POWDER METALLURGY PRODUCTS FOR ADVANCED GAS TURBINE APPLICATIONS

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ABSTRACT

Recent advances in the field of powder metallurgy have made possible the production of alloy powders exhibiting high levels of purity. By appropriate consolidation and subsequent thermomechanical processing, it has been possible to produce segregation free wrought forms of high alloy content which exhibit attractive mechanical properties for gas turbine applications.

At Avco Lycoming, powder metallurgy activity has focused upon a series of high strength nickel base superalloys. These alloys which are modifications of IN792 were developed for turbine disc applications where high strength-to-density properties are of interest. The alloy powders used for these development efforts carry the Lycoming designation of PA 101. Production of the powders was by argon gas atomization; after consolidation by extrusion and subsequent forging operations, oxygen levels were determined to be less than 100 ppm.

With this approach, processing conditions were developed that resulted in turbine discs which exhibited mechanical properties superior to those of conventionally processed D979, Inconel 718 and Rene' 95. In addition, workability and alloy homogeneity were determined to be excellent. The results of this work are presented in terms of microstructure, tensile, stress rupture and low cycle fatigue properties.

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INTRODUCTION

With the emergence of a new generation of high performance gas turbine engines such as the F102-LD-100, PLT 27, and AGT 1500, requirements are intensifying for improved high-strength wrought materials to meet stringent performance, weight and reliability criteria.

In particular, materials such as D979 and Inconel 718, although performing credibly in contemporary engines, do not possess the strength/density characteristics needed for advanced engines. Attempts to develop more highly alloyed compositions for this class of application utilizing conventional melting and working techniques unfortunately have been beset by a multitude of problems involving segregation, workability and ductility deficiencies. Recent advances in the area of powder metallurgy, however, have created potential for a whole new spectrum of improved high strength compositions for gas turbine applications. These advances, which have resulted in the availability of low oxygen content alloy powders, focus upon the ability of the powder metallurgy approach to produce highly alloyed segregation free material in a fully consolidated state.

At Avco Lycoming, work in the powder metallurgy area has centered upon the development of high strength/density compositions for moderate temperature turbine disc applications. In this work, a basic C101 alloy composition (a derivative of IN792 and designated as PA 101 in the wrought form) has been employed. As shown in Table I, the C101 alloy is a nickel base superalloy designed for cast turbine blade applications which develops its strength by the addition of refractory metal elements such as tungsten, molybdenum and chromium. In addition, a fine dispersion of gamma prime, Ni_3 (Al, Ti), provides age hardening. Hafnium is also present in the alloy to promote intermediate temperature strength and ductility.

Of the cast high strength superalloy compositions commercially available today none can outperform the strength capability of the C101 composition at temperatures up to 1400° F. Figure 1 shows a comparison of room temperature tensile and 1400° F stress rupture properties of cast C101 and IN100. As indicated, the C101 alloy is clearly superior in strength with more than adequate ductility.

Because of the outstanding level of strength and ductility exhibited by the cast form of the alloy, the potential existed for a wrought form of the alloy if thermomechanical processing (TMP) techniques could be tailored to the compositions' high alloy content. Powder metallurgy techniques, therefore, were considered for the alloy because this approach offered hope for improved workability through the development of a fully homogeneous structure.

Efforts to evaluate C101 as a powder metallurgy product began in 1970 when small heat lots of cast alloy remelt stock were argon atomized and consolidated by extrusion into small diameter (i.e., 0.5 inch diameter) bar stock for basic evaluation of extrusion parameters and heat treatment. The results of this early effort were sufficiently encouraging to justify the expansion of the program. As a result, additional material was argon atomized, extruded to two inch diameter bar stock and upset forged into sub-scale pancakes. After completing the evaluation of the two inch diameter bar and pancake forgings produced from this stock, the effort was scaled up to the production of four inch diameter extruded billet and subsequent forging of ten inch diameter turbine discs.

The following presents the details of Lycoming's PA 101 development activities ranging from the sub-scale two inch diameter extruded billet work through to the scale-up evaluation of the ten inch diameter forgings. Presented also is the status of alloy modification work which has recently been initiated for the PA 101 alloy system.

PROCESSING APPROACH

Sub-Scale Powder Atomization Effort

The PA 101 powder employed for this program was argon gas atomized by the Federal Mogul Corporation at their Ann Arbor, Michigan pilot plant facility. Starting material for the atomization was vacuum melted C101 remelt stock. The atomization process consisted of vacuum induction melting, back-filling of the melting chamber with a positive pressure of argon and atomizing by gravity feeding liquid metal through a ceramic nozzle. As the metal passed out the bottom of the nozzle a jet of argon impinged on the molten stream and atomized the material which was collected in an argon filled chamber below.

