127000           | 117000           | 10.00              | 23.00      | 0.1620 | 0.10     | 4.20     | 0.0170 | 0.0200 | 0.2700 | 0.0000 | 0.0000 |
| YY          | 127000           | 117000           | 10.00              | 23.00      | 0.1620 | 0.10     | 4.20     | 0.0170 | 0.0200 | 0.2700 | 0.0000 | 0.0000 |

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

| RUN NO. | OXYGEN<br>CONTENT<br>(1) | NITROGEN<br>CONTENT<br>(2) | OXYGEN<br>NITROGEN<br>INTERACTION<br>(1X2) | HYDROGEN<br>CONTENT<br>(4) | OXYGEN<br>HYDROGEN<br>INTERACTION<br>(1X4) | NITROGEN<br>HYDROGEN<br>INTERACTION<br>(2X4) | (7) | CODE<br>LETTER                        | AVERAGE<br>(KSI) | SIGMA  | NOMINAL<br>SIGNAL<br>TO<br>NOISE<br>RATIO<br>(db) |
|---------|--------------------------|----------------------------|--------------------------------------------|----------------------------|--------------------------------------------|----------------------------------------------|-----|---------------------------------------|------------------|--------|---------------------------------------------------|
| 1       | .1565                    | .0005                      | 1                                          | .0010                      | 1                                          | 1                                            | 1   | G, AA,<br>H, O                        | 126006           | 1539.4 | 30.26                                             |
| 2       | .1565                    | .0005                      | 1                                          | .0054                      | 2                                          | 2                                            | 2   | LL, K, H,<br>P, F, L, R               | 129497           | 3969.7 | 30.40                                             |
| 3       | .1565                    | .0134                      | 2                                          | .00000                     | 1                                          | 2                                            | 2   | NR, MM, S,<br>HH, X, V,<br>Y, N, D, T | 129900           | 3146.3 | 32.32                                             |
| 4       | .1565                    | .0134                      | 2                                          | .00065                     | 2                                          | 1                                            | 1   | O, C                                  | 120740           | 4182.3 | 29.74                                             |
| 5       | .1010                    | .0002                      | 2                                          | .00103                     | 2                                          | 1                                            | 2   | U, B, TT<br>FF, EE, Z                 | 131073           | 3569.7 | 31.25                                             |
| 6       | .1010                    | .0002                      | 2                                          | .0053                      | 1                                          | 2                                            | 1   | R, I,<br>M, BB                        | 131302           | 4213.3 | 29.07                                             |
| 7       | .1010                    | .01002                     | 1                                          | .00113                     | 2                                          | 2                                            | 1   | NH, GG,<br>XX                         | 133024           | 3940.3 | 30.62                                             |
| 8       | .1010                    | .01002                     | 1                                          | .0051                      | 1                                          | 1                                            | 2   | NH, DD,<br>YY, J                      | 133705           | 3083.4 | 32.71                                             |

FIGURE A2. TENSILE STRENGTH - L<sub>8</sub> ORTHOGONAL ARRAY FOR OXYGEN, HYDROGEN, AND NITROGEN

| RUN NO. | CARBON<br>CONTENT<br>(1) | IRON<br>CONTENT<br>(2) | CARBON<br>IRON<br>INTERACTION<br>(1X2) | ALUMINUM<br>CONTENT<br>(4) | CARBON<br>ALUMINUM<br>INTERACTION<br>(1X4) | IRON<br>ALUMINUM<br>INTERACTION<br>(2X4) | (7) | CODE<br>LETTER      | AVERAGE<br>(PSI) | SIGMA  | NOMINAL<br>SIGNAL<br>TO<br>NOISE<br>RATIO<br>(db) |
|---------|--------------------------|------------------------|----------------------------------------|----------------------------|--------------------------------------------|------------------------------------------|-----|---------------------|------------------|--------|---------------------------------------------------|
| 1       | .0253                    | .1273                  | 1                                      | 6.07                       | 1                                          | 1                                        | 1   | G,U,Z<br>Y,D,J      | 128482           | 2943.7 | 32.79                                             |
| 2       | .0253                    | .1273                  | 1                                      | 6.22                       | 2                                          | 2                                        | 2   | X,H,S<br>BB,AA      | 129400           | 1071.9 | 36.00                                             |
| 3       | .0253                    | .1027                  | 2                                      | 6.04                       | 1                                          | 2                                        | 2   | B,I,L<br>E,N        | 130412           | 4200.1 | 29.04                                             |
| 4       | .0253                    | .1027                  | 2                                      | 6.40                       | 2                                          | 1                                        | 1   | UU,V,XX<br>YY,WW,VV | 135955           | 5703.1 | 27.42                                             |
| 5       | .0405                    | .1550                  | 2                                      | 5.70                       | 2                                          | 1                                        | 2   | FF,DD<br>EE,HH      | 134049           | 901.0  | 42.70                                             |
| 6       | .0405                    | .1550                  | 2                                      | 6.04                       | 1                                          | 2                                        | 1   | R,K<br>P,T          | 130902           | 5049.6 | 20.20                                             |
| 7       | .0405                    | .1917                  | 1                                      | 5.97                       | 2                                          | 2                                        | 1   | O,Q,TT<br>RR,MM,CC  | 130056           | 4454.0 | 29.31                                             |
| 8       | .0405                    | .1917                  | 1                                      | 6.24                       | 1                                          | 1                                        | 2   | M,N,WW<br>R,L,F     | 127012           | 1000.0 | 37.03                                             |

FIGURE A3. TENSILE STRENGTH - L<sub>8</sub> ORTHOGONAL ARRAY FOR CARBON, IRON, AND ALUMINUM

| RUN NO. | OXYGEN<br>CONTENT<br>(1) | NITROGEN<br>CONTENT<br>(2) | OXYGEN<br>NITROGEN<br>INTERACTION<br>(1X2) | HYDROGEN<br>CONTENT<br>(4) | OXYGEN<br>HYDROGEN<br>INTERACTION<br>(1X4) | NITROGEN<br>HYDROGEN<br>INTERACTION<br>(2X4) | (7) | CODE<br>LETTER                 | AVERAGE<br>YIELD<br>(PSI) | SIGMA  | NOMINAL<br>SIGNAL<br>TO<br>NOISE<br>RATIO<br>(db) |
|---------|--------------------------|----------------------------|--------------------------------------------|----------------------------|--------------------------------------------|----------------------------------------------|-----|--------------------------------|---------------------------|--------|---------------------------------------------------|
| 1       | .1565                    | .0005                      | 1                                          | .0010                      | 1                                          | 1                                            | 1   | G,RR,<br>H,Q                   | 115491                    | 1000.3 | 40.50                                             |
| 2       | .1565                    | .0005                      | 1                                          | .0054                      | 2                                          | 2                                            | 2   | LL,K,H,<br>P,F,L,R             | 110517                    | 3912.9 | 29.62                                             |
| 3       | .1565                    | .0134                      | 2                                          | .00090                     | 1                                          | 2                                            | 2   | RR,MM,S,<br>HH,X,V,<br>Y,N,D,T | 119211                    | 3475.0 | 30.71                                             |
| 4       | .1565                    | .0134                      | 2                                          | .00965                     | 2                                          | 1                                            | 1   | O,C                            | 110000                    | 3198.9 | 31.34                                             |
| 5       | .1010                    | .0002                      | 2                                          | .00103                     | 2                                          | 1                                            | 2   | U,B,TT<br>FF,EE,Z              | 119760                    | 3909.0 | 29.72                                             |
| 6       | .1010                    | .0002                      | 2                                          | .0053                      | 1                                          | 2                                            | 1   | R,I<br>M,BB                    | 110771                    | 3431.6 | 30.70                                             |
| 7       | .1010                    | .01662                     | 1                                          | .00113                     | 2                                          | 2                                            | 1   | NN,GG,<br>XX                   | 122941                    | 3302.0 | 31.21                                             |
| 8       | .1010                    | .01662                     | 1                                          | .0051                      | 1                                          | 1                                            | 2   | MM,DD,<br>YY,J                 | 120500                    | 3040.5 | 29.92                                             |

FIGURE A4. YIELD STRENGTH - L<sub>8</sub> ORTHOGONAL ARRAY FOR OXYGEN, HYDROGEN, AND NITROGEN

| RUN NO. | CARBON<br>CONTENT<br>(1) | IRON<br>CONTENT<br>(2) | CARBON<br>IRON<br>INTERACTION<br>(1X2) | ALUMINUM<br>CONTENT<br>(4) | CARBON<br>ALUMINUM<br>INTERACTION<br>(1X4) | IRON<br>ALUMINUM<br>INTERACTION<br>(2X4) | (7) | CODE<br>LETTER      | AVERAGE<br>YIELD<br>(PSI) | SIGMA  | NOMINAL<br>SIGNAL<br>TO<br>NOISE<br>RATIO<br>(db) |
|---------|--------------------------|------------------------|----------------------------------------|----------------------------|--------------------------------------------|------------------------------------------|-----|---------------------|---------------------------|--------|---------------------------------------------------|
| 1       | .0253                    | .1273                  | 1                                      | 6.07                       | 1                                          | 1                                        | 1   | G,U,Z<br>Y,D,J      | 116863                    | 1983.5 | 35.40                                             |
| 2       | .0253                    | .1273                  | 1                                      | 6.22                       | 2                                          | 2                                        | 2   | X,H,S<br>BB,RR      | 117683                    | 1191.0 | 39.00                                             |
| 3       | .0253                    | .1027                  | 2                                      | 6.04                       | 1                                          | 2                                        | 2   | B,I,LL<br>E,M       | 117900                    | 3281.7 | 31.11                                             |
| 4       | .0253                    | .1027                  | 2                                      | 6.40                       | 2                                          | 1                                        | 1   | UU,V,XX<br>YY,MM,VV | 122462                    | 5113.0 | 27.50                                             |
| 5       | .0405                    | .1550                  | 2                                      | 5.70                       | 2                                          | 1                                        | 2   | FF,DD<br>EE,HH      | 124265                    | 789.6  | 44.16                                             |
| 6       | .0405                    | .1550                  | 2                                      | 6.04                       | 1                                          | 2                                        | 1   | R,K<br>P,T          | 120182                    | 5102.5 | 27.44                                             |
| 7       | .0405                    | .1917                  | 1                                      | 5.97                       | 2                                          | 2                                        | 1   | O,Q,TT<br>RR,MM,GG  | 120102                    | 4461.1 | 20.61                                             |
| 8       | .0405                    | .1917                  | 1                                      | 6.24                       | 1                                          | 1                                        | 2   | M,N,NN<br>R,L,F     | 116760                    | 1396.6 | 38.44                                             |

FIGURE A5. YIELD STRENGTH - L<sub>8</sub> ORTHOGONAL ARRAY FOR CARBON, IRON, AND ALUMINUM

the magnitude of the standard deviation of the response data (noise). For a nominal is best characteristic, the signal-to-noise ratio is defined generically as:

$$S/N = 10 \log_{10} ((\text{True Average})^2 / (\text{True Standard Deviation})^2).$$

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

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

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

TABLE A1 CONTRIBUTION OF ALLOYING ELEMENTS TO MECHANICAL PROPERTY VARIABILITY

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

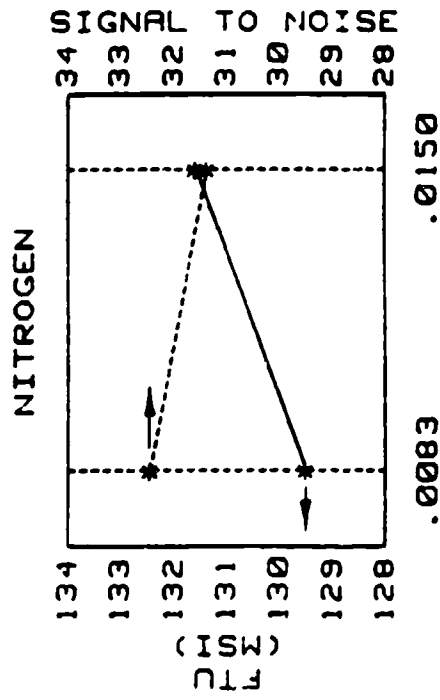
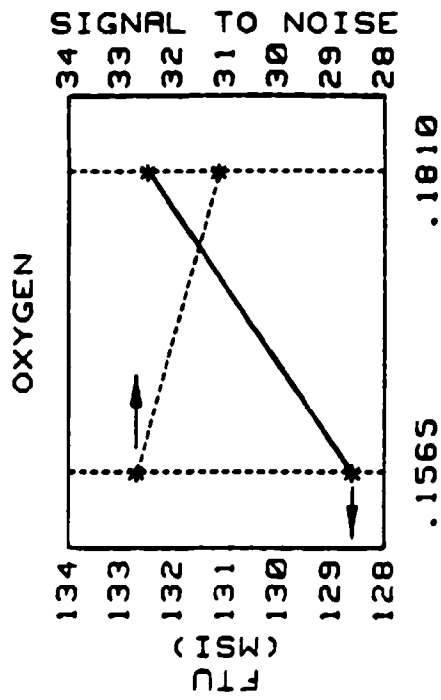
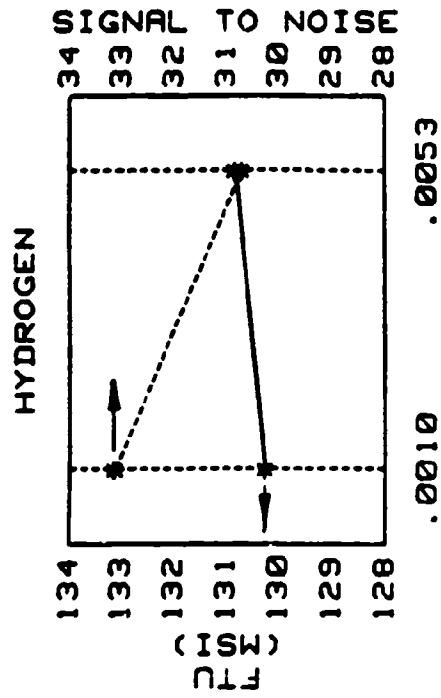


FIGURE A6. TENSILE STRENGTH - MAIN EFFECTS FOR OXYGEN, HYDROGEN, AND NITROGEN

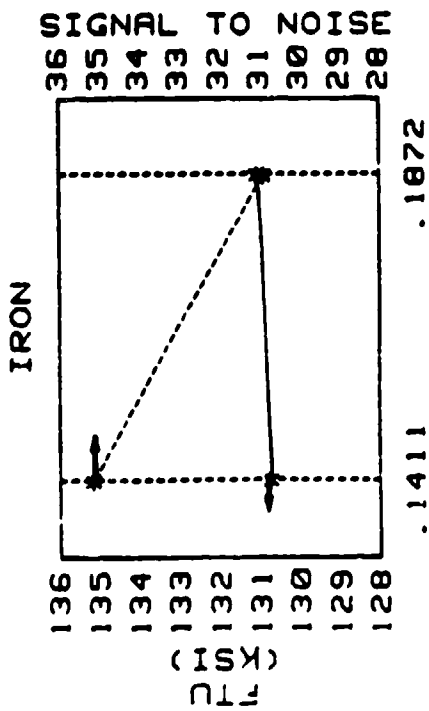
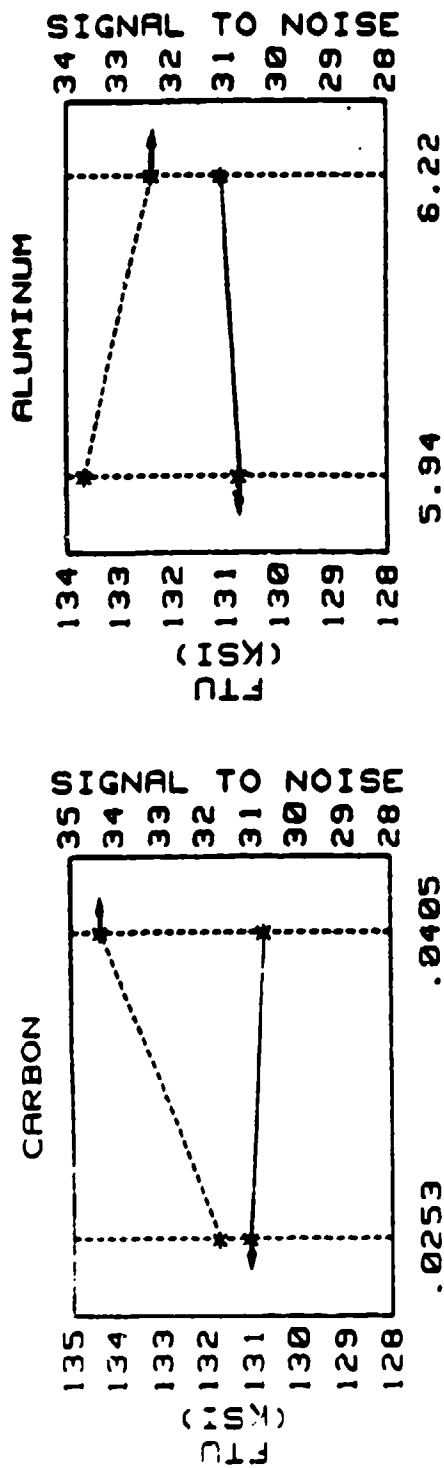


FIGURE A7. TENSILE STRENGTH - MAIN EFFECTS FOR CARBON, IRON, AND ALUMINUM

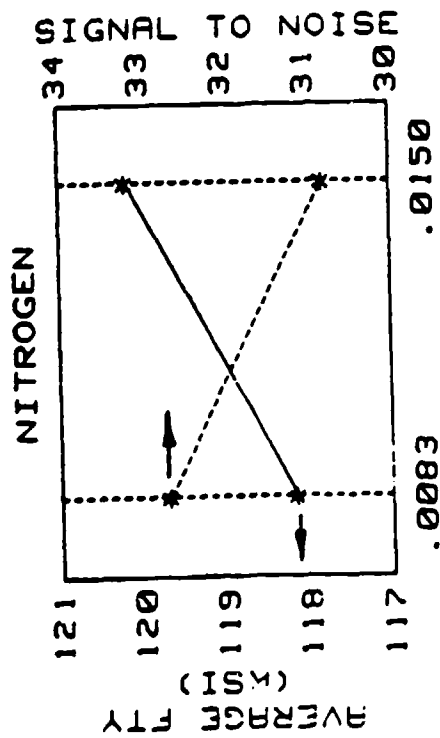
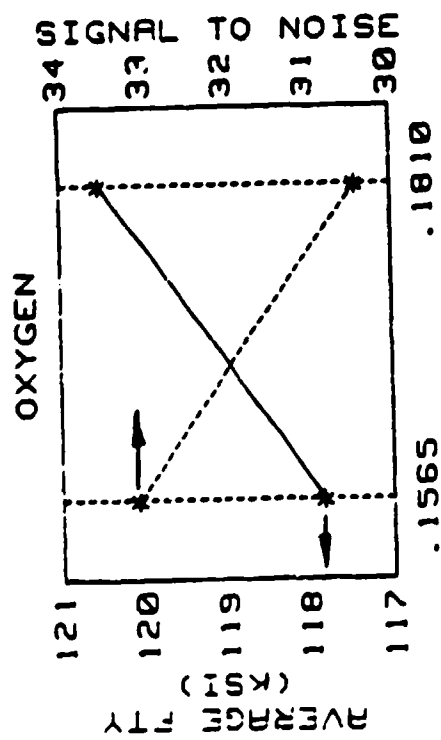
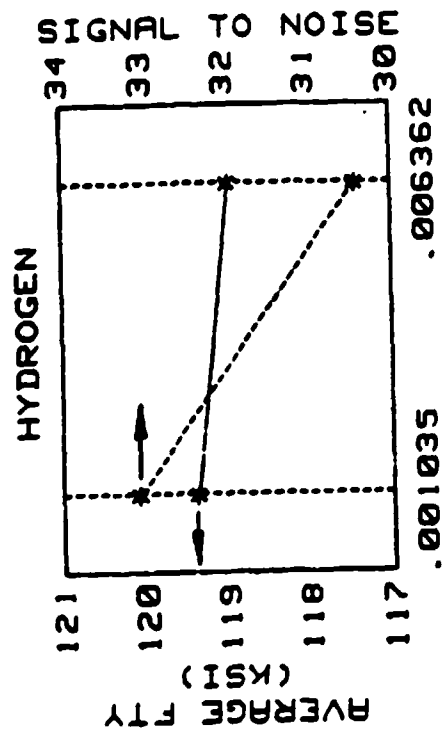


FIGURE A8. YIELD STRENGTH - MAIN EFFECTS FOR OXYGEN, HYDROGEN, AND NITROGEN

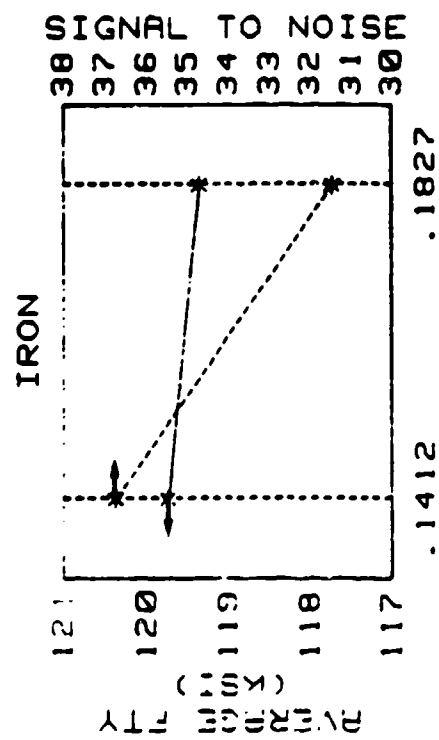
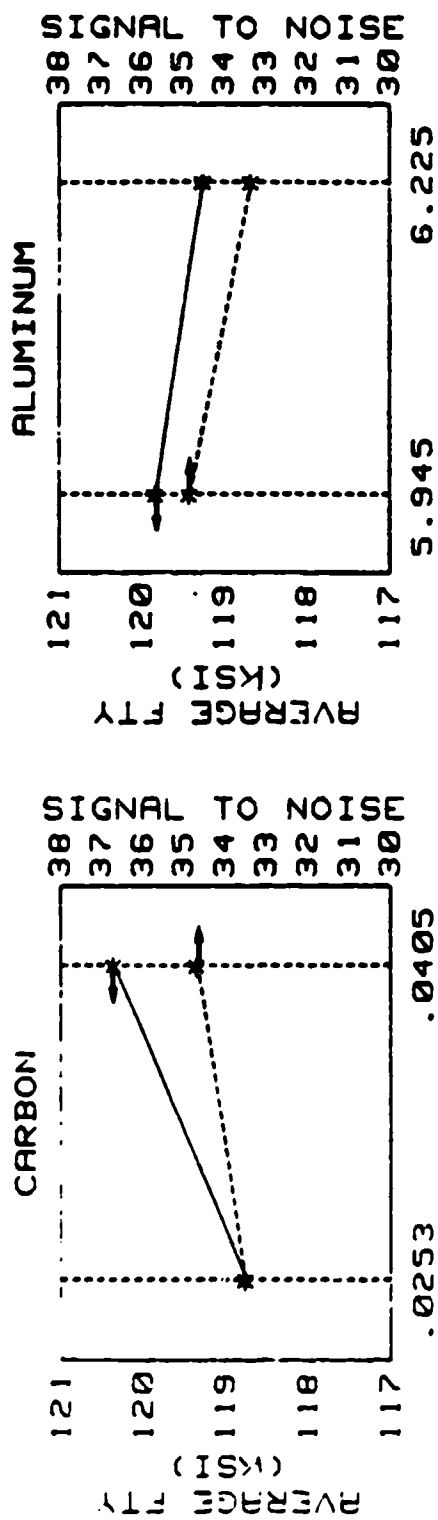


FIGURE A9. YIELD STRENGTH - MAIN EFFECTS FOR CARBON, IRON, AND ALUMINUM

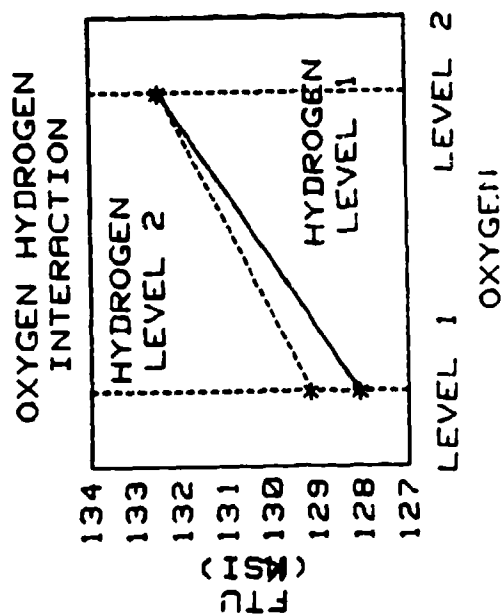
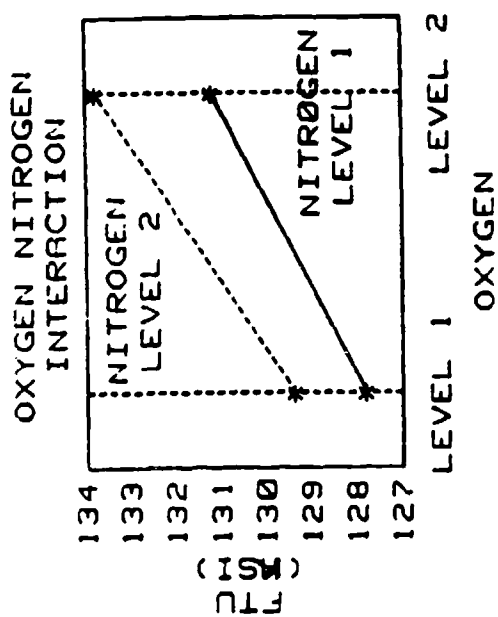
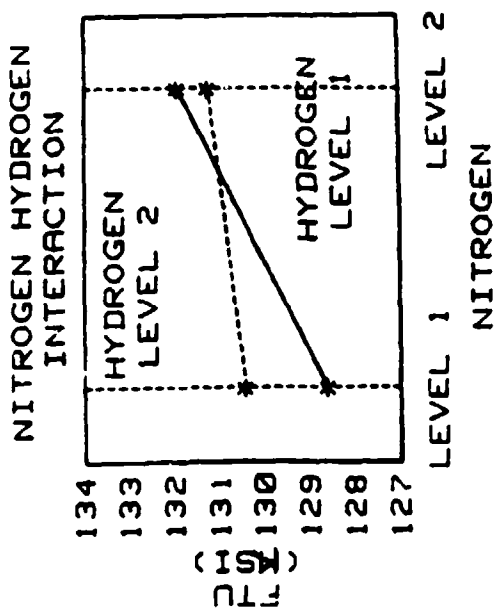


FIGURE A10. TENSILE STRENGTH - INTERACTIONS FOR OXYGEN, HYDROGEN, AND NITROGEN

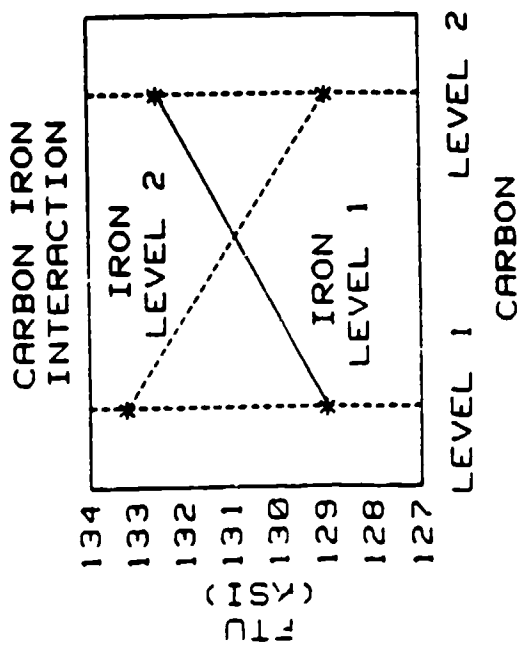
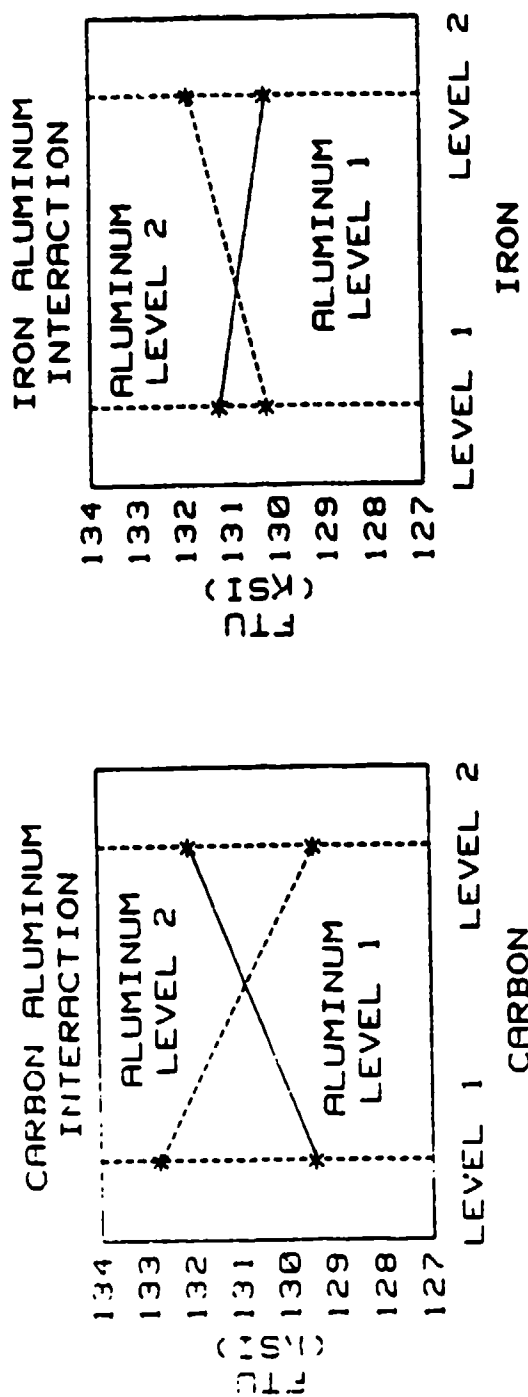


FIGURE A11. TENSILE STRENGTH - INTERACTIONS FOR CARBON, IRON, AND ALUMINUM

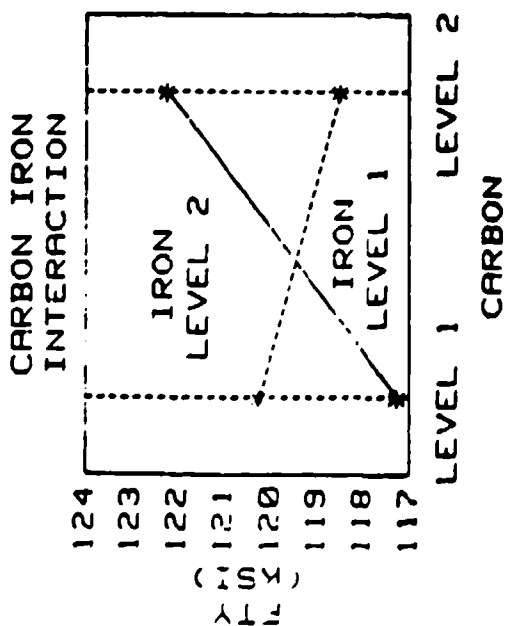
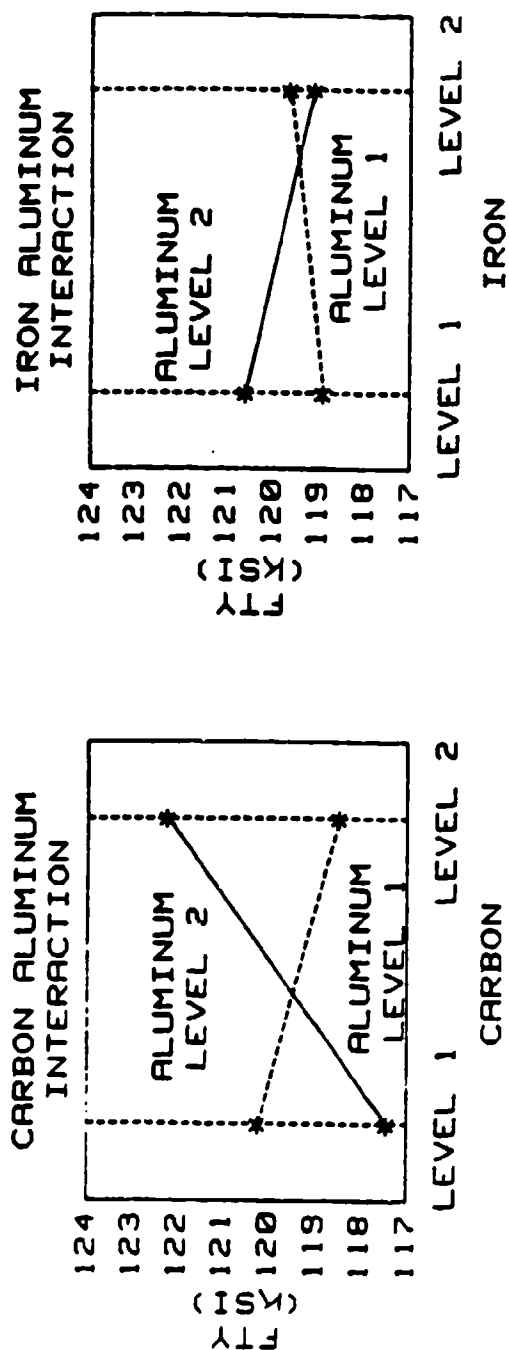


FIGURE A12. YIELD STRENGTH - INTERACTIONS FOR CARBON, IRON, AND ALUMINUM

## A.2 POST-CASTING TREATMENT

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

## A.3 BIBLIOGRAPHY

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

A B C D E F G H I J K L M

FIGURE A13. PROCESS AND POST-CASTING TREATMENT DATA

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

FIGURE A14. TENSILE STRENGTH - L<sub>4</sub> ARRAY FOR PROCESS AND POST-CASTING TREATMENT

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

FIGURE A15. YIELD STRENGTH - L<sub>4</sub> ARRAY FOR PROCESS AND POST-CASTING TREATMENT

**APPENDIX B**

**PREPRODUCTION PART ANALYSIS**

## **APPENDIX B**

### **PREPRODUCTION PART ANALYSIS**

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

# MECHANICAL PROPERTY DATA

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

## INSPECTION DATA

| SAMPLE   | PBGS  | GBA(E-4) | AC(E-3) | APS(E-4) | PBGS - PRIOR BETA GRAIN SIZE |
|----------|-------|----------|---------|----------|------------------------------|
| 5B-021   | 0.043 | 3.125    | 2.73    | 1.79     | GBA - GRAIN BOUNDARY ALPHA   |
| 5B-022   | 0.033 | 1.820    | 2.14    | 1.32     | AC - ALPHA COLONY            |
| 5B-023   | 0.047 | 3.125    | 3.36    | 1.14     | APS - ALPHA PLATELET SPACING |
| 5B-024   | 0.052 | 3.125    | 2.92    | 1.47     |                              |
| 5B-025   | 0.037 | 3.125    | 7.08    | 1.56     |                              |
| 5B-026   | 0.032 | 3.125    | 5.63    | 1.67     |                              |
| 5B-027   | 0.041 | 3.125    | 8.13    | 1.92     |                              |
| 5B-028   | 0.045 | 4.960    | 5.31    | 1.78     |                              |
| 5B-029   | 0.050 | 3.125    | 10.00   | 2.50     |                              |
| 5B-0210  | 0.040 | 3.020    | 7.08    | 2.08     |                              |
| 5B-0211  | 0.041 | 4.780    | 9.18    | 2.27     |                              |
| 5B-0212  | 0.045 | 6.250    | 4.06    | 2.08     |                              |
| 4G-001   | 0.038 | 2.600    | 2.71    | 2.50     |                              |
| 4G-012   | 0.048 | 3.520    | 2.38    | 1.47     |                              |
| 4G-013   | 0.055 | 2.080    | 3.44    | 1.47     |                              |
| 4G-015   | 0.043 | 2.340    | 2.75    | 1.56     |                              |
| SPA1     | 0.030 | 3.125    | 5.10    | 1.09     |                              |
| SPA2     | 0.044 | 2.813    | 2.50    | 1.32     |                              |
| SPA3     | 0.034 | 3.440    | 6.25    | 1.09     |                              |
| SPA4     | 0.055 | 3.125    | 2.50    | 1.19     |                              |
| SPA5     | 0.040 | 3.125    | 3.75    | 1.00     |                              |
| SPA6     | 0.040 | 3.281    | 3.75    | 2.08     |                              |
| SPA7     | 0.048 | -        | 2.50    | 1.56     |                              |
| SPA8     | 0.057 | 3.910    | 3.75    | 2.08     |                              |
| SPA9     | 0.040 | 3.125    | 7.50    | 1.67     |                              |
| SPA10    | 0.043 | 3.125    | 5.00    | 3.57     |                              |
| SPA11    | 0.057 | 3.125    | 6.88    | 2.02     |                              |
| SPA12    | 0.028 | 3.910    | 7.80    | 1.92     |                              |
| 4A-001   | 0.040 | 3.125    | 3.68    | 1.56     |                              |
| 4A-012   | 0.053 | 3.125    | 4.06    | 1.32     |                              |
| 4A-013   | 0.046 | 1.950    | 4.16    | 1.38     |                              |
| 4A-014   | 0.050 | 2.500    | 4.00    | 1.25     |                              |
| 4A-015   | 0.042 | 3.125    | 7.08    | 1.32     |                              |
| ADATA    | PBGS  | GBA      | AC      | APS      |                              |
| MEAN     | 0.044 | 3.121    | 4.72    | 1.62     |                              |
| STD DEV  | 0.009 | 0.464    | 1.77    | 0.62     |                              |
| N        | 17    | 16       | 17      | 17       |                              |
| BDATA    |       |          |         |          |                              |
| MEAN     | 0.043 | 3.328    | 4.93    | 1.79     |                              |
| STD DEV  | 0.006 | 1.127    | 2.61    | 0.41     |                              |
| N        | 16    | 16       | 16      | 16       |                              |
| ALL DATA |       |          |         |          |                              |
| MEAN     | 0.044 | 3.227    | 4.89    | 1.70     |                              |
| STD DEV  | 0.008 | 0.855    | 2.18    | 0.53     |                              |
| N        | 33    | 32       | 33      | 33       |                              |

**APPENDIX C**

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

## **APPENDIX C**

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

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

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

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

**1. SCOPE:**

**1.1 Form:**

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

**1.2 Application:**

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

**2. APPLICABLE DOCUMENTS:**

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

**2.1 SAE Publications:**

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

**AMS 2249    Chemical Check Analysis Limits, Titanium and  
                  Titanium Alloys**

**AMS 2360    Room Temperature Tensile Properties of Castings**

**AMS 2804    Identification, Castings**

**AMS 2750    Pyrometry**

**2.2 ASTM Publications:**

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

**ASTM E 8        Tension Testing of Metallic Materials**

**ASTM E 120     Chemical Analysis of Titanium and Titanium Alloys**

**ASTM E 1320    Standard Reference Radiographs for Titanium  
                  Castings**

**2.3 Government Publications:**

MIL-H-81200 Heat Treatment of Titanium and Titanium Alloys  
MIL-STD-453 Inspection, Radiographic  
MIL-STD-2073-1 DoD Material Procedures for Development and  
Application of Packaging Requirements  
MIL-STD-6866 Inspection, Liquid Penetrant  
MIL-STD-2175 Castings, Classification and Inspection of

### 3. TECHNICAL REQUIREMENTS:

#### 3.1 Composition:

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

Table 1 - Composition

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

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

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

#### 3.2 Melt Practice:

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

- 3.2.1 Alloy shall be multiple melted; the final melting cycle shall be under vacuum. The first melt shall be made by consumable electrode, nonconsumable electrode, electron beam, or plasma arc melting practice. The subsequent melt or melts shall be made using consumable electrode practice with no alloy additions permitted in the last consumable electrode melt.**
- 3.2.2 The metal for castings and specimens shall be melted and poured under vacuum without loss of vacuum between melting and pouring.**
- 3.2.3 Portions of two or more qualified master heats (see 3.4.1) may be melted together and poured into castings using a procedure authorized by purchaser. The two or more qualified master heats, when melted together and poured, shall be requalified and shall have a different master heat number.**
- 3.2.4 Vendor shall have a written procedure acceptable to purchaser which defines the controls, tests, and traceability criteria for castings. Control factors of 4.4.2.2 shall apply. The written procedure shall be only one used for the purchaser for a designated part once it is established and approved. Changes to the written procedure shall be made only when permitted by the purchaser.**
- 3.3 Condition:**
- Hot isostatically pressed**
- 3.4 Test Specimens:**
- Specimens shall be machined from castings.**
- 3.4.1 Each master heat shall be qualified by evaluation of chemical and tensile property specimens unless otherwise specified (see 8.2.4) by purchaser.**
- 3.4.2 Chemical Analysis Specimens: Shall be of any convenient size and shape.**
- 3.4.3 Tensile Specimens: Shall be of standard proportions in accordance with ASTM publications referenced in 3.6.**
- 3.5 Heat Treatment:**
- Castings and representative tensile specimens shall be hot isostatically pressed in accordance with 3.5.1, and heat treated as specified in 3.5.2. Pyrometry shall be in accordance with AMS 2750.**

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

3.5.2 Anneal: Heat to  $1550^\circ\text{F} \pm 25^\circ\text{F}$  ( $843^\circ\text{C} \pm 14^\circ\text{C}$ ) for 2 hours in a vacuum.