After atomization, the powder was classified according to particle size. A typical particle size distribution curve for the PA 101 powder is shown in Figure 2. As indicated, about 20 percent of the entire powder yield was +100 mesh size, 45 percent -100 + 325 mesh size and 35 percent -325 mesh size. Oxygen contents of the powders produced for the program typically were 50 ppm for the -20 +100 mesh particles, 80 ppm for the -100 +325 mesh particles and 120 ppm for the -325 mesh particles.

Sub-Scale Consolidation Effort

Extrusion was selected as the technique for the consolidation of the PA 101 powders because it offered the best potential for obtaining fully dense structures. In addition, the advanced nature of extrusion technology and the wide availability of extrusion equipment indicated that minimal difficulties with consolidation were likely to occur during the critical early phases of the program.

Of the alloy powder produced, only the -100 mesh particles were used for canning. The +100 mesh particles were not used because they contained higher impurity levels (i. e., non-metallic inclusions). The cans utilized consisted of stainless steel tubes, 4-3/4 inches inside diameter and 5-5/8 inches outside diameter, each of which had a stainless steel plug approximately two inches thick electron beam welded to one end. The cans were vibrated as the powder was added to achieve the greatest possible tap density (e. g., 65 to 70 percent). Once the cans were filled with approximately 50 pounds of powder, two inch thick stainless steel plugs containing hollow stems for evacuation were electron beam welded to the open ends. The cans were evacuated to 10^{-4} microns, during which they were induction heated to approximately 1000° F to drive off adsorbed gases. Sealing was performed by peening the evacuation tube and TIG welding.

Extrusion of the cans was performed at Allegheny Ludlum Steel Corporation's Watervliet, New York plant using a 2200 ton horizontal press. An extrusion temperature of 2025° F, an extrusion ratio of 8:1 and a ram speed of 150 inches/minute were employed for this work because prior experience had indicated these to be optimum for the PA 101 alloy. Yield from the extrusion run was excellent; it consisted of 80 to 85 percent of the starting powder material and no cracking or other abnormalities were developed in the extruded product.

After extrusion, each of the bars was evaluated for oxygen content, microstructure and tensile properties. Oxygen analysis showed all billets to contain less than 100 ppm, indicating that canning procedures had been satisfactory and that air contamination had not occurred. Examination of the specimens representative of these bars with an optical microscope (Figure 3) revealed an extremely fine uniform structure; small MC-type carbides were randomly distributed throughout and a large amount of gamma prime precipitate was present. Due to the fineness of the structure, however, it was not possible to determine grain size. Consequently, the electron microscope was employed to further resolve the structure.

Electron microscopy (Figure 3) revealed an extremely fine grain size determined to be between two and four microns in diameter (i. e. , ASTM No. 14). The large gamma prime particles were in the range from one to two microns in size and a very fine gamma prime precipitate of approximately 1/4 to 1/2 microns in size was also evident. No large carbides were apparent, and grain boundries were free of precipitate.

Because of the ultra fine grain size developed in this material a superplasticity study was initiated. As a result, several tensile specimens were sectioned from as-extruded bar. The first of these was tested at 1850° F at a strain rate of 0. 005 inches/inch/second and exhibited an elongation of over 1000 percent, clearly indicating superplastic behavior. Since interest in the alloy was primarily for moderate temperature turbine disc applications in which good fatigue and tensile strength are the mechanical properties of major concern, the study was expanded and included testing at additional temperatures to define the lower limit of workability, which would also establish the condition for finest grain size in the forged product. Consequently, additional tests were run at 1800° F, 1750° F, 1700° F and 1650° F.

As indicated by Figure 4, superplastic behavior was exhibited to test temperatures as low as 1750° F. When these test temperatures were translated into forging furnace temperatures, it appeared that the material could be forged at 1850° F and possibly even lower (e. g. , a 1750° F press temperature is roughly equivalent to a furnace temperature of 1850° F because of heat lost during transfer).

The results of this work were considered significant because an alloy system with high strength potential was exhibiting outstanding workability. These characteristics could lead to forging closer to net shape with reduced input weight and machining requirements.

In addition to workability studies, a limited amount of mechanical property testing was conducted on heat treated material to establish a baseline for determining the effects of subsequent thermomechanical processing on the alloy. Specifically, sections of bars were heat treated and tensile tested at room temperature. The heat treatment employed for this and subsequent work was a direct age at 1300°F for 50 hours. Selection of this cycle was based upon previous work with 0.5 inch diameter extruded bar which demonstrated yield strengths in excess of 200 ksi, ultimate strengths in excess of 250 ksi and elongations of 12 percent and better.