3.6 Properties:

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

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

TABLE 2 - Minimum Tensile Properties, Specimens Machined from Casting

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

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

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

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

3.8.1.2 Castings shall not be exposed to chlorinated solvents.

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

- 3.8.2 Acceptance standards for radiographic, fluorescent penetrant, visual, and other inspection methods shall be as agreed upon by purchaser and vendor.**
- 3.8.2.1 Unless otherwise specified, MIL-STD-2175 may be used to specify frequency of inspection (casting class).**
- 3.8.2.2 Unless otherwise specified, ASTM E 1320 may be used to specify radiographic standards (casting grade).**
- 3.8.2.3 When acceptance standards are not specified, grade C of MIL-STD-2175 shall apply. In designated areas, Grade B is required.**
- 3.8.3 Castings shall be produced under radiographic control. This control shall consist of radiographic examination of each casting part number until foundry manufacturing controls in accordance with 4.4.2 have been established. Additional radiography shall be conducted in accordance with the frequency of inspection specified by purchaser, or as necessary to ensure continued maintenance of internal quality.**
- 3.8.3.1 Unless otherwise specified, radiographic inspection shall be conducted in accordance with MIL-STD-453 or other process method specified by purchaser.**
- 3.8.4 Fluorescent penetrant inspection in accordance with MIL-STD-6866 or other process method specified by purchaser.**
- 3.8.5 Castings shall not be peened, plugged, impregnated, or welded unless authorized by purchaser.**
- 3.8.5.1 Purchaser shall define critical or no weld zones.**
- 3.8.5.2 If in-process welding of castings that have been hot isostatically pressed is authorized by purchaser, castings shall be annealed in accordance with 4.6.3 after welding.**

#### **4.0 QUALITY ASSURANCE PROVISIONS:**

##### **4.1 Responsibility for Inspection:**

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

##### **4.2 Classification of Tests:**

- 4.2.1 Except as specified in 4.2.2, tests for composition (3.1), tensile properties (3.6.1), surface contamination (3.7), and quality requirements (3.8) are acceptance tests and shall be performed as specified in 4.3.**
- 4.2.2 Periodic Tests: Tests for radiographic soundness (3.8.3) are periodic tests and shall be performed at a frequency selected by vendor unless a frequency of testing is specified by purchaser.**
- 4.2.3 Pre-production Tests: Tests for conformance to all technical requirements of this specification are pre-production tests and shall be performed on the first-article control casting (4.3.2), when change in control factors (4.4.2.2) occurs, or when purchaser deems confirmatory testing to be required.**

#### **4.3 Sampling and Testing**

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

- 4.3.1 One chemical analysis specimen or a casting from each master heat shall be tested for conformance with Table 1. Hydrogen, nitrogen, and oxygen determinations shall be obtained on a lot basis after all thermal and chemical processing are completed.**
- 4.3.2 One pre-production casting, in accordance with 4.4 shall be tested to the requirements of the casting drawing and to all technical requirements of this specification.**
  - 4.3.2.1 First article dimensional inspection sample quantity shall be as specified by purchaser.**
- 4.3.3 Tensile tests shall be conducted to determine conformance with 3.6.1. Sampling and test frequency is dependent upon the type and origin of specimens specified by purchaser.**
  - 4.3.3.1 At least one casting of the lowest radiographic quality shall be selected from each lot (see 8.2.6) and tested after hot isostatic pressing and annealing at each location shown on the engineering drawing for conformance with 3.6.1.**
    - 4.3.3.1.1 When size and location of specimens are not shown, at least three test specimens shall be tested, including one from the thickest section and one from the thinnest section. Once established under 4.4.2.2, test locations may be changed only as agreed upon by purchaser and vendor.**

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

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

#### 4.4 Approval:

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

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

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

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

TABLE 3 - Control Factors

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

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

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

#### **4.5 Reports:**

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

#### **4.6 Resampling and Retesting:**

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

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

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

### **6. PREPARATION FOR DELIVERY:**

#### **6.1 Identification:**

Individual castings shall be identified in accordance with AMS 2804.

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

#### **6.2 Packaging:**

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

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

**6. ACKNOWLEDGEMENT:**

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

**7. REJECTIONS:**

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

**8. NOTES:**

**8.1 Marginal Indicia:**

New issue. Not used.

**8.2 Definitions:**

- 8.2.1 "Acceptable to purchaser": Does not require prior written approval from purchaser, but allows vendor to make a decision and purchaser the right to disapprove the decision.
- 8.2.2 "Purchaser": The cognizant engineering organization responsible for casting design and fitness for use, or the designee of this engineering organization.
- 8.2.3 "Authorized by purchaser": Requires prior written approval from the purchaser.
- 8.2.4 "Specified": Requires documented instruction from purchaser through casting drawing, purchase order, specification, or other engineering documentation.
- 8.2.5 "Agreed upon by purchaser and vendor": Requires concurrence of both purchaser and vendor. Such concurrence is typically documented by way of the casting drawing, purchase order, or other engineering documentation.

- 8.2.6 "Lot": For hydrogen testing, and for room temperature tensile testing, a lot shall consist of all castings of the same part number, poured from a single master heat in one or more consecutive melts (see 8.2.7) through a single furnace campaign of not longer than twelve hours and processed through each hot isostatic pressing and anneal in the same furnace loads. For visual and nondestructive testing, a lot shall consist of castings of the same part number, manufactured under the same process control parameters of 4.4.2.2.
- 8.2.7 "Melt": All castings poured from a single furnace charge. Also referred to as remelt, submelt, heat, or subheat.
- 8.3 Dimensions and properties in inch/pound units and the Fahrenheit temperatures are primary; dimensions and properties in SI units, and the Celsius temperatures are shown as the approximate equivalents of the primary units and are presented only for information.
- 8.4 Purchase documents, including those for direct U.S. Military procurement, should specify not less than the following:
- Title, number, and date of this specification
  - Part number or pattern number of castings desired
  - Quantity of castings desired
  - Size and location of specimens for room temperature, elevated temperature tensile and creep rupture testing are specified (see 3.4.4.2 and 3.6)
  - Inspection methods and acceptance standards (see 3.8.2)
  - Level A packaging, if required (see 5.2.1)

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

**PREPARED UNDER THE JURISDICTION OF AMS COMMITTEE G.**

**APPENDIX D**

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

## **APPENDIX D**

### **CAST TI-6AL-4V PRODUCTION FIN ANALYSIS**

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

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

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

| SAMPLE     | FTU   | FTY   | MODUL US | ELONGATION | PBGS  | GBA(E-4) | AC(E-3) | APS(E-4) | PBGS - PRIOR BETA GRAIN SIZE<br>GBA - GRAIN BOUNDARY ALPHA<br>AC - ALPHA COLONY<br>APS - ALPHA PLATELET SPACING |
|------------|-------|-------|----------|------------|-------|----------|---------|----------|-----------------------------------------------------------------------------------------------------------------|
| SUPPLIER 2 |       |       |          |            |       |          |         |          |                                                                                                                 |
| 4A-001     | 133.5 | 127.7 | 17.5     | 9.2        | 0.040 | 3.125    | 3.68    | 1.56     |                                                                                                                 |
| 4A-012     | 134.1 | 129.2 | 17.3     | 8.4        | 0.053 | 3.125    | 4.06    | 1.32     |                                                                                                                 |
| 4A-013     | 133.8 | 128.6 | 17.3     | 8.9        | 0.046 | 1.950    | 4.16    | 1.38     |                                                                                                                 |
| 4A-014     | 134.1 |       |          |            | 0.050 | 2.500    | 4.00    | 1.25     |                                                                                                                 |
| 4A-015     | 132.2 | 127.4 | 17.3     | 8.1        | 0.042 | 3.125    | 7.08    | 1.32     |                                                                                                                 |
| 4A-021     | 135.8 | 130.1 | 17.2     | 9.0        | 0.039 | 3.125    | 3.75    | 1.47     |                                                                                                                 |
| 4A-022     | 133.2 | 127.2 | 16.8     | 9.3        | 0.047 | 1.560    | 3.31    | 1.00     |                                                                                                                 |
| 4A-023     | 132.1 | 126.5 | 17.9     | 9.9        | 0.030 | 4.170    | 1.88    | 1.78     |                                                                                                                 |
| 4A-024     | 132.7 | 127.3 | 17.1     | 8.9        | 0.027 | 3.125    | 2.27    | 1.47     |                                                                                                                 |
| 4A-025     | 131.5 | 125.8 | 16.5     | 9.3        | 0.027 | 3.125    | 3.64    | 1.25     |                                                                                                                 |
| 4G-001     | 128.7 | 123.4 | 16.9     | 11.2       | 0.038 | 2.600    | 2.71    | 2.50     |                                                                                                                 |
| 4G-012     | 130.1 | 124.0 | 16.8     | 9.3        | 0.048 | 3.520    | 2.38    | 1.47     |                                                                                                                 |
| 4G-013     | 129.9 | 123.6 | 16.7     | 8.0        | 0.055 | 2.080    | 3.44    | 1.47     |                                                                                                                 |
| 4G-015     | 130.1 | 125.1 | 16.8     | 8.6        | 0.043 | 2.340    | 2.75    | 1.58     |                                                                                                                 |
| 4G-021     | 128.9 | 123.0 | 16.7     | 10.6       | 0.052 | 3.125    | 2.81    | 1.38     |                                                                                                                 |
| 4G-022     | 129.3 | 124.1 | 16.4     | 11.1       | 0.040 | 2.340    | 2.58    | 1.78     |                                                                                                                 |
| 4G-023     | 129.6 | 124.1 | 16.6     | 8.7        | 0.044 | 3.125    | 7.50    | 1.47     |                                                                                                                 |
| 4G-024     | 128.1 | 123.2 | 16.8     | 11.3       | 0.045 | 2.030    | 2.50    | 1.58     |                                                                                                                 |
| 4G-025     | 129.3 | 124.3 | 17.3     | 9.7        | 0.080 | 3.125    | 6.58    | 1.67     |                                                                                                                 |
| 4H-021     | 129.5 | 123.9 | 16.7     | 11.8       | 0.037 | 2.340    | 2.92    | 1.38     |                                                                                                                 |
| 4H-022     | 129.2 | 123.6 | 16.9     | 9.0        | 0.055 | 1.580    | 2.18    | 1.25     |                                                                                                                 |
| 4H-023     | 127.8 | 122.5 | 16.6     | 10.8       | 0.057 | 3.125    | 3.43    | 1.04     |                                                                                                                 |
| 4H-024     | 128.1 | 122.5 | 16.7     | 11.3       | 0.052 | 3.480    | 2.03    | 1.09     |                                                                                                                 |
| 4H-025     | 127.8 | 123.6 | 17.1     | 5.8        | 0.038 | 3.580    | 4.38    | 1.14     |                                                                                                                 |
| 4H-021     | 132.8 | 126.9 | 16.8     | 8.7        | 0.033 | 2.180    | 3.75    | 2.08     |                                                                                                                 |
| 4H-022     | 133.1 | 127.1 | 17.4     | 11.1       | 0.037 | 3.750    | 4.27    | 1.39     |                                                                                                                 |
| 4H-023     | 132.1 | 126.0 | 17.2     | 9.5        | 0.034 | 1.880    | 3.25    | 1.25     |                                                                                                                 |
| 4H-024     | 132.5 | 126.6 | 17.1     | 9.5        | 0.042 | 2.400    | 3.44    | 1.09     |                                                                                                                 |
| 4H-025     | 132.9 | 127.1 | 17.0     | 11.5       | 0.037 | 3.125    | 3.75    | 1.78     |                                                                                                                 |
| 4P-011     | 132.5 | 126.3 | 17.1     | 12.7       | 0.035 | 3.125    | 2.97    | 1.47     |                                                                                                                 |
| 4P-012     | 132.2 | 126.4 | 16.9     | 11.1       | 0.040 | 3.125    | 3.91    | 1.14     |                                                                                                                 |

| SAMPLE  | FTU   | FTY   | MODULUS | ELONGATION | PBGS  | GBA(E-4) | AC(E-3) | APS(E-4) |
|---------|-------|-------|---------|------------|-------|----------|---------|----------|
| AP-013  | 132.4 | 126.7 | 17.2    | 9.6        | 0.034 | 3.125    | 2.81    | 1.14     |
| AP-014  | 132.1 | 126.6 | 16.7    | 10.6       | 0.037 | 3.125    | 3.96    | 1.39     |
| AP-015  | 132.4 | 126.6 | 17.0    | 6.9        | 0.043 | 4.680    | 3.28    | 1.32     |
| AP-021  | 134.6 | 127.6 | 17.3    | 9.3        | 0.043 | 2.140    | 3.59    | 1.56     |
| AP-022  | 133.0 | 126.8 | 17.2    | 8.8        | 0.034 | 3.125    | 4.37    | 1.25     |
| AP-023  | 132.4 | 126.8 | 17.1    | 8.8        | 0.033 | 3.125    | 3.43    | 1.25     |
| AP-024  | 132.6 | 126.2 | 17.1    | 9.7        | 0.030 | 2.730    | 3.59    | 2.27     |
| AP-025  | 133.3 | 127.9 | 17.2    | 10.1       | 0.033 | 3.125    | 2.66    | 0.96     |
| AT-011  | 131.4 | 125.8 | 17.3    | 11.4       | N/A   | N/A      | N/A     | N/A      |
| AT-012  | 131.6 | 125.5 | 17.1    | 11.9       | N/A   | N/A      | N/A     | N/A      |
| AT-013  | 131.0 | 124.7 | 17.3    | 10.5       | N/A   | N/A      | N/A     | N/A      |
| AT-014  | 131.1 | 125.9 | 17.1    | 11.3       | N/A   | N/A      | N/A     | N/A      |
| AT-015  | 130.4 | 124.4 | 17.2    | 11.5       | N/A   | N/A      | N/A     | N/A      |
| AT-021  | 131.7 | 125.9 | 17.4    | 10.4       | 0.023 | 2.340    | 5.72    | 1.25     |
| AT-022  | 132.4 | 126.5 | 17.3    | 10.5       | 0.034 | 3.125    | 6.46    | 1.39     |
| AT-023  | 131.8 | 126.1 | 17.2    | 9.0        | 0.026 | 1.560    | 5.47    | 1.47     |
| AT-024  | 131.9 | 125.8 | 16.9    | 8.5        | 0.035 | 3.125    | 7.34    | 1.66     |
| AT-025  | 130.9 | 125.1 | 17.1    | 10.0       | 0.030 | 1.560    | 4.17    | 1.67     |
| AAA-011 | 130.4 | 124.7 | 17.2    | 9.3        | 0.049 | 2.340    | 2.81    | 1.47     |
| AAA-012 | 129.1 | 125.0 | 17.2    | 8.4        | 0.033 | 3.125    | 2.58    | 1.14     |
| AAA-013 | 129.2 | 124.2 | 17.4    | 9.3        | 0.037 | 2.600    | 2.75    | 1.04     |
| AAA-014 | 130.4 | 123.4 | 17.1    | 9.7        | 0.060 | 1.870    | 3.85    | 1.39     |
| AAA-021 | 130.8 | 125.2 | 17.2    | 9.4        | 0.046 | 1.560    | 2.97    | 1.19     |
| AAA-022 | 131.1 | 124.8 | 17.0    | 10.4       | 0.045 | 2.600    | 2.73    | 1.47     |
| AAA-023 | 131.9 | 126.1 | 17.5    | 12.2       | 0.035 | 4.690    | 4.63    | 1.79     |
| AAA-024 | 131.2 | 125.9 | 17.2    | 10.7       | 0.040 | 4.170    | 4.38    | 1.39     |
| AAA-025 | 129.7 | 124.3 | 17.1    | 10.8       | 0.030 | 3.125    | 8.54    | 1.19     |
| AAC-011 | 131.6 | 125.3 | 16.5    | 10.6       | 0.035 | 1.880    | 4.37    | 1.56     |
| AAC-012 | 130.3 | 124.3 | 17.0    | 11.3       | 0.038 | 2.730    | 4.06    | 1.56     |
| AAC-013 | 130.4 | 124.7 | 17.4    | 11.9       | 0.055 | 2.920    | 8.75    | 2.08     |
| AAC-014 | 129.3 | 123.8 | 16.8    | 7.1        | 0.046 | 2.560    | 4.75    | 1.47     |
| AAC-015 | 130.0 | 124.5 | 17.3    | 9.9        | 0.043 | 2.600    | 4.06    | 1.25     |

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

| SAMPLE | FTU   | FTY   | MODULUS | ELONGATION | PBGS  | GBA(E-4) | AC(E-3) | APS(E-4) |
|--------|-------|-------|---------|------------|-------|----------|---------|----------|
| A4     | 127.8 | 121.5 | 16.6    | 10.1       | 0.035 | 3.125    | 7.00    | 1.92     |
| A5     | 127.7 | 121.5 | 16.3    | 9.7        | 0.045 | 3.125    | 8.13    | 1.14     |
| B1     | 129.1 | 122.6 | 16.6    | 9.8        | 0.050 | 2.730    | 4.68    | 1.47     |
| B2     | 128.1 | 122.2 | 16.6    | 10.9       | 0.040 | 5.470    | 4.29    | 1.39     |
| B3     | 127.8 | 121.5 | 16.6    | 10.4       | 0.055 | 2.730    | 4.38    | 2.50     |
| B4     | 127.5 | 120.7 | 16.4    | 9.2        | 0.045 | 4.060    | 4.29    | 1.39     |
| B5     | 127.4 | 121.6 | 16.6    | 9.4        | 0.050 | .        | 3.91    | 1.47     |

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

ALL FTU DATA  
SUPPLIERS 1, 2, AND 3

Sample Size = 125      Error Return Code IER = 0

ALLOWABLES

3p-Weibull Allowables

A = 125.112      B = 127.834

Normal Allowables

A = 125.593      B = 127.965

Nonparametric Allowables

A = \*\*\*\*\*      B = 127.800

Weibull Parameter Estimates (3p-Weibull)

Threshold = 125.595      Scale = 6.144      Shape = 2.832

Normal estimates of 1- and 10-percentiles

x(.01) = 126.247      x(.10) = 128.413

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

x(.01) = 126.806      x(.10) = 128.371

Other Sample Statistics

Mean = 131.070      Stand. Deviation = 2.073

Skewness = .481      Kurtosis = .782

Coeff. of Variation = .016

Test for Normality

AD = .627      P-value = .105518      IEX = 0

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

Test for the 3p-Weibull Distribution

AD = .637      P-value = .093499      IEX = 0

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

The 13 smallest data values are

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

The 13 largest data values are

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

# PTU

## SUPPLIERS 2 AND 3

Sample Size = 115      Error Return Code IER = 0

### ALLOWABLES

#### 3p-Weibull Allowables

A = 124.970      B = 128.113

#### Normal Allowables

A = 126.175      B = 128.466

#### Nonparametric Allowables

A = \*\*\*\*\*      B = 128.200

#### Weibull Parameter Estimates (3p-Weibull)

Threshold = 125.686      Scale = 6.305      Shape = 3.075

#### Normal estimates of 1- and 10-percentiles

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

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

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

#### Other Sample Statistics

Mean = 131.335      Stand. Deviation = 1.942

Skewness = .590      Kurtosis = 1.297

Coeff. of Variation = .015

#### Test for Normality

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

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

#### Test for the 3p-Weibull Distribution

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

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

#### The 12 smallest data values are

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

#### The 12 largest data values are

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

**PTU****SUPPLIER 2**

Sample Size = 108      Error Return Code IER = 0

**ALLOWABLES****3p-Weibull Allowables**

A = 126.190      B = 128.522

**Normal Allowables**

A = 126.621      B = 128.570

**Nonparametric Allowables**

A = \*\*\*\*\*      B = 128.200

**Weibull Parameter Estimates (3p-Weibull)**

Threshold = 126.075      Scale = 5.639      Shape = 3.346

**Normal estimates of 1- and 10-percentiles**

x(.01) = 127.201      x(.10) = 128.968

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

x(.01) = 127.501      x(.10) = 128.953

**Other Sample Statistics**

Mean = 131.137      Stand. Deviation = 1.692

Skewness = -.065      Kurtosis = -.386

Coeff. of Variation = .013

**Test for Normality**

AD = .570      P-value = .139710      IEX = 0

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

**Test for the 3p-Weibull Distribution**

AD = .513      P-value = .192532      IEX = 0

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

**The 12 smallest data values are**

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

**The 12 largest data values are**

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

ALL FTY DATA  
SUPPLIERS 1, 2, AND 3

Sample Size = 124      Error Return Code IER = 0

ALLOWABLES

3p-Weibull Allowables

A = 116.963      B = 121.720

Normal Allowables

A = 120.079      B = 122.277

Nonparametric Allowables

A = \*\*\*\*\*      B = 121.600

Weibull Parameter Estimates (3p-Weibull)

Threshold = 111.922      Scale = 14.039      Shape = 7.950

Normal estimates of 1- and 10-percentiles

x(.01) = 120.688      x(.10) = 122.695

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

x(.01) = 119.793      x(.10) = 122.500

Other Sample Statistics

Mean = 125.156      Stand. Deviation = 1.921

Skewness = -.431      Kurtosis = .396

Coeff. of Variation = .015

Test for Normality

AD = .729      P-value = .060571      IEX = 0

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

Test for the 3p-Weibull Distribution

AD = .377      P-value = .379999      IEX = 1

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

The 13 smallest data values are

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

The 13 largest data values are

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

**FTY**  
**SUPPLIERS 2 AND 3**

Sample Size = 114      Error Return Code IER = 0

**ALLOWABLES**

**3p-Weibull Allowables**

A = 119.932      B = 122.662

**Normal Allowables**

A = 120.925      B = 122.880

**Nonparametric Allowables**

A = \*\*\*\*\*      B = 122.500

**Weibull Parameter Estimates (3p-Weibull)**

Threshold = 118.020      Scale = 8.069      Shape = 4.903

**Normal estimates of 1- and 10-percentiles**

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

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

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

**Other Sample Statistics**

Mean = 125.452      Stand. Deviation = 1.703

Skewness = -.462      Kurtosis = 1.550

Coeff. of Variation = .014

**Test for Normality**

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

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

**Test for the 3p-Weibull Distribution**

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

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

**The 12 smallest data values are**

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

**The 12 largest data values are**

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

**FTY**  
**SUPPLIER 2**

Sample Size = 107      Error Return Code IER = 0

**ALLOWABLES**

**3p-Weibull Allowables**

A = 121.854      B = 123.296

**Normal Allowables**

A = 121.522      B = 123.241

**Nonparametric Allowables**

A = \*\*\*\*\*      B = 123.200

**Weibull Parameter Estimates (3p-Weibull)**

Threshold = 121.925      Scale = 4.023      Shape = 2.583

**Normal estimates of 1- and 10-percentiles**

x(.01) = 122.036      x(.10) = 123.593

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

x(.01) = 122.603      x(.10) = 123.608

**Other Sample Statistics**

Mean = 125.503      Stand. Deviation = 1.490

Skewness = .213      Kurtosis = -.037

Coeff. of Variation = .012

**Test for Normality**

AD = .400      P-value = .310509      IEX = 1

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

**Test for the 3p-Weibull Distribution**

AD = .468      P-value = .246515      IEX = 0

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

**The 11 smallest data values are**

122.500 122.500 122.500 122.500 123.000 123.200 123.400 123.400  
123.600 123.600 123.600

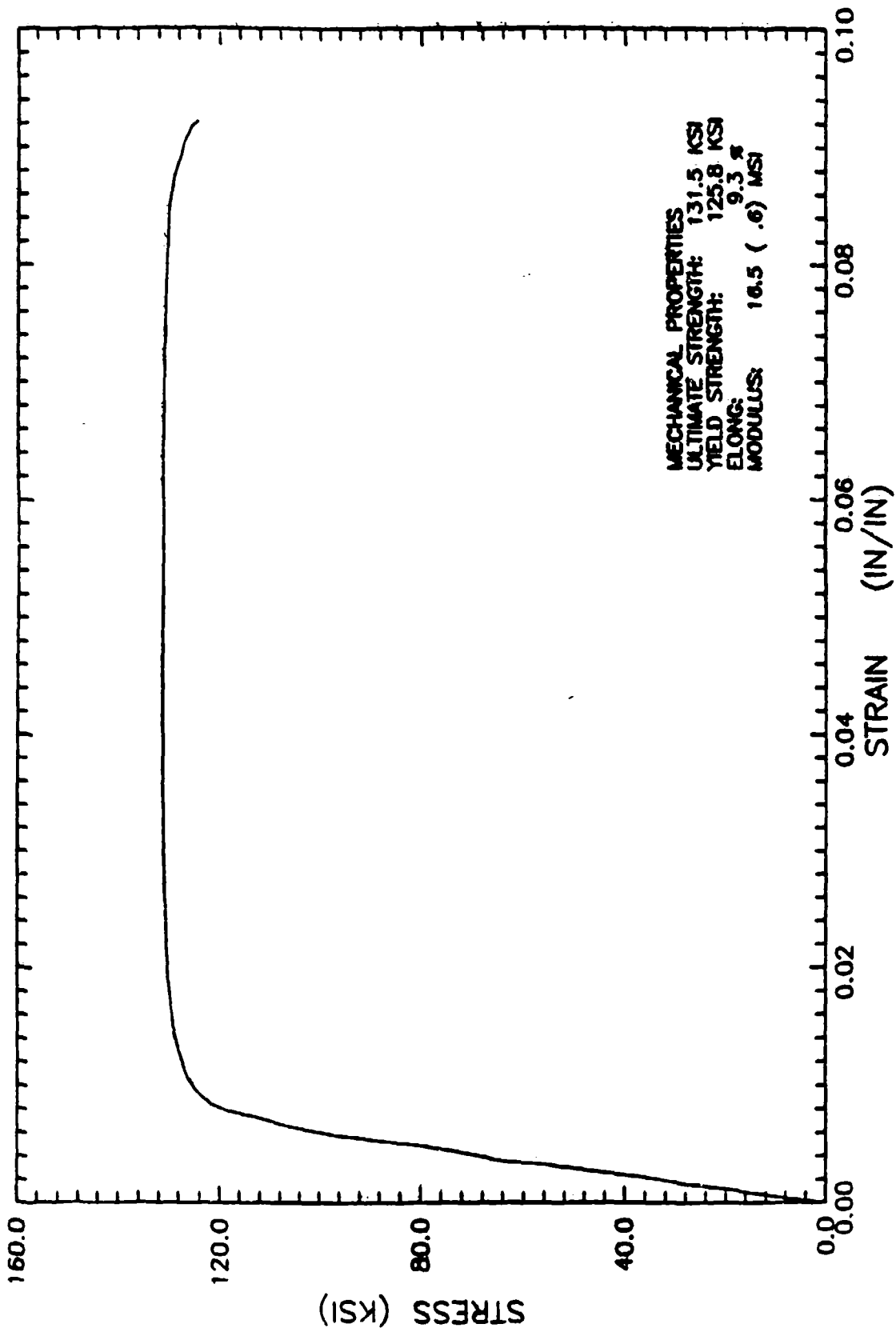
**The 11 largest data values are**

127.400 127.400 127.400 127.400 127.600 127.700 127.900 128.200  
128.600 129.200 130.100

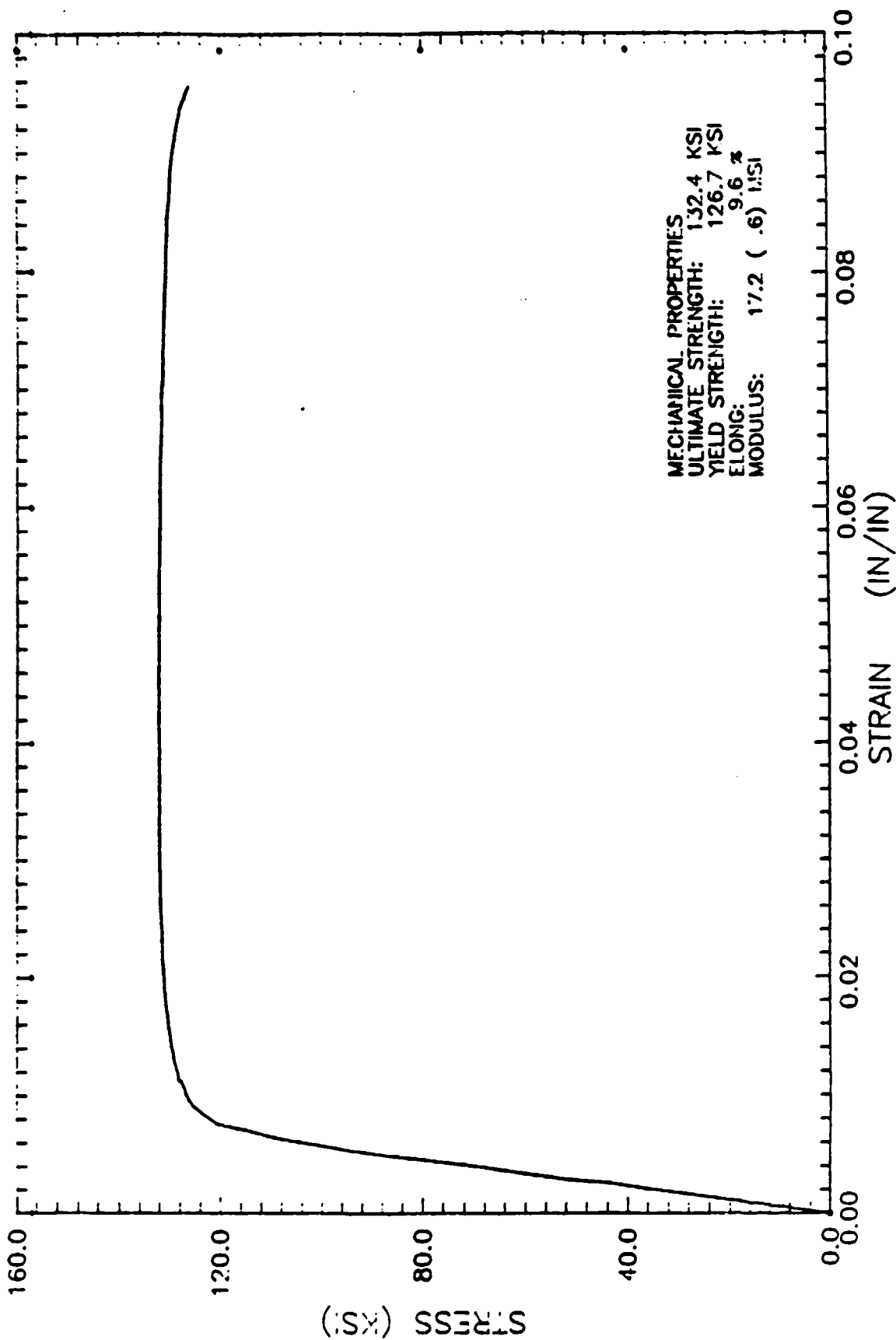
### **D.3 TYPICAL STRESS-STRAIN CURVES**

Ti-6-4 Coating -- TEST TEMP: RT -- SAMPLE: 4A-025  
DIA: .2525 IN. GL: 1 IN

DATE: 1-22-1992



Ti-6-4 Casting -- TEST TEMP: RT -- SAMPLE: 4P-013  
DIA: .253 IN. GL: 1 IN DATE: 1-23-1992



#### **D.4 COMPRESSION, BEARING, AND SHEAR DATA**

### BACKGROUND

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

### TEST RESULTS

#### Compression Testing

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

| <u>Pin Identification</u> | <u>Compressive<br/>Yield Strength, psi<br/>(0.2% offset)</u> |
|---------------------------|--------------------------------------------------------------|
| 4A-01                     | 133,000                                                      |
| 4G-01                     | 125,000                                                      |
| 4G-02                     | 125,000                                                      |

#### Pin Bearing Tests

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

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

Shear Testing

The remaining three fins were cut to obtain specimens for shear testing. The specimens were machined to the greatest thickness possible to be obtained from each fin. The shear specimens were machined and tested in accordance with MIL-STD-1312, test #20 with reference to ASTM Proceedings, Volume 38, Evaluation of Single-Shear Specimen for Sheet Material. The results of these tests are shown in the table below.

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

Respectfully submitted,

TAUSIG ASSOCIATES, INC.

*Mark A. Hineman*

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

MAH/nb

**APPENDIX E**

**FRACTURE MECHANICS DATA**

## **APPENDIX E**

### **FRACTURE MECHANICS DATA**

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

## BACKGROUND

Six samples of titanium castings were submitted to our laboratory for mechanical testing. The testing was performed in accordance with "Engineering Work Statement for Fracture Mechanics Testing for Use of Titanium Castings Without a Casting Factor", WS-MAT-7163. The mechanical tests were to include fatigue crack growth testing of three specimens per ASTM E647, and plane-strain toughness testing of three specimens per ASTM E992 and E399, and R-curve determination per E561.

## TEST RESULTS

### Fatigue Crack Growth Testing

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

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

$$A/W = 1.0010 - 4.6695 U_x + 18.46 U_x^2 - 236.82 U_x^3 \\ + 1214.9 U_x^4 - 2.43.6 U_x^5$$

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

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

### Fracture Toughness per E399

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



| Sample | K <sub>IC</sub> KSI (in) <sup>3/2</sup> | Valid/Invalid | No. of Invalids |
|--------|-----------------------------------------|---------------|-----------------|
| 4AA-01 | 70.6                                    | Invalid       | 3               |
| 4AC-01 | 66.8                                    | Invalid       | 3               |
| 4G-02  | 70.0                                    | Invalid       | 3               |

K-Curve Determination

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

| Sample | K <sub>max</sub> KSI (in) <sup>3/2</sup> | K <sub>min</sub> KSI (in) <sup>3/2</sup> | Valid/Invalid |
|--------|------------------------------------------|------------------------------------------|---------------|
| 4AA-01 | 122.7                                    | 140.9                                    | Invalid       |
| 4AC-01 |                                          | 112.7                                    | Invalid       |
| 4G-02  | 118.6                                    | 125.0                                    | Invalid       |

Fracture Toughness Per E992

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

| Sample | K <sub>IC</sub> KSI (in) <sup>3/2</sup> |
|--------|-----------------------------------------|
| 4AA-01 | 147.1                                   |
| 4AC-01 | 117.9                                   |
| 4G-02  | 131.6                                   |

Respectfully submitted,

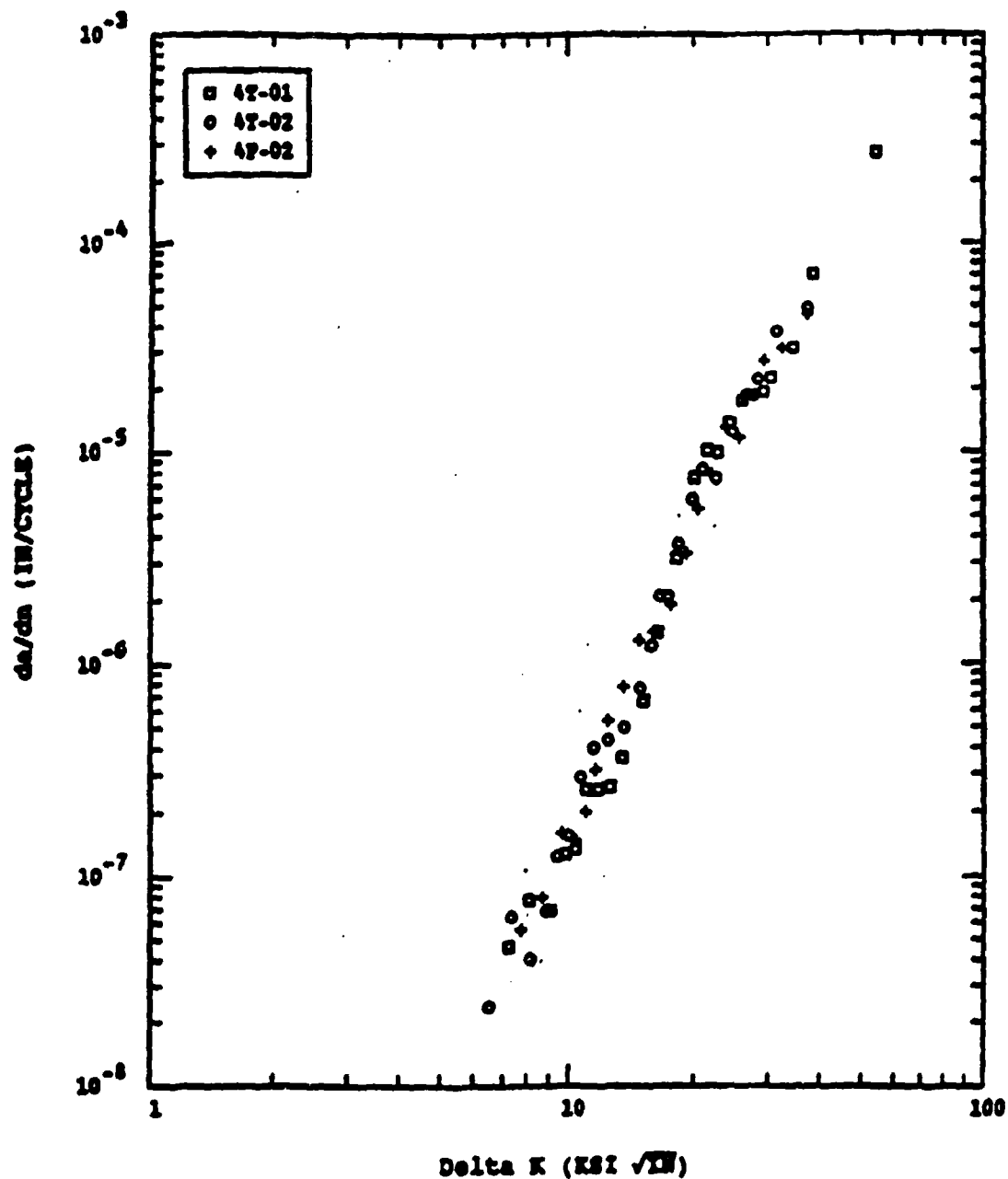
TAUSSIG ASSOCIATES, INC.