Results of the tensile tests performed on material representative of the two inch extrusions are presented in Table II. As indicated, the material exhibited excellent levels of strength with good levels of ductility. By comparison, these properties are superior to those of conventional wrought Inco 718 (i.e., typical: 0.2 percent yield strength - 170 ksi, elongation - 25 percent at room temperature) and comparable to those of forged Rene' 95 powder product (i.e., 0.2 percent yield strength - 210 ksi, elongation 15 percent). Metallographic examination performed on these test specimens revealed the volume of aging gamma prime in the matrix increased slightly over that present in the as-extruded material. Other than this no significant changes had occurred to the structure. An electron photomicrograph of the heat treated microstructures is presented in Figure 5.

Sub-Scale Pancake Forgings

Because of the superplastic behavior and excellent levels of tensile strength demonstrated by the two inch diameter extruded PA 101 bar stock, a forging program was initiated to explore the alloy's forgeability and mechanical property capability. Consequently, forging mults five inches long were sectioned from the two inch bar. The surface of each mult was turned to clean off the oxide scale and the ends were beveled to 45°. The machined mults were then wrapped in Silltemp for insulation and 1/16 inch thick mild steel sheets were attached to the top and bottom faces. Forging of the mults was conducted at the Wyman Gordon Company, North Grafton, Massachusetts on a 1500 ton laboratory press. A forging furnace temperature of 1850°F was selected on the basis of the as-extruded tensile test results previously discussed. Prior to forging, the mults were equalized for one hour at 1600°F following which they were charged at 1850°F and held for four hours.

Each five inch high mult was successfully forged in one pass to 3/4 inch thickness. All pancakes were crack free and exhibited outstanding surface smoothness at their edges. Less than ten percent of the press capacity was required for this work, much less than for conventional superalloys. Photographs of two typical pancake forgings produced from this effort are presented in Figure 6.

After forging, the pancakes were examined metallographically with both the optical and electron microscope. As in the case of the two inch extruded bar, the structure was very uniform and grain size could not be resolved due to its fineness. Examination of the structure with the electron microscope revealed a grain size of approximately ASTM No. 14. By comparison (Figure 7) to the microstructure developed in the as-extruded bar, the as-forged structure was very similar, although there was not as much fine gamma prime in the forging due to the intermediate temperature processing which resulted in a partial solutioning of the fine cooling gamma prime previously present.

After evaluation of microstructure, the pancake forgings were heat treated and tensile properties at room temperature, stress rupture properties at 1200° F/150 ksi and smooth bar low cycle fatigue properties at 900° F were determined.

As shown in Figure 8, an outstanding level of tensile capability was developed in the pancake forgings. By comparison, to the as-extruded bar stock, strength was higher reflecting the increased warm work introduced into the material by the forging process. Of major interest, however, was the superior tensile strength levels developed relative to Inco 718 and D979, two superalloys which are bill-of-material in several different contemporary gas turbine engine designs.

Stress rupture properties developed for the pancake forgings are presented in Figure 9. As with the tensile properties, the stress rupture capability of the PA 101 alloy was substantially improved over that obtainable with either the Inco 718 or D979 alloys. In addition, the forgings exhibited good levels of stress rupture ductility (7 percent elongation), a characteristic often difficult to develop in high strength alloys.

Load controlled smooth bar low cycle fatigue properties developed for the forgings at 900° F are shown in Figure 10. As indicated, the low cycle fatigue strength exhibited by the forgings was outstanding, outperforming both Inco 718 and D979 tested to similar conditions. From an engineering standpoint, these levels of strength mean longer life and lower weight turbine discs for advanced engine applications.

Overall, the workability, microstructural uniformity and mechanical properties developed for this series of forgings was outstanding. With this encouragement, the program was scaled-up to produce and evaluate full sized Lycoming turbine discs.

Scale-Up for Turbine Hardware

A ten inch diameter Lycoming turbine disc for an upgraded T53 engine design was chosen as the scale-up configuration to be made from the PA 101 alloy. Selection was based upon the rigorous low cycle fatigue and stress rupture characteristics required by the application, the ready availability of the forging tooling and the opportunities which existed for engine testing.

Scale-Up Atomization Effort

The same basic atomization procedure and the same master remelt heat used previously for the sub-scale effort was employed. In total, five laboratory sized heats of the PA 101 alloy were argon gas atomized, screened to eliminate the coarse fraction (i. e., +100 mesh) and blended together thoroughly. Analysis of the powders revealed an oxygen content of less than 100 ppm and indicated that the material was within the desired composition range.