*Mark A. Hineman*

Mark A. Hineman  
Senior Metallurgical Engineer

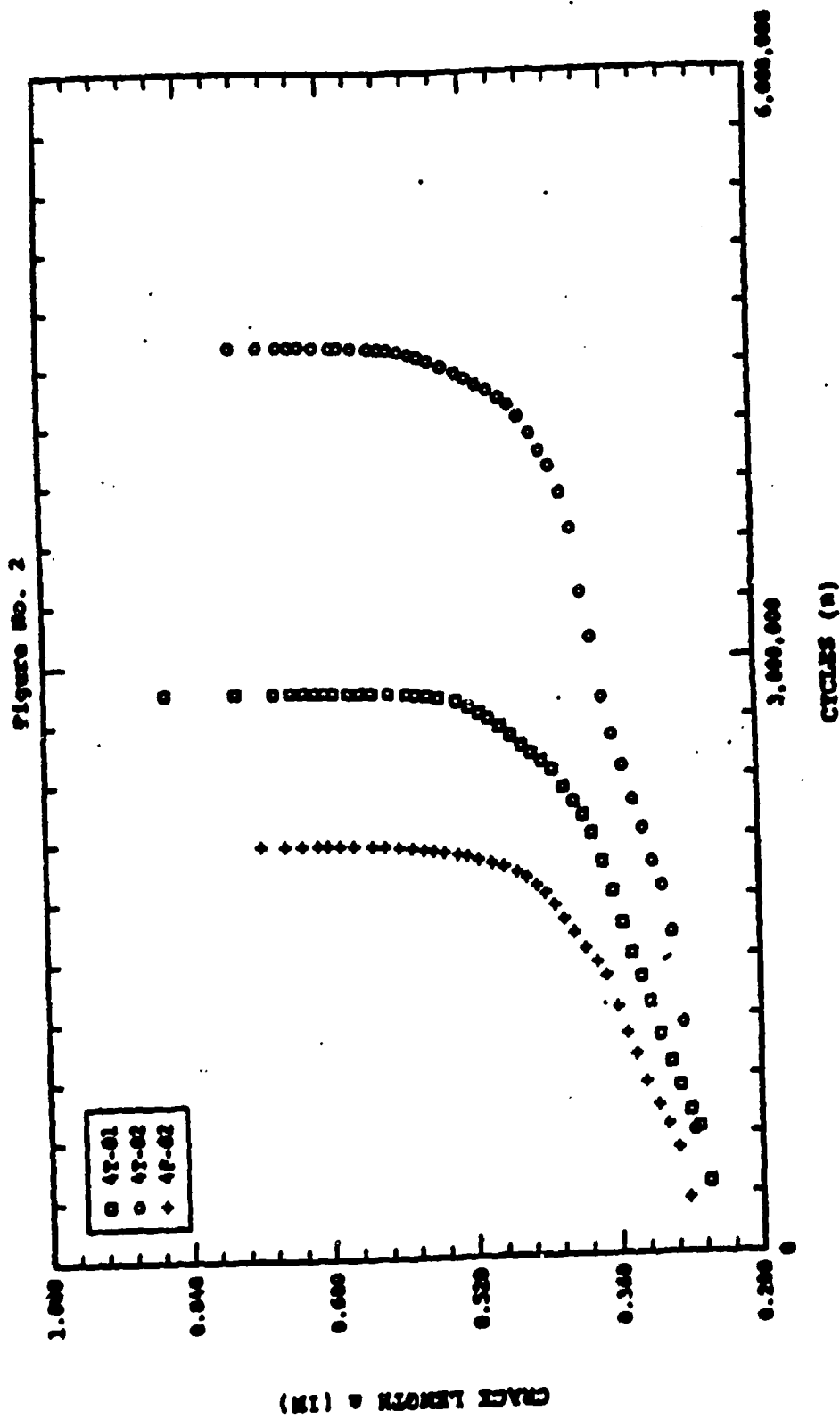
MAH/nb

Figure No. 1



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

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Report No. 103903



a vs n Graph for all three specimens.

McDonnell Douglas Missile Systems Co.  
Report No. 103983

Table 1: Test Data for Sample 4T-01

**FATIGUE CRACK GROWTH TEST REPORT**

**PRELIMINARY INFORMATION:**

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

TEST DATE: 07-09-1992  
MODULUS: 16.3 MSI  
HUMIDITY: 45%

**SPECIMEN MEASUREMENTS:**

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

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

**PRECRACKING SUMMARY:**

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

**TEST PARAMETERS:**

MAXIMUM LOAD = 150 LBS.  
LOAD RANGE = 133 LBS.  
STRESS RATIO = .1

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

**CRACK CURVATURE CORRECTION:**

PRECRACK FRONT: NONE REQUIRED  
TERMINAL FATIGUE CRACK: NONE REQUIRED

**VALIDITY CHECKS PER ASTM E647-86:**

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

**ALL VALIDITY CHECKS ARE VALID.**

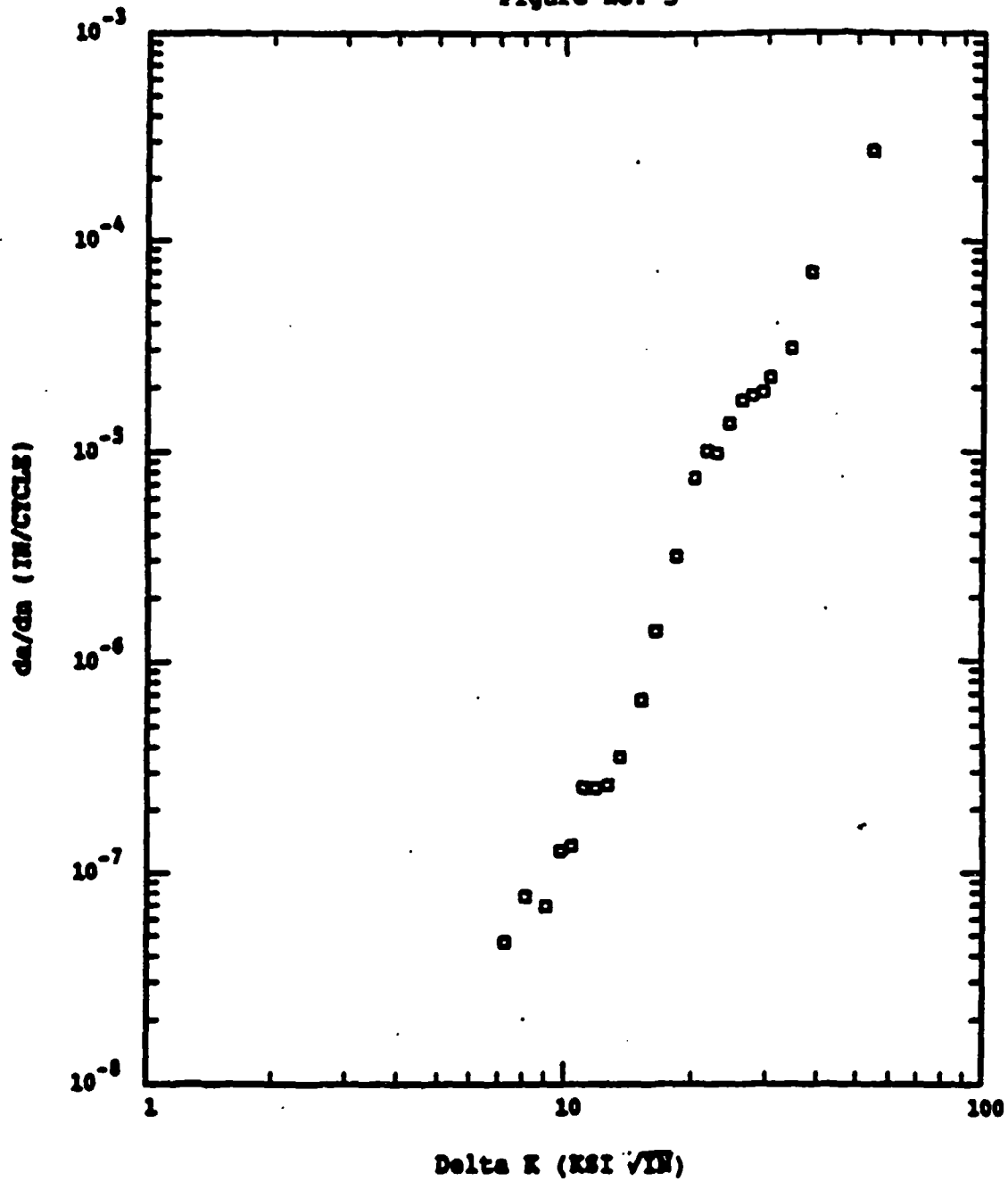
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Report No. 103983

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

| Force<br>(LBS) | $\Delta S (V/P)$ | $a$<br>(IN) | $N$     | $da$<br>(IN) | $dN$   | $da/dN$<br>(IN/CYCLE) | $\Delta K$<br>(KSI/IN) | Ich |
|----------------|------------------|-------------|---------|--------------|--------|-----------------------|------------------------|-----|
| 150            | 25.07            | 0.2992      | 951011  |              | 960505 | 4.6739E-06            | 7.25                   | 0   |
| 150            | 29.29            | 0.3013      | 961013  | 0.0449       | 549989 | 7.7614E-06            | 8.12                   | 0   |
| 150            | 34.30            | 0.3440      | 1511002 | 0.0427       | 600004 | 6.9615E-06            | 9.05                   | 0   |
| 150            | 37.15            | 0.3858      | 2111006 | 0.0418       | 159998 | 1.2850E-07            | 9.81                   | 0   |
| 150            | 40.72            | 0.4063      | 2271004 | 0.0206       | 169999 | 1.3541E-07            | 10.40                  | 0   |
| 150            | 44.78            | 0.4294      | 2441003 | 0.0230       | 89997  | 2.5791E-07            | 11.07                  | 0   |
| 150            | 49.36            | 0.4526      | 2531000 | 0.0232       | 90002  | 2.5652E-07            | 11.83                  | 0   |
| 150            | 54.75            | 0.4757      | 2621002 | 0.0231       | 90007  | 2.6378E-07            | 12.66                  | 0   |
| 150            | 60.37            | 0.4994      | 2711009 | 0.0237       | 60001  | 3.6018E-07            | 13.51                  | 0   |
| 151            | 70.66            | 0.5210      | 2771010 | 0.0216       | 49993  | 6.6314E-07            | 15.19                  | 0   |
| 150            | 79.86            | 0.5542      | 2821003 | 0.0332       | 17499  | 1.4678E-06            | 16.42                  | 0   |
| 150            | 94.80            | 0.5738      | 2838992 | 0.0246       | 10003  | 3.1482E-06            | 18.23                  | 0   |
| 150            | 105.28           | 0.6103      | 2848985 | 0.0315       | 2499   | 7.5469E-06            | 20.14                  | 0   |
| 150            | 113.40           | 0.6291      | 2851004 | 0.0189       | 1246   | 1.0003E-05            | 21.53                  | 0   |
| 150            | 122.30           | 0.6417      | 2852290 | 0.0126       | 1251   | 9.8734E-06            | 22.79                  | 0   |
| 150            | 136.35           | 0.6541      | 2853501 | 0.0124       | 1254   | 1.3567E-05            | 24.38                  | 0   |
| 150            | 146.48           | 0.6711      | 2854755 | 0.0170       | 622    | 1.7294E-05            | 26.07                  | 0   |
| 150            | 158.54           | 0.6819      | 2855377 | 0.0100       | 625    | 1.8349E-05            | 27.59                  | 1   |
| 150            | 172.73           | 0.6933      | 2856062 | 0.0115       | 626    | 1.9091E-05            | 29.29                  | 1   |
| 152            | 191.73           | 0.7053      | 2856628 | 0.0120       | 624    | 2.2282E-05            | 30.40                  | 1   |
| 150            | 223.35           | 0.7192      | 2857252 | 0.0139       | 626    | 3.0739E-05            | 34.40                  | 1   |
| 144            | 331.60           | 0.7384      | 2857878 | 0.0192       | 623    | 6.9719E-05            | 38.59                  | 1   |
| 136            | 905.33           | 0.7819      | 2858501 | 0.0434       | 299    | 2.6931E-04            | 54.25                  | 1   |

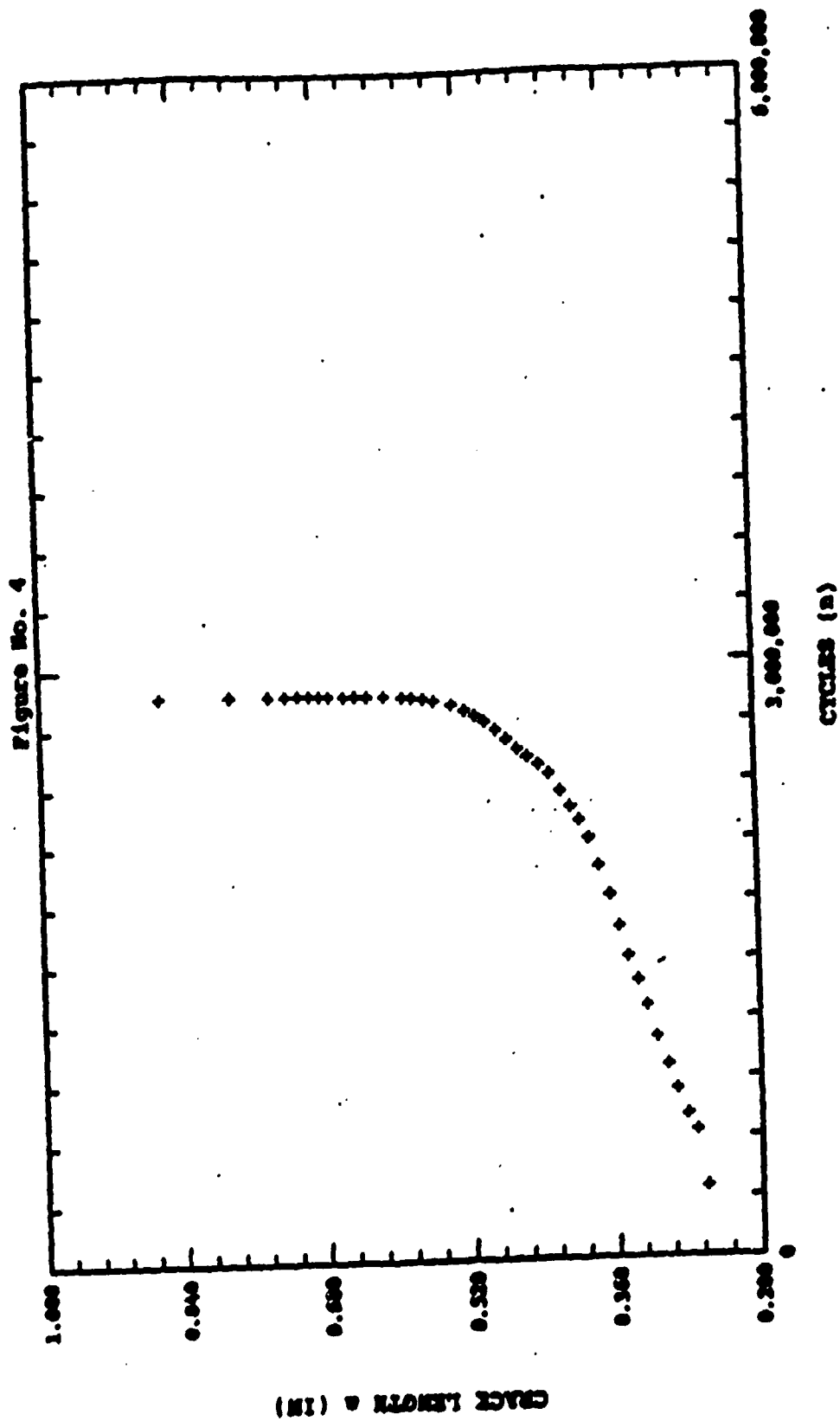
An Ich value of 1 indicates that the data violates the specimen size requirements ( $v-a > (4/\pi)((bmx/ys)^2)$ )

Figure No. 3



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

McDonnell Douglas Missile Systems Co.  
Report No. 103983



a vs n Graph for sample 4T-01.

McDonnell Douglas Missile Systems Co.  
Report No. 103983

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

**FATIGUE CRACK GROWTH TEST REPORT**

**PRELIMINARY INFORMATION:**

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

TEST DATE: 07-09-1992  
MODULUS: 16.3 MSI  
HUMIDITY: 45%

**SPECIMEN MEASUREMENTS:**

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

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

**PRECRACKING SUMMARY:**

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

**TEST PARAMETERS:**

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

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

**CRACK CURVATURE CORRECTION:**

PRECRACK FRONT: NONE REQUIRED  
TERMINAL FATIGUE CRACK: NONE REQUIRED

**VALIDITY CHECKS PER ASTM E647-86:**

1. DIFFERENCE BETWEEN A1 AND A2 MUST BE  $< 0.25 \cdot B$  VALID  
DIFFERENCE = 0.002 IN.  $0.25 \cdot B = .025$
2. THE CRACK MUST NOT DEVIATE MORE THAN 32 FROM THE PLANE OF SYMMETRY VALID

**ALL VALIDITY CHECKS ARE VALID.**

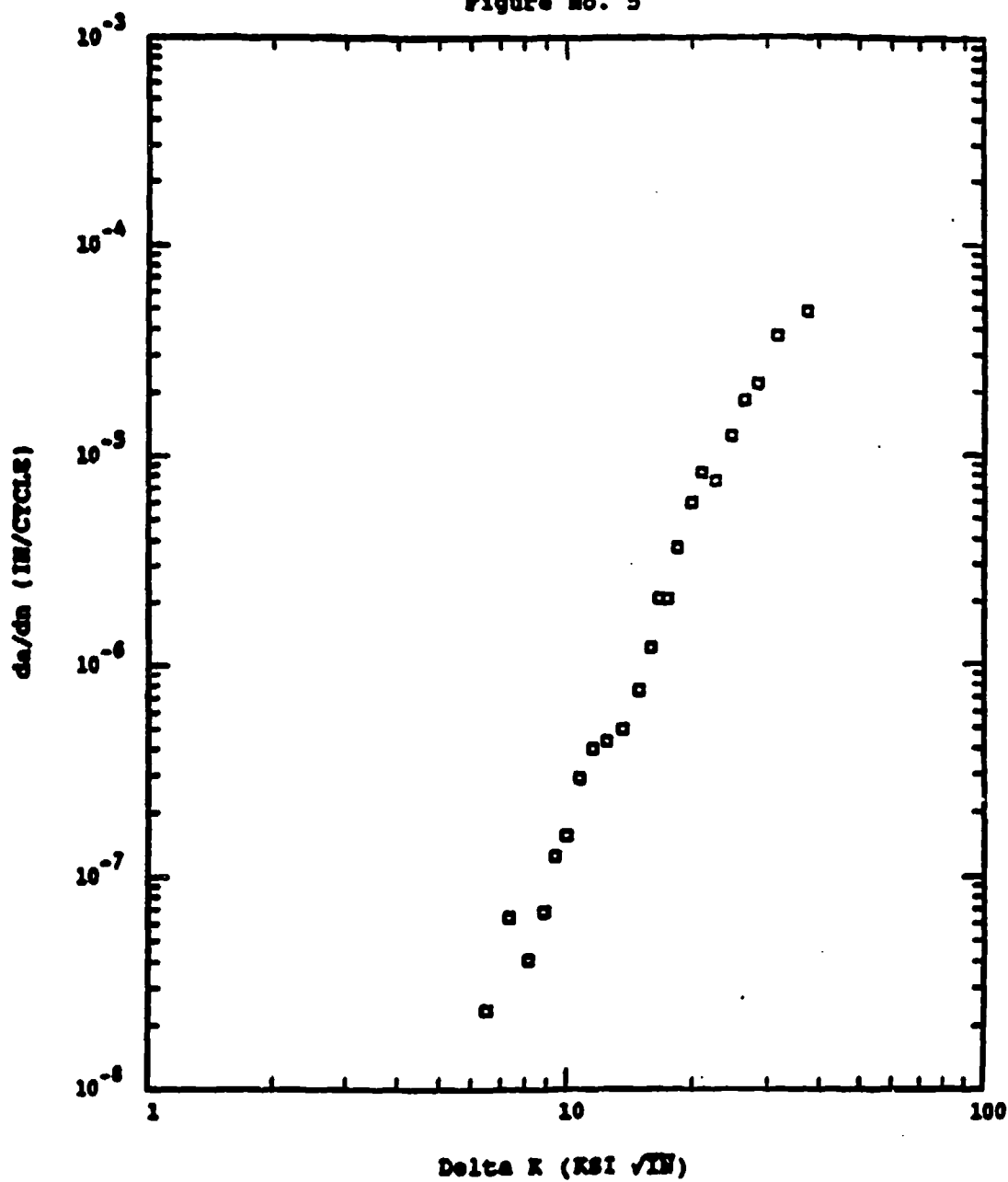
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Report No. 103983