T53 Billet Consolidation

Four inch diameter billet stock was required for the forging of the T53 turbine disc. A single extrusion at a ratio of 8:1, successfully employed on sub-scale billets, was preferred for the production of this stock. However, due to scheduling difficulties and tooling limitations, it became necessary to produce the billet by a double extrusion process. For the first extrusion, a ratio of approximately 5:1 was employed to produce a billet 7.5 inches in diameter. A second extrusion at approximately 3:1 was then employed to reduce the 7.5 inch diameter material to 4.5 inches which included the canning material. Total reduction for the two extrusions was approximately 15:1.

The first extrusion was conducted on a 20,000 ton vertical press and utilized an 18 inch diameter stainless steel can containing about 500 pounds of PA 101 powder. The canning techniques and can design employed were similar to those used with the two inch diameter extrusions. Prior to extrusion, the can was soaked for 34 hours in the temperature range of 2025°F to 2050°F. Extrusion was conducted with a can temperature of 2030°F. From the yield of the extrusion, two 13.5 inch long sections of the 7.5 inch diameter billet were selected for re-extrusion. These sections each had end plugs of mild steel welded to them, and were re-extruded at a 1950°F furnace temperature on a 3800 ton horizontal press. The preheat time at the extrusion temperature was four hours. No difficulties were encountered during extrusion and the bars were free from cracks and other deleterious imperfections.

To cross check the effectiveness of the extrusion processes in scaling up from two inch bar to 7.5 inch billet to 4.5 inch billet, tensile bars were machined from both the 7.5 inch single and 4.5 inch double extrusions and heat treated. The results of these tests are presented in Table II along with the results developed earlier for the two inch diameter baseline material. As indicated, the tensile properties of both the 7.5 inch and 4.5 inch material were comparable, however, both the yield and ultimate strengths of this material were substantially lower than the two inch bar. Metallographic examination performed on heat treated test specimens representative of each of the three bars revealed extremely fine structures containing large amounts of gamma prime phase as shown in Figure 11. The coarse gamma prime particle size in the 7.5 inch and 4.5 inch billet was comparable and generally larger (three to four microns versus one to two microns in diameter) than those in the two inch billet. This difference in gamma prime particle size is believed to be related to the combination of the longer soak time used prior to extrusion which effectively overaged the structure (soak temperature was 2025 to 2050°F for 34 hours; gamma prime solutioning temperature in the alloy is 2250°F) and slower cooling rates after consolidation due to the larger billet sizes.

Of all the resolvable structural characteristics, gamma prime particle size appeared to be most influential in controlling the tensile performance of the three different extruded bars. Best properties were developed for the two inch bar whose structure contained the finest gamma prime precipitate.

T53 Disc Forging

Subsequent to extrusion, efforts were initiated to evaluate double extruded 4.5 inch diameter billet stock upset forged into T53 turbine discs. Prior to forging, the billets were lathe turned to four inches in diameter to remove the stainless steel can. They were then ultrasonically inspected by surface contact at one inch increments along their entire length. The billets were rotated 90° and tested in the same manner to detect flat "plate-like" defects which could have been oriented incorrectly during the first run. No indications of internal defects were observed.

After inspection the material was sectioned into 6-1/2 inch high forging mults. The ends of each mult were faced on a lathe and the corners received a 45° bevel. The mults were wrapped with insulating cloth and mild steel end plates approximately 3/16 inch thick were attached to both top and bottom. The mults were heated for 6 hours at 1850° F and closed die forged to the T53 turbine wheel configuration in one pass on the laboratory press at Wyman-Gordon. The full capacity of the 1500 ton press was required to bring the dies to closure, however, by comparison, a high strength superalloy in conventional billet form could never have been forged at that low a temperature without utilizing heavier equipment. After forging, the parts were removed from the die and the can was peeled away from the top and the part was air cooled. Figure 12 shows a typical forged part and the canning material. In summary, forgeability of these discs was excellent; no cracking was noted with any of the forgings and forging probably could be done colder and closer to finish tolerances with heavier equipment.

Following forging, the T53 discs were examined metallographically. A cross section of one of the discs showing the ultra fine macrostructure of this material are clearly shown in Figure 13. Microstructurally, a fine grain size (i. e., ASTM No. 12) and a high degree of uniformity was revealed. By comparison to the five inch diameter pancakes, however, the T53 forgings contained much more fine cooling gamma prime. These differences, shown in Figure 14, indicate that the cooling rate of the T53 discs through the aging temperature region was much more retarded than that for the five inch pancake forgings. This observation is consistent with both the mass difference in the forgings and the canning techniques employed for forging.