Table 4: Fatigue Crack Growth Test Results for Sample 47-02.

| Pmax<br>(LBS) | ES(V/P) | a<br>(IN) | N       | da<br>(IN) | dN      | da/dN<br>(IN/CYCLE) | delta K<br>(KSI/IN) | Ick |
|---------------|---------|-----------|---------|------------|---------|---------------------|---------------------|-----|
| 131           | 26.76   | 0.3166    | 1951012 | 0.0465     | 1960514 | 2.3736E-06          | 6.52                | 0   |
| 131           | 31.23   | 0.3194    | 1961019 | 0.0417     | 649993  | 6.4220E-06          | 7.32                | 0   |
| 130           | 36.76   | 0.3612    | 2611012 | 0.0424     | 1039993 | 4.0612E-06          | 8.15                | 0   |
| 130           | 40.10   | 0.4036    | 3651005 | 0.0219     | 320002  | 6.8430E-06          | 8.87                | 0   |
| 130           | 43.73   | 0.4255    | 3971007 | 0.0213     | 169995  | 1.2552E-07          | 9.48                | 0   |
| 130           | 48.27   | 0.4468    | 4141002 | 0.0235     | 1500001 | 1.5690E-07          | 10.00               | 0   |
| 130           | 53.41   | 0.4704    | 4291003 | 0.0234     | 80009   | 2.9223E-07          | 10.71               | 0   |
| 130           | 59.53   | 0.4938    | 4371012 | 0.0242     | 59993   | 4.0309E-07          | 11.57               | 0   |
| 129           | 67.34   | 0.5180    | 4431005 | 0.0263     | 59996   | 4.3009E-07          | 12.50               | 0   |
| 129           | 76.16   | 0.5442    | 4491001 | 0.0256     | 50009   | 5.0026E-07          | 13.65               | 0   |
| 129           | 85.76   | 0.5693    | 4541010 | 0.0229     | 29997   | 7.6468E-07          | 14.91               | 0   |
| 129           | 91.92   | 0.5922    | 4571007 | 0.0121     | 9995    | 1.2074E-06          | 15.89               | 0   |
| 129           | 96.95   | 0.6043    | 4581002 | 0.0104     | 5006    | 2.0837E-06          | 16.62               | 0   |
| 129           | 102.84  | 0.6147    | 4586008 | 0.0104     | 5000    | 2.0793E-06          | 17.30               | 0   |
| 129           | 102.84  | 0.6251    | 4591008 | 0.0104     | 4992    | 3.8731E-06          | 18.36               | 0   |
| 129           | 114.56  | 0.6434    | 4596000 | 0.0183     | 2507    | 5.9799E-06          | 19.88               | 0   |
| 129           | 125.68  | 0.6584    | 4598507 | 0.0150     | 1245    | 8.2741E-06          | 21.83               | 0   |
| 128           | 134.25  | 0.6687    | 4599752 | 0.0103     | 2503    | 7.4967E-06          | 22.68               | 0   |
| 129           | 152.22  | 0.6875    | 4602255 | 0.0188     | 1252    | 1.2378E-05          | 24.68               | 0   |
| 130           | 169.86  | 0.7030    | 4603507 | 0.0155     | 623     | 1.8142E-05          | 26.46               | 1   |
| 130           | 184.70  | 0.7143    | 4604130 | 0.0113     | 621     | 2.1960E-05          | 28.41               | 1   |
| 129           | 205.30  | 0.7279    | 4604751 | 0.0136     | 625     | 3.6852E-05          | 31.56               | 1   |
| 129           | 246.65  | 0.7510    | 4605376 | 0.0230     | 626     | 4.7934E-05          | 37.39               | 1   |
| 130           | 328.85  | 0.7810    | 4606002 | 0.0300     |         |                     |                     |     |

An Ick value of 1 indicates that the data violates the specimen size requirements ( $w-a \geq (4/\pi)((K_{max}/\sigma)^2)$ )

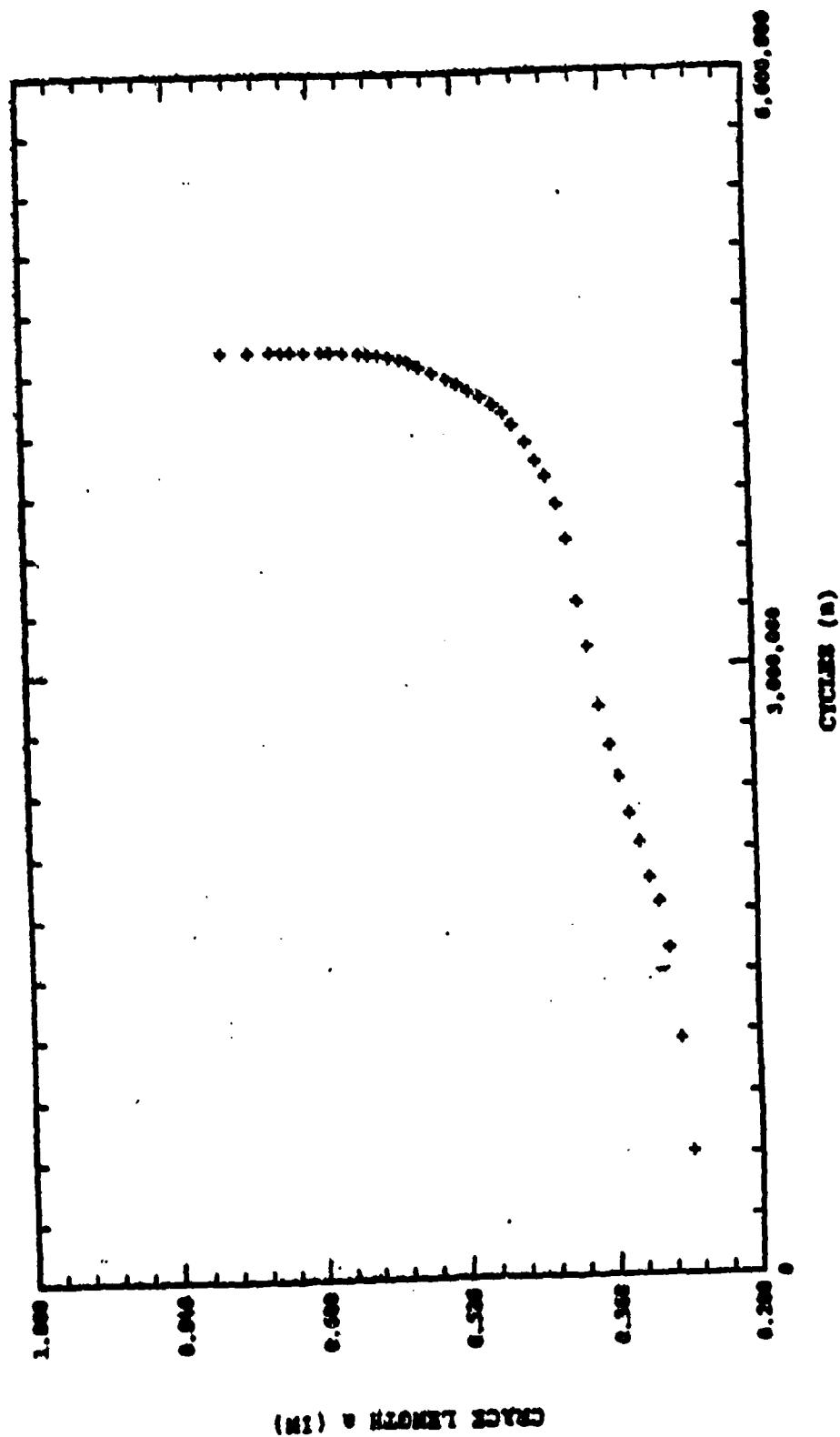
Figure No. 5



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

McDonnell Douglas Missile Systems  
Report No. 103903

Figure No. 6



a vs n Graph for sample 4T-02

Table 5: Test Data for Sample 4P-02

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FATIGUE CRACK GROWTH TEST REPORT

---

PRELIMINARY INFORMATION:

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

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

SPECIMEN MEASUREMENTS:

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

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

PRECRACKING SUMMARY:

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

TEST PARAMETERS:

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

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

CRACK CURVATURE CORRECTION:

PRECRACK FRONT: NONE REQUIRED  
TERMINAL FATIGUE CRACK: NONE REQUIRED

VALIDITY CHECKS PER ASTM E647-86:

1. DIFFERENCE BETWEEN A1 AND A2 MUST BE  $< 0.25 \pm 3$  VALID  
DIFFERENCE = 0.006 IN.  $0.25 \pm 3 = .025$
2. THE CRACK MUST NOT DEVIATE MORE THAN 5% FROM THE PLANE OF SYMMETRY VALID

ALL VALIDITY CHECKS ARE VALID.

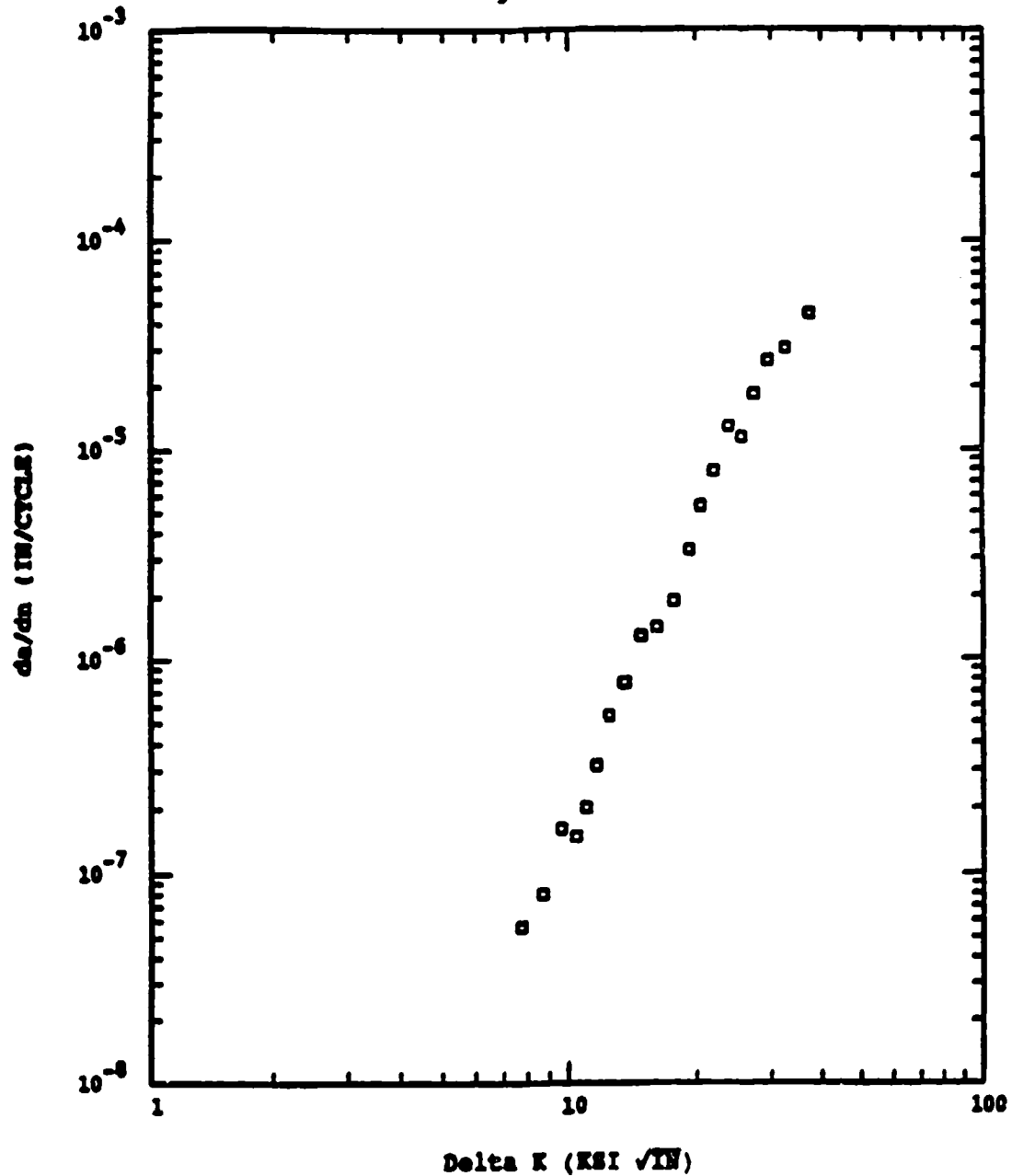
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Report No. 103983

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

| Pmax<br>(LBS) | ED(V/F) | a<br>(IN) | N       | da<br>(IN) | da/dN<br>(IN/CYCLE) | delta K<br>(KSI/√IN) | Ick |
|---------------|---------|-----------|---------|------------|---------------------|----------------------|-----|
| 151           | 27.71   | 0.3259    | 851003  | 0.0492     | 5.6020E-08          | 7.74                 | 0   |
| 151           | 32.55   | 0.3293    | 861007  | 0.0432     | 8.0009E-08          | 8.69                 | 0   |
| 150           | 37.36   | 0.3725    | 1401003 | 0.0432     | 1.6184E-07          | 9.63                 | 0   |
| 150           | 40.57   | 0.4081    | 1621009 | 0.0356     | 1.4830E-07          | 10.42                | 0   |
| 150           | 44.05   | 0.4289    | 1761001 | 0.0208     | 2.0168E-07          | 11.00                | 0   |
| 150           | 48.35   | 0.4490    | 1861011 | 0.0202     | 3.1743E-07          | 11.67                | 0   |
| 149           | 54.34   | 0.4713    | 1931000 | 0.0222     | 5.3679E-07          | 12.51                | 0   |
| 150           | 61.44   | 0.4982    | 1981015 | 0.0269     | 7.7528E-07          | 13.61                | 0   |
| 149           | 69.44   | 0.5253    | 2016010 | 0.0271     | 1.2903E-06          | 14.84                | 0   |
| 149           | 77.20   | 0.5511    | 2036006 | 0.0258     | 1.4234E-06          | 16.09                | 0   |
| 149           | 89.68   | 0.5725    | 2051003 | 0.0213     | 1.9093E-06          | 17.62                | 0   |
| 149           | 98.25   | 0.6011    | 2066001 | 0.0286     | 3.3033E-06          | 19.24                | 0   |
| 149           | 106.03  | 0.6177    | 2071010 | 0.0165     | 5.3478E-06          | 26.58                | 0   |
| 149           | 119.31  | 0.6310    | 2073500 | 0.0133     | 7.8763E-06          | 22.04                | 0   |
| 149           | 132.05  | 0.6507    | 2076005 | 0.0197     | 1.2881E-05          | 23.88                | 0   |
| 149           | 145.08  | 0.6668    | 2077256 | 0.0161     | 1.1478E-05          | 25.62                | 0   |
| 149           | 157.03  | 0.6811    | 2078501 | 0.0143     | 1.8423E-05          | 27.36                | 1   |
| 149           | 177.20  | 0.6927    | 2079127 | 0.0115     | 2.6758E-05          | 29.46                | 1   |
| 150           | 205.07  | 0.7095    | 2079755 | 0.0168     | 3.0589E-05          | 32.44                | 1   |
| 150           | 259.53  | 0.7285    | 2080378 | 0.0191     | 4.4762E-05          | 37.22                | 1   |
| 150           |         | 0.7566    | 2081005 | 0.0281     |                     |                      |     |

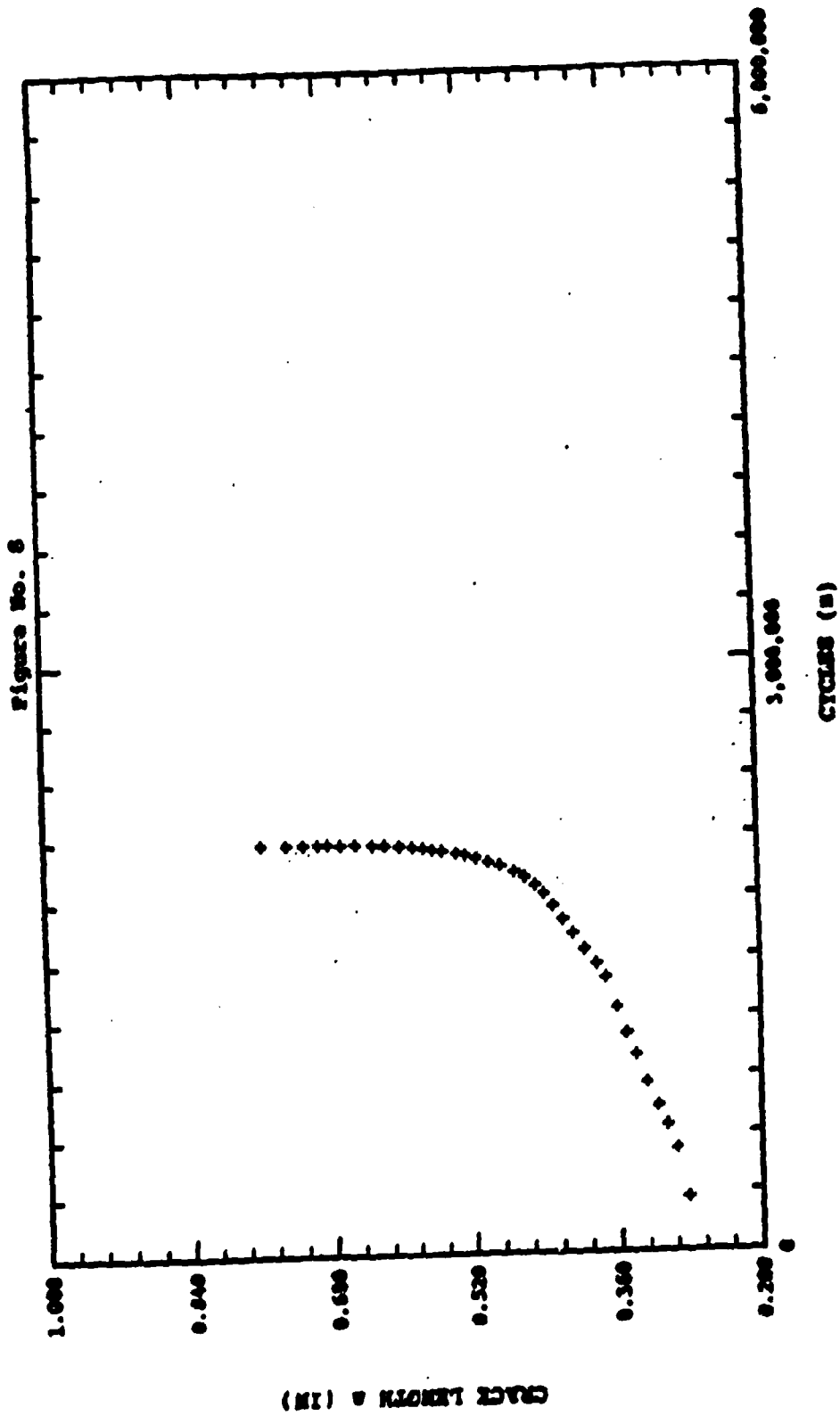
An Ick value of 1 indicates that the data violates the specimen size requirements  $(v-a) > (4/pl)((kmax/ys)^2)$

Figure No. 7



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

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a vs n Graph for Sample 4P-02.