After metallographic examination, the discs were heat treated and tensile tested at room temperature and 1200° F. In addition, stress rupture tests were run at 1200° F/ 150 ksi.

The resultant mechanical properties, while disappointing, were clearly superior to those of D979 and Inco 718. As shown in Figure 15, ultimate tensile and yield strengths were reduced by as much as 30 ksi relative to the five inch diameter pancakes, however, stress rupture properties were comparable.

As mentioned previously, the microstructural differences between the small pancakes and the forgings were significant and suggested that a slower cooling rate for the larger T53 disc may have been responsible. Consequently, a study was initiated to evaluate the effect of cooling rate off of the forging press on mechanical properties.

Two additional forging mults were prepared as before and upset forged at 1850° F. One of these was stripped of its insulation and air cooled while the other was stripped and oil quenched. Both parts required the full 1500 ton capacity of Wyman-Gordon's laboratory press and, as in the case of the previous T53 discs, exhibited excellent forgeability.

The forgings were heat treated and specimens were sectioned for mechanical property testing. The results of room temperature and 1200° F tensile tests revealed

(Figure 16 and 17) that significant increases in tensile strength were achieved with increases in cooling rate off the press. The tensile data generated for the oil quenched disc were comparable to those of Rene' 95, a nickel base superalloy developed for similar turbine disc applications.

Stress rupture tests performed on these discs at 1200°F/150 ksi and 1300°F/85 ksi showed similar trends (Figures 18 and 19). The 1200°F rupture properties increased directly as a function of cooling rate off of the press. By comparison, the PA 101 alloy in its oil quenched condition exhibited better stress rupture properties than Rene' 95. The stress rupture properties at 1300°F did not show as distinct a trend as the 1200°F properties, however, the oil quenched material exhibited an improvement over the slow cooled T53 discs and achieved a rupture life comparable to that of Waspaloy. This suggests a higher temperature capability than had originally been anticipated for the alloy.

Microstructural examination of the forgings revealed that the size of the cooling gamma prime decreased with more rapid cooling off the press. Figure 20 shows electron micrographs exhibiting these structures. The slowest cooled T53 forging had the largest cooling gamma prime particle size. The oil quenched forging correspondingly exhibited the finest cooling gamma prime size of all. These trends further emphasize the importance of fine gamma prime particle size in the attainment of high strength properties in the PA 101 alloy.

WORK IN PROGRESS

The workability and levels of strength developed to date for the PA 101 composition are very encouraging and demonstrate outstanding potential for the successful utilization of the alloy in advanced gas turbine applications. Current work with the alloy system involves the procurement of additional quantities of PA 101 billet material, forging of the material into turbine discs, and engine testing. Due to a major change in engineering emphasis at Lycoming, however, the disc configuration being evaluated is the F102-LD-100 fan engine configuration rather than the T53 turboshaft configuration previously evaluated.

This change in program planning has occurred as a result of increased materials requirements in up rated versions of the F102 engine. As in the original T53 work, the PA 101 billet material required for the forging is a powder product consolidated by extrusion, although the F102 billet material is slightly larger (5 inch versus 4 inch diameter) due to the slightly increased sizing of the F102 disc.

In parallel with efforts to produce, evaluate and engine test F102 turbine discs, work in the area of alloy modification is being conducted. Concurrent with the T53 turbine disc evaluation effort, a limited amount of alloy modification work has been performed to the basic PA 101 system. This work involved modification to the alloy's carbon, aluminum, titanium, and refractory alloy content and, although limited and incomplete, two inch diameter billet and five inch diameter pancake forgings have resulted in the development of some outstanding tensile and stress rupture properties as shown in Figures 21 and 22.

In addition, work in the area of heat treat modification is being pursued. Initial efforts with the PA 101 composition emphasized a fine grained condition for moderate temperature applications where tensile and fatigue properties were of major concern. Preliminary activities with the modified alloy series, however, indicate that in the grain coarsened condition the alloy system has an excellent potential for developing a level of tensile and stress rupture strength suitable for turbine disc applications to 1400°F. Shown in Figure 23 are some preliminary tensile and stress rupture properties developed for a titanium modified PA 101 material which was grain coarsened. Although exhibiting certain ductility deficiencies the basic strength capability is sufficiently encouraging to justify continuing work in this area. Payoffs of such an effort could well be increased rim temperature capability for turbine discs in advanced engines.

Overall, the PA 101 composition employed as a powder metallurgy product offers a potential for advanced engine applications which has barely been touched. Added activity in this area will likely result in new benefits for future generation gas turbine engines.

ACKNOWLEDGEMENTS

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TABLE I

Nominal C101 Composition

C	Cr	Co	Mo	W	Ta	Ti	Al	Hf	B	Zr
0.16	12.20	9.00	1.95	3.95	3.95	4.10	3.40	1.00	0.015	0.11

TABLE II

Room Temperature Tensile Properties* of Extruded PA 101 Bar Stock

Description	UTS (Ksi)	0.2% YS (Ksi)	El (%)	RA (%)
2" Diameter Extrusion	263,300	216,300	13.2	12.7
7.5" Diameter Extrusion	248,800	193,700	12.3	11.4
4.5" Diameter Extrusion	250,000	196,200	12.8	12.5

*Heat Treated: 1300°F/50 Hrs./AC

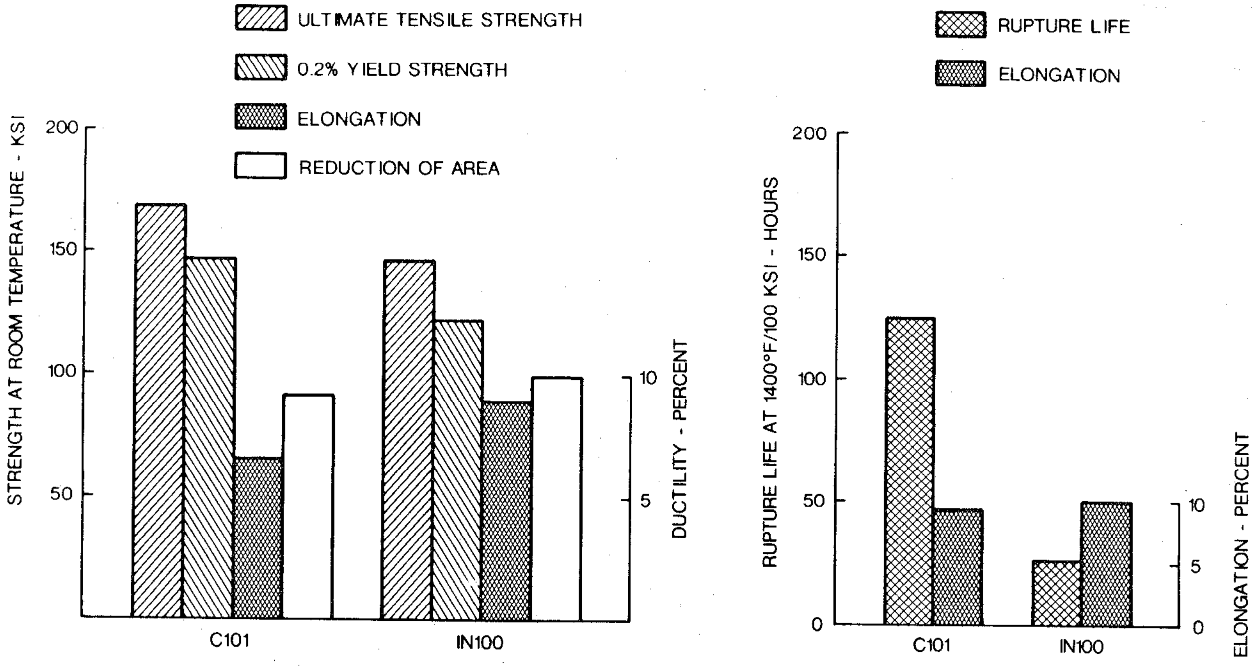


Figure 1: **MECHANICAL PROPERTIES OF CAST C101 AND IN100**

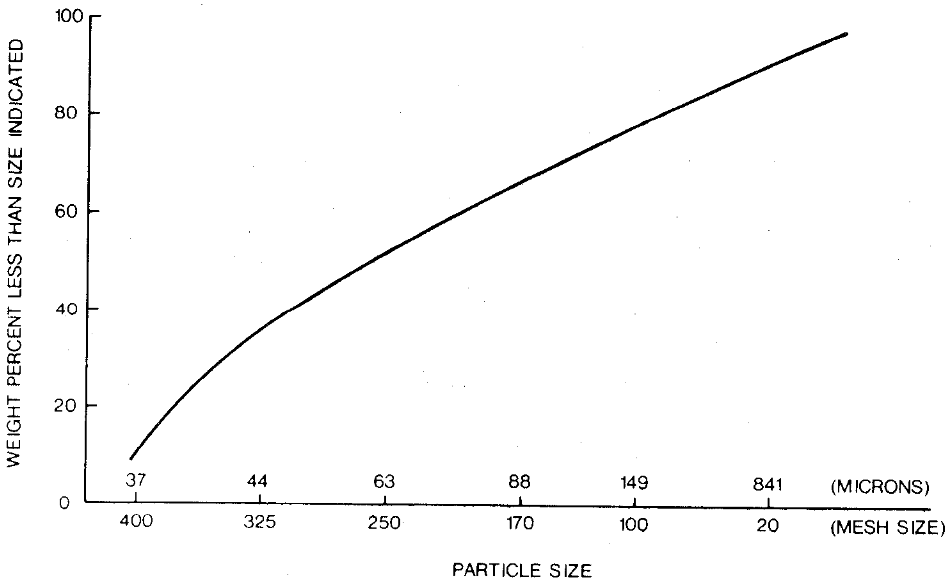
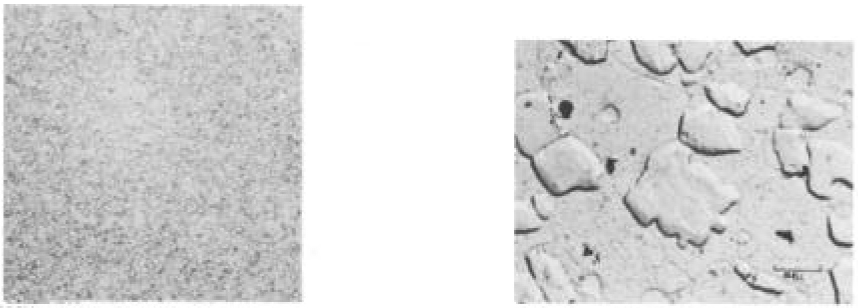


Figure 2: **PA101 PARTICLE SIZE DISTRIBUTION**



1000X 934

30,000X 682-2

Figure 3: MICROSTRUCTURES OF AS-EXTRUDED PA101 2 INCH DIAMETER BAR

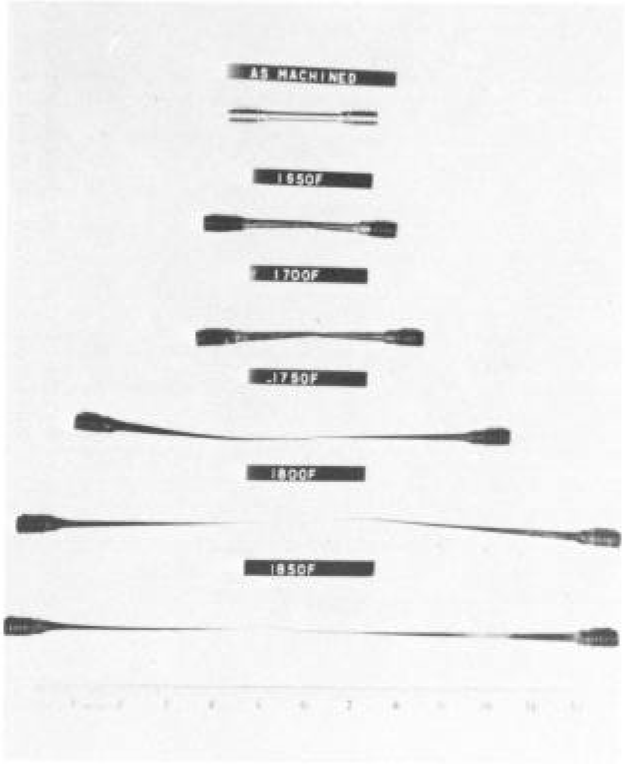
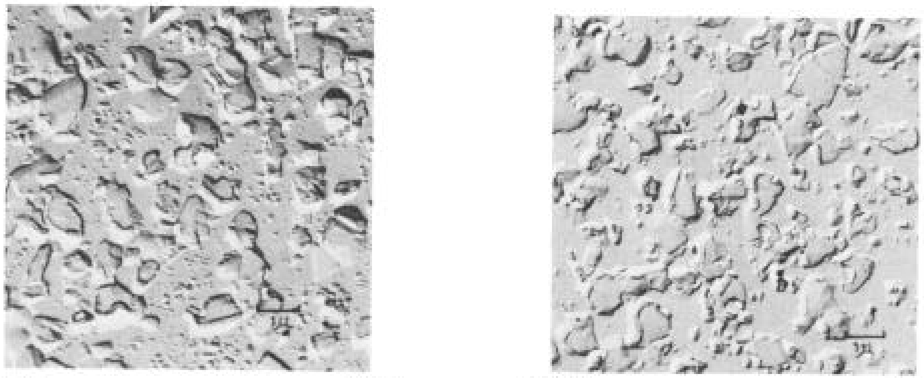