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

**FRACTURE TOUGHNESS TEST REPORT**

**PRELIMINARY INFORMATION:**

SAMPLE: 4AA-01

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

MATERIAL SPEC.: NONE

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

**SPECIMEN MEASUREMENTS:**

THICKNESS (B) = 0.226 IN.  
WIDTH (W) = 0.789 IN.  
AVE. CRACK LENGTH (A) = 0.386 IN.  
FRACTURE APPEARANCE = 47% FRACTION OBLIQUE  
HEIGHT (2H) = 0.866 IN.  
TOTAL WIDTH (W1) = 1.030 IN.  
NOTCH TO HOLE (H1) = 0.220 IN.

**CRACK LENGTHS**

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

**FATIGUE PRECRACKING SUMMARY:**

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

LOAD RATIO = 0.1  
CYCLES = 133080

**TEST RESULTS:**

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

MAXIMUM LOAD (P<sub>MAX</sub>) = 2345 LBS  
K-RATE = 43.2 KSI (SQRT.IN.)/MIN

**VALIDITY CHECKS PER ASTM E399**

- |                                                                                                        |         |
|--------------------------------------------------------------------------------------------------------|---------|
| 1. B MUST BE > OR = $B = 2.5 \cdot (KQ/YE)^{1/2}$<br>B = 0.226                                         | INVALID |
| 2. A MUST BE > OR = $A = 2.5 \cdot (KQ/YE)^{1/2}$<br>A = 0.386                                         | INVALID |
| 3. P <sub>MAX</sub> /P <sub>Q</sub> MUST BE < OR = 1.10<br>P <sub>MAX</sub> /P <sub>Q</sub> = 1.51     | INVALID |
| 4. A/W MUST BE BETWEEN 0.45 AND 0.55<br>A/W = 0.48                                                     | VALID   |
| 5. DIFFERENCE BETWEEN ANY TWO OF A2, A3, A4 MUST BE < OR = .10A<br>MAX. DIFF = 0.012                   | VALID   |
| 6. A1 AND A5 MUST BE BETWEEN 0.322 AND 0.444<br>A1 = 0.368, A5 = 0.377                                 | VALID   |
| 7. DIFFERENCE BETWEEN A1 AND A5 MUST BE < OR = .10A<br>DIFFERENCE = 0.009                              | VALID   |
| 8. $0.60 \cdot KQ$ MUST BE > OR = KF (MAX)<br>KF (MAX) = 13.6 KSI(SQRT.IN.)                            | VALID   |
| 9. KF (MAX)/E MUST BE < OR = 0.002<br>KF (MAX)/E = 0.001                                               | VALID   |
| 10. K-RATE MUST BE BETWEEN 30 AND 150 KSI(SQRT.IN.)/MIN<br>K-RATE = 43 KSI (SQRT.IN.)/MIN              | VALID   |
| 11. PRECRACK LENGTH MUST BE > OR = $0.025 \cdot W$ OR 0.05 IN.<br>$0.025 \cdot W$ OR 0.050 = 0.050 IN. | VALID   |
| 12. FATIGUE PRECRACK PLANE MUST BE < OR = 10 DEG                                                       | VALID   |
| 13. TEST CURVES INITIAL SLOPE MUST BE BETWEEN 0.7 AND 1.5<br>ACTUAL SLOPE = 1.3                        | VALID   |

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

Table 8: FRACTURE TOUGHNESS PER E399, Sample 4AC-01  
FRACTURE TOUGHNESS TEST REPORT

PRELIMINARY INFORMATION:

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

ALLOY & TEMPER: TI 64  
PRODUCT THICKNESS: 0.000  
TEST TYPE & ORIENT: 0.400-C(T) R/A  
TEST DATE: 920430  
YIELD STR.(YS): 125.0 KSI

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

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

SPECIMEN MEASUREMENTS:

THICKNESS (B) = 0.220 IN.  
WIDTH (W) = 0.799 IN.  
AVE. CRACK LENGTH (A) = 0.382 IN.  
FRACTURE APPEARANCE = 50% FRACTURE OBLIQUE  
HEIGHT (2H) = 0.960 IN.  
TOTAL WIDTH (W1) = 1.000 IN.  
NOTCH TO HOLE (H1) = 0.220 IN.

CRACK LENGTHS

SIDE 1 (A1) = 0.371 IN.  
QUARTER POINT 1 (A2) = 0.374 IN.  
QUARTER POINT (A3) = 0.384 IN.  
QUARTER POINT (A4) = 0.389 IN.  
SIDE 2 (A5) = 0.376 IN.

FATIGUE PRECRACKING SUMMARY:

MAXIMUM FATIGUE LOAD = 300 LBS  
KF (MAX) = 13.8 KSI(SQRT.IN.)

LOAD RATIO = 0.1  
CYCLES = 276730

TEST RESULTS:

CANDIDATE LOAD (PQ) = 1450 LBS  
KQ = 66.8 KSI(SQRT.IN.)  
SPECIMEN STRENGTH RATIO = 1.709

MAXIMUM LOAD (PMAX) = 2060 LBS  
K-RATE = 44.0 KSI (SQRT.IN.)/MIN

VALIDITY CHECKS PER ASTM E399

1. B MUST BE > OR =  $B-2.5 \cdot (KQ/YS)^{1/2}$   
B = 0.220 B = 0.713 INVALID
2. A MUST BE > OR =  $A-2.5 \cdot (KQ/YS)^{1/2}$   
A = 0.382 A = 0.713 INVALID
3. PMAX/PQ MUST BE < OR = 1.10  
PMAX/PQ = 1.42 INVALID
4. A/W MUST BE BETWEEN 0.45 AND 0.55  
A/W = 0.48 VALID
5. DIFFERENCE BETWEEN ANY TWO OF A2,A3,A4 MUST BE < OR = .1\*A  
MAX. DIFF = 0.013 0.10\*A = 0.038 VALID
6. A1 AND A5 MUST BE BETWEEN 0.325 AND 0.439  
A1 = 0.371 A5 = 0.376 VALID
7. DIFFERENCE BETWEEN A1 AND A5 MUST BE < OR = .1\*A  
DIFFERENCE = 0.005 0.10\*A = 0.038 VALID
8.  $0.60 \cdot KQ$  MUST BE > OR = KF(MAX)  
KF(MAX) = 13.8 KSI(SQRT.IN.)  $0.6 \cdot KQ = 40.1$  KSI(SQRT.IN.) VALID
9. KF(MAX)/B MUST BE < OR = 0.002  
KF(MAX)/B = 0.001 VALID
10. K-RATE MUST BE BETWEEN 30 AND 150 KSI(SQRT.IN.)/MIN  
K-RATE = 44 KSI (SQRT.IN.)/MIN VALID
11. PRECRACK LENGTH MUST BE > OR =  $0.025 \cdot W$  OR 0.03 IN.  
 $0.025 \cdot W$  OR 0.030 = 0.050 IN. MIN. LENGTH = 0.033 IN. VALID
12. FATIGUE PRECRACK PLANE MUST BE < OR = 10 DEG. VALID
13. TEST CURVES INITIAL SLOPE MUST BE BETWEEN 0.7 AND 1.5  
ACTUAL SLOPE = 1.2 VALID

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

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

FRACTURE TOUGHNESS TEST REPORT

PRELIMINARY INFORMATION:

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

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

ALLOY & TEMPER: T1 64  
PRODUCT: HILTISS: 0.000  
TEST TYPE & ORIENT: 0.400-C(T) N/A  
TEST DATE: 9/20/80  
YIELD STR.(TS): 125.0 KSI

PRODUCT: NONE  
LAB: 103983  
TEST PLANT: T/2  
TEST TEMP: 71 75  
MODULUS: 16.0 MSI

SPECIMEN MEASUREMENTS:

THICKNESS (B) = 0.246 IN.  
WIDTH (W) = 0.799 IN.  
AVE. CRACK LENGTH (A) = 0.379 IN.  
FRACTURE APPEARANCE = 311 FRACTION OBLIQUE  
HEIGHT (2H) = 0.960 IN.  
TOTAL WIDTH (W1) = 1.000 IN.  
NOTCH TO HOLE (H1) = 0.220 IN.

CRACK LENGTHS

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

FATIGUE PRECRACKING SUMMARY:

MAXIMUM FATIGUE LOAD = 300 LBS  
K<sub>F</sub> (MAX) = 12.2 KSI(SQRT.IN.)

LOAD RATIO = +0.1  
CYCLES = 181460

TEST RESULTS:

CANDIDATE LOAD (PQ) = 1720 LBS  
K<sub>D</sub> = 70.0 KSI(SQRT.IN.)  
SPECIMEN STRENGTH RATIO = 1.774

MAXIMUM LOAD (P<sub>MAX</sub>) = 2410 LBS  
K-RATE = 39.1 KSI (SQRT.IN.)/MIN

VALIDITY CHECKS PER ASTM E399

1. B MUST BE > OR =  $B-2.3 \cdot (H_0/Y_8)^{1/2}$   
B = 0.246 B = 0.785 **INVALID**
2. A MUST BE > OR =  $A-2.3 \cdot (H_0/Y_8)^{1/2}$   
A = 0.379 A = 0.785 **INVALID**
3. P<sub>MAX</sub>/P<sub>Q</sub> MUST BE < OR = 1.10  
P<sub>MAX</sub>/P<sub>Q</sub> = 1.41 **INVALID**
4. A/W MUST BE BETWEEN 0.45 AND 0.55  
A/W = 0.47 **VALID**
5. DIFFERENCE BETWEEN ANY TWO OF A2, A3, A4 MUST BE < OR = .10A  
MAX. DIFF = 0.007 0.10A = 0.038 **VALID**
6. A1 AND A5 MUST BE BETWEEN 0.322 AND 0.436  
A1 = 0.372 A5 = 0.372 **VALID**
7. DIFFERENCE BETWEEN A1 AND A5 MUST BE < OR = .10A  
DIFFERENCE = 0.000 0.10A = 0.038 **VALID**
8.  $0.40 \cdot H_0$  MUST BE > OR = K<sub>F</sub>(MAX)  
K<sub>F</sub>(MAX) = 12.2 KSI(SQRT.IN.)  $0.40 \cdot H_0 = 42.0$  KSI(SQRT.IN.) **VALID**
9. K<sub>F</sub>(MAX)/B MUST BE < OR = 0.002  
K<sub>F</sub>(MAX)/B = 0.001 **VALID**
10. K-RATE MUST BE BETWEEN 30 AND 150 KSI(SQRT.IN.)/MIN  
K-RATE = 39 KSI (SQRT.IN.)/MIN **VALID**
11. PRECRACK LENGTH MUST BE > OR = 0.025W OR 0.05 IN.  
0.025W OR 0.050 IN. MIN. LENGTH = 0.052 IN. **VALID**
12. FATIGUE PRECRACK PLANE MUST BE < OR = 10 DEG. **VALID**
13. TEST CURVE INITIAL SLOPE MUST BE BETWEEN 0.7 AND 1.5  
ACTUAL SLOPE = 1.3 **VALID**

\*\*\* TEST IS INVALID PER ASTM-E399 ; K<sub>Q</sub> = 70.0 KSI(SQRT.IN.) \*\*\*

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

## CONTACT ELASTIC FRACTURE TOUGHNESS TEST REPORT (R-CURVE)

|                           |                           |                       |
|---------------------------|---------------------------|-----------------------|
| PRODUCT: NONE             | TEST TYPE: 0.400-C(T)     | ALLOY & TEMPER: TI 64 |
| MATERIAL SPEC.: NONE      | LAS NO.: 103923           | J.O. NO.: NONE        |
| LOT NUMBER: AAA-51        | PRODUCT THICKNESS: 0.000  | REC'D FROM: NONE      |
| TEST DATE: 620430         | TEST PLANE: 2/2           | TESTED AT: +73 F      |
| LOADING RATE: 931 LB/MIN. | DIRECTION: N/A            | MODULUS: 16.0 MEX     |
|                           | 48% RELATIVE HUMIDITY     |                       |
|                           | YIELD STRENGTH: 125.0 MEX |                       |

$\Delta X = 0.306$  INCH  
 $\Delta Y = 0.228$  INCH  
 $\Delta Z = 0.799$  INCH

```

VL = 0.0140 INCH
FM = 1.120 KIIPS
ADJUSTED R = 1.7919.79 KNI
R2C1 = 20.7811
R2C2 = 2.215 KIIPS
C2C3 = 0.4359045-03
AMR25 = 0.5434
RMR23 = 1.0844
RMR21 = 1.044 KNI
AC23 = 0.438 INCH

```

**EXCO - 50.7811**

**V25 = 0.0372 INCH**  
**CR25 = 60.225**      **ENC25 = 6.749078E-02**

0445 = 140.9 05 0000: 0000

| IN | P     | V     | A     | STRESS | K      | DAF   | RY    | SECAFT | ACME  | ICME |
|----|-------|-------|-------|--------|--------|-------|-------|--------|-------|------|
| 1  | 1.120 | 0.014 | 0.386 | 5.544  | 30.416 | 0.000 | 0.026 |        | 0.209 |      |
| 2  | 1.125 | 0.020 | 0.394 | 7.728  | 30.405 | 0.000 | 0.033 |        | 0.217 |      |
| 3  | 1.130 | 0.026 | 0.404 | 9.912  | 30.395 | 0.000 | 0.040 |        | 0.225 |      |
| 4  | 1.135 | 0.032 | 0.414 | 10.096 | 30.385 | 0.000 | 0.047 |        | 0.233 |      |
| 5  | 1.140 | 0.038 | 0.425 | 10.280 | 30.375 | 0.000 | 0.054 |        | 0.241 |      |
| 6  | 1.145 | 0.044 | 0.436 | 10.464 | 30.365 | 0.000 | 0.061 |        | 0.249 |      |
| 7  | 1.150 | 0.050 | 0.447 | 10.648 | 30.355 | 0.000 | 0.068 |        | 0.257 |      |
| 8  | 1.155 | 0.056 | 0.458 | 10.832 | 30.345 | 0.000 | 0.075 |        | 0.265 |      |
| 9  | 1.160 | 0.062 | 0.469 | 11.016 | 30.335 | 0.000 | 0.082 |        | 0.273 |      |
| 10 | 1.165 | 0.068 | 0.480 | 11.200 | 30.325 | 0.000 | 0.089 |        | 0.281 |      |
| 11 | 1.170 | 0.074 | 0.491 | 11.384 | 30.315 | 0.000 | 0.096 |        | 0.289 |      |
| 12 | 1.175 | 0.080 | 0.502 | 11.568 | 30.305 | 0.000 | 0.103 |        | 0.297 |      |
| 13 | 1.180 | 0.086 | 0.513 | 11.752 | 30.295 | 0.000 | 0.110 |        | 0.305 |      |
| 14 | 1.185 | 0.092 | 0.524 | 11.936 | 30.285 | 0.000 | 0.117 |        | 0.313 |      |
| 15 | 1.190 | 0.098 | 0.535 | 12.120 | 30.275 | 0.000 | 0.124 |        | 0.321 |      |
| 16 | 1.195 | 0.104 | 0.546 | 12.304 | 30.265 | 0.000 | 0.131 |        | 0.329 |      |
| 17 | 1.200 | 0.110 | 0.557 | 12.488 | 30.255 | 0.000 | 0.138 |        | 0.337 |      |
| 18 | 1.205 | 0.116 | 0.568 | 12.672 | 30.245 | 0.000 | 0.145 |        | 0.345 |      |
| 19 | 1.210 | 0.122 | 0.579 | 12.856 | 30.235 | 0.000 | 0.152 |        | 0.353 |      |
| 20 | 1.215 | 0.128 | 0.590 | 13.040 | 30.225 | 0.000 | 0.159 |        | 0.361 |      |
| 21 | 1.220 | 0.134 | 0.601 | 13.224 | 30.215 | 0.000 | 0.166 |        | 0.369 |      |
| 22 | 1.225 | 0.140 | 0.612 | 13.408 | 30.205 | 0.000 | 0.173 |        | 0.377 |      |
| 23 | 1.230 | 0.146 | 0.623 | 13.592 | 30.195 | 0.000 | 0.180 |        | 0.385 |      |
| 24 | 1.235 | 0.152 | 0.634 | 13.776 | 30.185 | 0.000 | 0.187 |        | 0.393 |      |
| 25 | 1.240 | 0.158 | 0.645 | 13.960 | 30.175 | 0.000 | 0.194 |        | 0.401 |      |
| 26 | 1.245 | 0.164 | 0.656 | 14.144 | 30.165 | 0.000 | 0.201 |        | 0.409 |      |
| 27 | 1.250 | 0.170 | 0.667 | 14.328 | 30.155 | 0.000 | 0.208 |        | 0.417 |      |
| 28 | 1.255 | 0.176 | 0.678 | 14.512 | 30.145 | 0.000 | 0.215 |        | 0.425 |      |
| 29 | 1.260 | 0.182 | 0.689 | 14.696 | 30.135 | 0.000 | 0.222 |        | 0.433 |      |
| 30 | 1.265 | 0.188 | 0.700 | 14.880 | 30.125 | 0.000 | 0.229 |        | 0.441 |      |
| 31 | 1.270 | 0.194 | 0.711 | 15.064 | 30.115 | 0.000 | 0.236 |        | 0.449 |      |
| 32 | 1.275 | 0.200 | 0.722 | 15.248 | 30.105 | 0.000 | 0.243 |        | 0.457 |      |
| 33 | 1.280 | 0.206 | 0.733 | 15.432 | 30.095 | 0.000 | 0.250 |        | 0.465 |      |
| 34 | 1.285 | 0.212 | 0.744 | 15.616 | 30.085 | 0.000 | 0.257 |        | 0.473 |      |
| 35 | 1.290 | 0.218 | 0.755 | 15.800 | 30.075 | 0.000 | 0.264 |        | 0.481 |      |
| 36 | 1.295 | 0.224 | 0.766 | 15.984 | 30.065 | 0.000 | 0.271 |        | 0.489 |      |
| 37 | 1.300 | 0.230 | 0.777 | 16.168 | 30.055 | 0.000 | 0.278 |        | 0.497 |      |
| 38 | 1.305 | 0.236 | 0.788 | 16.352 | 30.045 | 0.000 | 0.285 |        | 0.505 |      |
| 39 | 1.310 | 0.242 | 0.799 | 16.536 | 30.035 | 0.000 | 0.292 |        | 0.513 |      |

REMAINING UNCRACKED LIGAMENT LENGTH IS LESS THAN (1.27324\*(R/YLDSR)\*\*2)  
LIMITING VALUES ARE R= 49.68 KSI SORT(IN) LIGAMENT LENGTH = 0.3957 IN.

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

COMPACT TENSION FRACTURE TOUGHNESS TEST REPORT (R-CURVE)

|                           |                           |                       |
|---------------------------|---------------------------|-----------------------|
| PRODUCT: NONE             | TEST TYPE: 0.400-C(T)     | ALLOY & TEMPER: TI 64 |
| MATERIAL SPEC.: NONE      | LAB NO.: 103983           | J.O. NO.: NONE        |
| LOT NUMBER: 4AC-01        | PRODUCT THICKNESS: 0.000  | REC'D FROM: NONE      |
| TEST DATE: 920430         | TEST FLAKE: 7/2           | TESTED AT: +73 F      |
| LOADING RATE: 936 LB/MIN. | DIRECTION: W/A            | MODULUS: 16.0 MSI     |
|                           | 48% RELATIVE HUMIDITY     |                       |
|                           | YIELD STRENGTH: 123.0 KSI |                       |

AI = 0.262 INCH  
S = 0.250 INCH  
W = 0.799 INCH

VL = 0.0130 INCH  
PL = 1.035 KIPS  
ADJUSTED S = 13974.07 KSI  
RCL = 40.8003  
PL = 2.044 KIPS  
CC = 1.079943E-05  
RCL = 0.5983  
PL = 18.7336  
RCL = 10.479 KSI  
AC = 0.429 INCH

EDCO = 49.8803

VC = 0.0379 INCH  
CHSCN = 64.783 EDC = 6.465756E-02

KMAX = 112.7 KSI SQRT. INCH

| N | P     | V     | A     | STRESS | K       | DAF   | RY    | SECANT | ACHK  | ICBK |
|---|-------|-------|-------|--------|---------|-------|-------|--------|-------|------|
| 1 | 1.055 | 0.015 | 0.262 | 5.345  | 48.399  | 0.000 | 0.024 | 0      | 0.191 | 0    |
| 2 | 1.450 | 0.025 | 0.370 | 7.374  | 64.442  | 0.009 | 0.049 | 0      | 0.282 | 0    |
| 3 | 1.720 | 0.037 | 0.400 | 8.747  | 84.266  | 0.018 | 0.072 | 10     | 0.378 | 0    |
| 4 | 1.900 | 0.051 | 0.410 | 9.642  | 89.334  | 0.028 | 0.094 | 15     | 0.459 | 0    |
| 5 | 2.020 | 0.064 | 0.421 | 10.272 | 107.157 | 0.039 | 0.117 | 20     | 0.536 | 0    |
| 6 | 2.040 | 0.068 | 0.429 | 10.475 | 112.743 | 0.046 | 0.130 | 25     | 1.036 | 1    |

1 = REMAINING UNCRACKED LIGAMENT LENGTH IS 1.200 INCH (1.27124\*(R/TLDSTR)\*\*2)  
LIMITING VALUES ARE S= 71.09 KSI SQRT(IN) LIGAMENT LENGTH = 0.4118 IN.

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

COMPACT TENSION FRACTURE TOUGHNESS TEST REPORT (R-CURVE)

|                           |                           |                       |
|---------------------------|---------------------------|-----------------------|
| PRODUCT: NONE             | TEST TYPE: C-400-C(T)     | ALLOT & TEMPER: TI 64 |
| MATERIAL SPEC: NONE       | AS NO: 103983             | J.O. NO: 1 NONE       |
| LOT NUMBER: 44-01         | PRODUCT THICKNESS: 0.000  | REC'D FROM: NONE      |
| TEST DATE: 920410         | TEST PLANE: 7/1           | TESTED AT: +75 F      |
| LOADING RATE: 900 LB/MIN. | DIRECTION: R/A            | MODULUS: 16.0 ksi     |
|                           | 431 RELATIVE HUMIDITY     |                       |
|                           | YIELD STRENGTH: 125.0 ksi |                       |

AZ = 0.379 INCH  
B = 0.344 INCH  
W = 0.799 INCH

VL = 0.0111 INCH  
FM = 0.948 KIPS  
ADJUSTED S = 17098.65 ksi  
SCL = 49.0878  
V25 = 0.0373 INCH  
C15 = 6.496315E-02  
SCL25 = 10.8087  
SCL15 = 10.8087  
AC15 = 0.430 INCH

EMCO = 49.0878

V25 = 0.0373 INCH  
C15 = 6.496315E-02  
SCL25 = 10.8087

EMAS = 125.0 ksi  
EMIS = 118.8 ksi

| N   | P      | V      | A     | STRESS  | K        | DAF   | KY    | SECANT | ACIK   | ICIK |
|-----|--------|--------|-------|---------|----------|-------|-------|--------|--------|------|
| 1   | 0.948  | 0.0111 | 0.379 | 4.311   | 25.483   | 0.000 | 0.013 | 0      | 0.121  | 0    |
| 2   | 1.720  | 0.0211 | 0.379 | 7.822   | 72.083   | 0.000 | 0.023 | 0      | 0.242  | 0    |
| 3   | 2.492  | 0.0311 | 0.379 | 11.333  | 118.883  | 0.000 | 0.033 | 0      | 0.363  | 0    |
| 4   | 3.264  | 0.0411 | 0.379 | 14.844  | 165.683  | 0.000 | 0.043 | 0      | 0.484  | 0    |
| 5   | 4.036  | 0.0511 | 0.379 | 18.355  | 212.483  | 0.000 | 0.053 | 0      | 0.605  | 0    |
| 6   | 4.808  | 0.0611 | 0.379 | 21.866  | 259.283  | 0.000 | 0.063 | 0      | 0.726  | 0    |
| 7   | 5.580  | 0.0711 | 0.379 | 25.377  | 306.083  | 0.000 | 0.073 | 0      | 0.847  | 0    |
| 8   | 6.352  | 0.0811 | 0.379 | 28.888  | 352.883  | 0.000 | 0.083 | 0      | 0.968  | 0    |
| 9   | 7.124  | 0.0911 | 0.379 | 32.399  | 399.683  | 0.000 | 0.093 | 0      | 1.089  | 0    |
| 10  | 7.896  | 0.1011 | 0.379 | 35.910  | 446.483  | 0.000 | 0.103 | 0      | 1.210  | 0    |
| 11  | 8.668  | 0.1111 | 0.379 | 39.421  | 493.283  | 0.000 | 0.113 | 0      | 1.331  | 0    |
| 12  | 9.440  | 0.1211 | 0.379 | 42.932  | 540.083  | 0.000 | 0.123 | 0      | 1.452  | 0    |
| 13  | 10.212 | 0.1311 | 0.379 | 46.443  | 586.883  | 0.000 | 0.133 | 0      | 1.573  | 0    |
| 14  | 10.984 | 0.1411 | 0.379 | 49.954  | 633.683  | 0.000 | 0.143 | 0      | 1.694  | 0    |
| 15  | 11.756 | 0.1511 | 0.379 | 53.465  | 680.483  | 0.000 | 0.153 | 0      | 1.815  | 0    |
| 16  | 12.528 | 0.1611 | 0.379 | 56.976  | 727.283  | 0.000 | 0.163 | 0      | 1.936  | 0    |
| 17  | 13.300 | 0.1711 | 0.379 | 60.487  | 774.083  | 0.000 | 0.173 | 0      | 2.057  | 0    |
| 18  | 14.072 | 0.1811 | 0.379 | 63.998  | 820.883  | 0.000 | 0.183 | 0      | 2.178  | 0    |
| 19  | 14.844 | 0.1911 | 0.379 | 67.509  | 867.683  | 0.000 | 0.193 | 0      | 2.299  | 0    |
| 20  | 15.616 | 0.2011 | 0.379 | 71.020  | 914.483  | 0.000 | 0.203 | 0      | 2.420  | 0    |
| 21  | 16.388 | 0.2111 | 0.379 | 74.531  | 961.283  | 0.000 | 0.213 | 0      | 2.541  | 0    |
| 22  | 17.160 | 0.2211 | 0.379 | 78.042  | 1008.083 | 0.000 | 0.223 | 0      | 2.662  | 0    |
| 23  | 17.932 | 0.2311 | 0.379 | 81.553  | 1054.883 | 0.000 | 0.233 | 0      | 2.783  | 0    |
| 24  | 18.704 | 0.2411 | 0.379 | 85.064  | 1101.683 | 0.000 | 0.243 | 0      | 2.904  | 0    |
| 25  | 19.476 | 0.2511 | 0.379 | 88.575  | 1148.483 | 0.000 | 0.253 | 0      | 3.025  | 0    |
| 26  | 20.248 | 0.2611 | 0.379 | 92.086  | 1195.283 | 0.000 | 0.263 | 0      | 3.146  | 0    |
| 27  | 21.020 | 0.2711 | 0.379 | 95.597  | 1242.083 | 0.000 | 0.273 | 0      | 3.267  | 0    |
| 28  | 21.792 | 0.2811 | 0.379 | 99.108  | 1288.883 | 0.000 | 0.283 | 0      | 3.388  | 0    |
| 29  | 22.564 | 0.2911 | 0.379 | 102.619 | 1335.683 | 0.000 | 0.293 | 0      | 3.509  | 0    |
| 30  | 23.336 | 0.3011 | 0.379 | 106.130 | 1382.483 | 0.000 | 0.303 | 0      | 3.630  | 0    |
| 31  | 24.108 | 0.3111 | 0.379 | 109.641 | 1429.283 | 0.000 | 0.313 | 0      | 3.751  | 0    |
| 32  | 24.880 | 0.3211 | 0.379 | 113.152 | 1476.083 | 0.000 | 0.323 | 0      | 3.872  | 0    |
| 33  | 25.652 | 0.3311 | 0.379 | 116.663 | 1522.883 | 0.000 | 0.333 | 0      | 3.993  | 0    |
| 34  | 26.424 | 0.3411 | 0.379 | 120.174 | 1569.683 | 0.000 | 0.343 | 0      | 4.114  | 0    |
| 35  | 27.196 | 0.3511 | 0.379 | 123.685 | 1616.483 | 0.000 | 0.353 | 0      | 4.235  | 0    |
| 36  | 27.968 | 0.3611 | 0.379 | 127.196 | 1663.283 | 0.000 | 0.363 | 0      | 4.356  | 0    |
| 37  | 28.740 | 0.3711 | 0.379 | 130.707 | 1710.083 | 0.000 | 0.373 | 0      | 4.477  | 0    |
| 38  | 29.512 | 0.3811 | 0.379 | 134.218 | 1756.883 | 0.000 | 0.383 | 0      | 4.598  | 0    |
| 39  | 30.284 | 0.3911 | 0.379 | 137.729 | 1803.683 | 0.000 | 0.393 | 0      | 4.719  | 0    |
| 40  | 31.056 | 0.4011 | 0.379 | 141.240 | 1850.483 | 0.000 | 0.403 | 0      | 4.840  | 0    |
| 41  | 31.828 | 0.4111 | 0.379 | 144.751 | 1897.283 | 0.000 | 0.413 | 0      | 4.961  | 0    |
| 42  | 32.600 | 0.4211 | 0.379 | 148.262 | 1944.083 | 0.000 | 0.423 | 0      | 5.082  | 0    |
| 43  | 33.372 | 0.4311 | 0.379 | 151.773 | 1990.883 | 0.000 | 0.433 | 0      | 5.203  | 0    |
| 44  | 34.144 | 0.4411 | 0.379 | 155.284 | 2037.683 | 0.000 | 0.443 | 0      | 5.324  | 0    |
| 45  | 34.916 | 0.4511 | 0.379 | 158.795 | 2084.483 | 0.000 | 0.453 | 0      | 5.445  | 0    |
| 46  | 35.688 | 0.4611 | 0.379 | 162.306 | 2131.283 | 0.000 | 0.463 | 0      | 5.566  | 0    |
| 47  | 36.460 | 0.4711 | 0.379 | 165.817 | 2178.083 | 0.000 | 0.473 | 0      | 5.687  | 0    |
| 48  | 37.232 | 0.4811 | 0.379 | 169.328 | 2224.883 | 0.000 | 0.483 | 0      | 5.808  | 0    |
| 49  | 38.004 | 0.4911 | 0.379 | 172.839 | 2271.683 | 0.000 | 0.493 | 0      | 5.929  | 0    |
| 50  | 38.776 | 0.5011 | 0.379 | 176.350 | 2318.483 | 0.000 | 0.503 | 0      | 6.050  | 0    |
| 51  | 39.548 | 0.5111 | 0.379 | 179.861 | 2365.283 | 0.000 | 0.513 | 0      | 6.171  | 0    |
| 52  | 40.320 | 0.5211 | 0.379 | 183.372 | 2412.083 | 0.000 | 0.523 | 0      | 6.292  | 0    |
| 53  | 41.092 | 0.5311 | 0.379 | 186.883 | 2458.883 | 0.000 | 0.533 | 0      | 6.413  | 0    |
| 54  | 41.864 | 0.5411 | 0.379 | 190.394 | 2505.683 | 0.000 | 0.543 | 0      | 6.534  | 0    |
| 55  | 42.636 | 0.5511 | 0.379 | 193.905 | 2552.483 | 0.000 | 0.553 | 0      | 6.655  | 0    |
| 56  | 43.408 | 0.5611 | 0.379 | 197.416 | 2599.283 | 0.000 | 0.563 | 0      | 6.776  | 0    |
| 57  | 44.180 | 0.5711 | 0.379 | 200.927 | 2646.083 | 0.000 | 0.573 | 0      | 6.897  | 0    |
| 58  | 44.952 | 0.5811 | 0.379 | 204.438 | 2692.883 | 0.000 | 0.583 | 0      | 7.018  | 0    |
| 59  | 45.724 | 0.5911 | 0.379 | 207.949 | 2739.683 | 0.000 | 0.593 | 0      | 7.139  | 0    |
| 60  | 46.496 | 0.6011 | 0.379 | 211.460 | 2786.483 | 0.000 | 0.603 | 0      | 7.260  | 0    |
| 61  | 47.268 | 0.6111 | 0.379 | 214.971 | 2833.283 | 0.000 | 0.613 | 0      | 7.381  | 0    |
| 62  | 48.040 | 0.6211 | 0.379 | 218.482 | 2880.083 | 0.000 | 0.623 | 0      | 7.502  | 0    |
| 63  | 48.812 | 0.6311 | 0.379 | 221.993 | 2926.883 | 0.000 | 0.633 | 0      | 7.623  | 0    |
| 64  | 49.584 | 0.6411 | 0.379 | 225.504 | 2973.683 | 0.000 | 0.643 | 0      | 7.744  | 0    |
| 65  | 50.356 | 0.6511 | 0.379 | 229.015 | 3020.483 | 0.000 | 0.653 | 0      | 7.865  | 0    |
| 66  | 51.128 | 0.6611 | 0.379 | 232.526 | 3067.283 | 0.000 | 0.663 | 0      | 7.986  | 0    |
| 67  | 51.900 | 0.6711 | 0.379 | 236.037 | 3114.083 | 0.000 | 0.673 | 0      | 8.107  | 0    |
| 68  | 52.672 | 0.6811 | 0.379 | 239.548 | 3160.883 | 0.000 | 0.683 | 0      | 8.228  | 0    |
| 69  | 53.444 | 0.6911 | 0.379 | 243.059 | 3207.683 | 0.000 | 0.693 | 0      | 8.349  | 0    |
| 70  | 54.216 | 0.7011 | 0.379 | 246.570 | 3254.483 | 0.000 | 0.703 | 0      | 8.470  | 0    |
| 71  | 54.988 | 0.7111 | 0.379 | 250.081 | 3301.283 | 0.000 | 0.713 | 0      | 8.591  | 0    |
| 72  | 55.760 | 0.7211 | 0.379 | 253.592 | 3348.083 | 0.000 | 0.723 | 0      | 8.712  | 0    |
| 73  | 56.532 | 0.7311 | 0.379 | 257.103 | 3394.883 | 0.000 | 0.733 | 0      | 8.833  | 0    |
| 74  | 57.304 | 0.7411 | 0.379 | 260.614 | 3441.683 | 0.000 | 0.743 | 0      | 8.954  | 0    |
| 75  | 58.076 | 0.7511 | 0.379 | 264.125 | 3488.483 | 0.000 | 0.753 | 0      | 9.075  | 0    |
| 76  | 58.848 | 0.7611 | 0.379 | 267.636 | 3535.283 | 0.000 | 0.763 | 0      | 9.196  | 0    |
| 77  | 59.620 | 0.7711 | 0.379 | 271.147 | 3582.083 | 0.000 | 0.773 | 0      | 9.317  | 0    |
| 78  | 60.392 | 0.7811 | 0.379 | 274.658 | 3628.883 | 0.000 | 0.783 | 0      | 9.438  | 0    |
| 79  | 61.164 | 0.7911 | 0.379 | 278.169 | 3675.683 | 0.000 | 0.793 | 0      | 9.559  | 0    |
| 80  | 61.936 | 0.8011 | 0.379 | 281.680 | 3722.483 | 0.000 | 0.803 | 0      | 9.680  | 0    |
| 81  | 62.708 | 0.8111 | 0.379 | 285.191 | 3769.283 | 0.000 | 0.813 | 0      | 9.801  | 0    |
| 82  | 63.480 | 0.8211 | 0.379 | 288.702 | 3816.083 | 0.000 | 0.823 | 0      | 9.922  | 0    |
| 83  | 64.252 | 0.8311 | 0.379 | 292.213 | 3862.883 | 0.000 | 0.833 | 0      | 10.043 | 0    |
| 84  | 65.024 | 0.8411 | 0.379 | 295.724 | 3909.683 | 0.000 | 0.843 | 0      | 10.164 | 0    |
| 85  | 65.796 | 0.8511 | 0.379 | 299.235 | 3956.483 | 0.000 | 0.853 | 0      | 10.285 | 0    |
| 86  | 66.568 | 0.8611 | 0.379 | 302.746 | 4003.283 | 0.000 | 0.863 | 0      | 10.406 | 0    |
| 87  | 67.340 | 0.8711 | 0.379 | 306.257 | 4050.083 | 0.000 | 0.873 | 0      | 10.527 | 0    |
| 88  | 68.112 | 0.8811 | 0.379 | 309.768 | 4096.883 | 0.000 | 0.883 | 0      | 10.648 | 0    |
| 89  | 68.884 | 0.8911 | 0.379 | 313.279 | 4143.683 | 0.000 | 0.893 | 0      | 10.769 | 0    |
| 90  | 69.656 | 0.9011 | 0.379 | 316.790 | 4190.483 | 0.000 | 0.903 | 0      | 10.890 | 0    |
| 91  | 70.428 | 0.9111 | 0.379 | 320.301 | 4237.283 | 0.000 | 0.913 | 0      | 11.011 | 0    |
| 92  | 71.200 | 0.9211 | 0.379 | 323.812 | 4284.083 | 0.000 | 0.923 | 0      | 11.132 | 0    |
| 93  | 71.972 | 0.9311 | 0.379 | 327.323 | 4330.883 | 0.000 | 0.933 | 0      | 11.253 | 0    |
| 94  | 72.744 | 0.9411 | 0.379 | 330.834 | 4377.683 | 0.000 | 0.943 | 0      | 11.374 | 0    |
| 95  | 73.516 | 0.9511 | 0.379 | 334.345 | 4424.483 | 0.000 | 0.953 | 0      | 11.495 | 0    |
| 96  | 74.288 | 0.9611 | 0.379 | 337.856 | 4471.283 | 0.000 | 0.963 | 0      | 11.616 | 0    |
| 97  | 75.060 | 0.9711 | 0.379 | 341.367 | 4518.083 | 0.000 | 0.973 | 0      | 11.737 | 0    |
| 98  | 75.832 | 0.9811 | 0.379 | 344.878 | 4564.883 | 0.000 | 0.983 | 0      | 11.858 | 0    |
| 99  | 76.604 | 0.9911 | 0.379 | 348.389 | 4611.683 | 0.000 | 0.993 | 0      | 11.979 | 0    |
| 100 | 77.376 | 1.0011 | 0.379 | 351.900 | 4658.483 | 0.000 | 1.003 | 0      | 12.100 | 0    |

1 - REMAINING UNCRACKED LIGAMENT LENGTH IS LESS THAN  $(1.37324 \cdot (E/YLDSR)^{0.2})$   
LIMITING VALUES ARE E = 69.94 ksi SQRT(IN) LIGAMENT LENGTH = 0.3969 IN.

**SUPPLEMENTARY**

**INFORMATION**



DEPARTMENT OF THE AIR FORCE

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

*ERRATA - A264414*

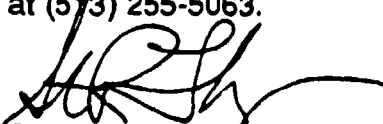
FROM: WL/MLSE Bldg 652  
2179 Twelfth St Ste 1  
Wright-Patterson AFB OH 45433-7718

4 June 93

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

TO: Distribution List

1. Please note that an error has been found in the subject report on page 31. The error is in the derived properties; compression, bearing, and shear.
2. Attached is a corrected table to replace the one in error.
3. If you have any questions concerning this, the point of contact is Steven Thompson at (513) 255-5063.

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

1 Atch  
Distribution List

**Mechanical & Physical Properties For  
TI-64, Investment Cast**

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

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

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