Figure 4: AS-EXTRUDED PA101 FOLLOWING TENSILE TESTING

7600X 698-4

Figure 5: AS-HEAT TREATED MICROSTRUCTURE
2 INCH DIAMETER PA101 EXTRUDED B

Figure 6: TYPICAL PA101 5 INCH DIAMETER PANCAKE FORGINGS



7600X 699-10
AS-EXTRUDED

7600X 696-8
AS-FORGED

Figure 7: MICROSTRUCTURES OF TWO INCH DIAMETER AS-EXTRUDED PA101 BARSTOCK BEFORE AND AFTER FORGING

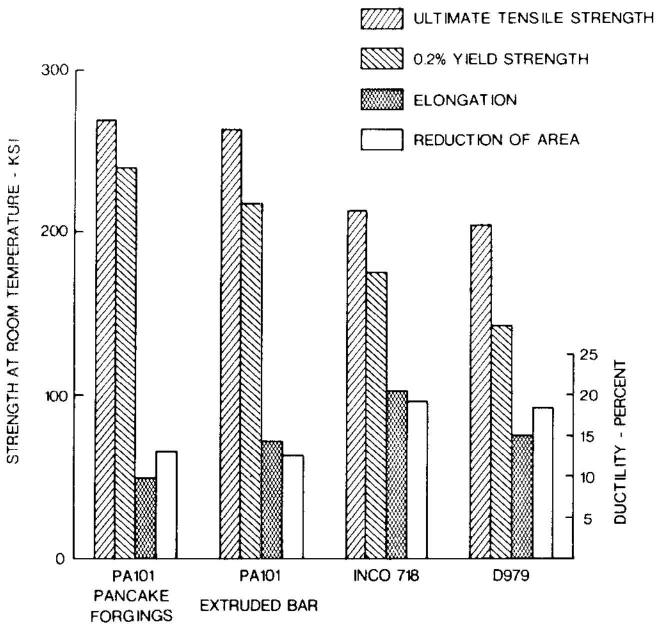


Figure 8: **TENSILE PROPERTIES OF PA101, INCO 718 AND D979**

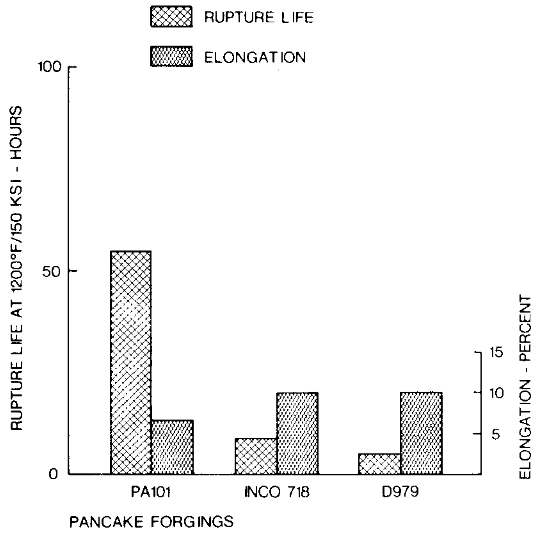


Figure 9: **RELATIVE PA101 STRESS RUPTURE CAPABILITY**

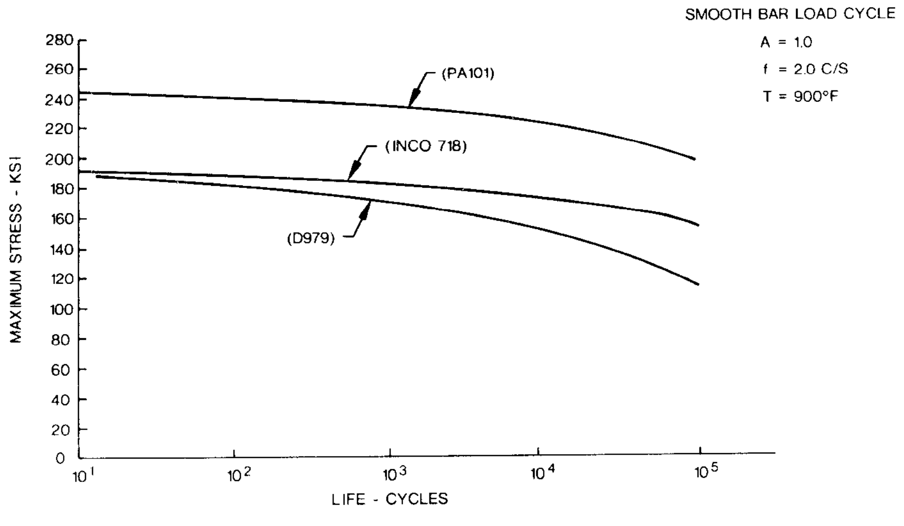
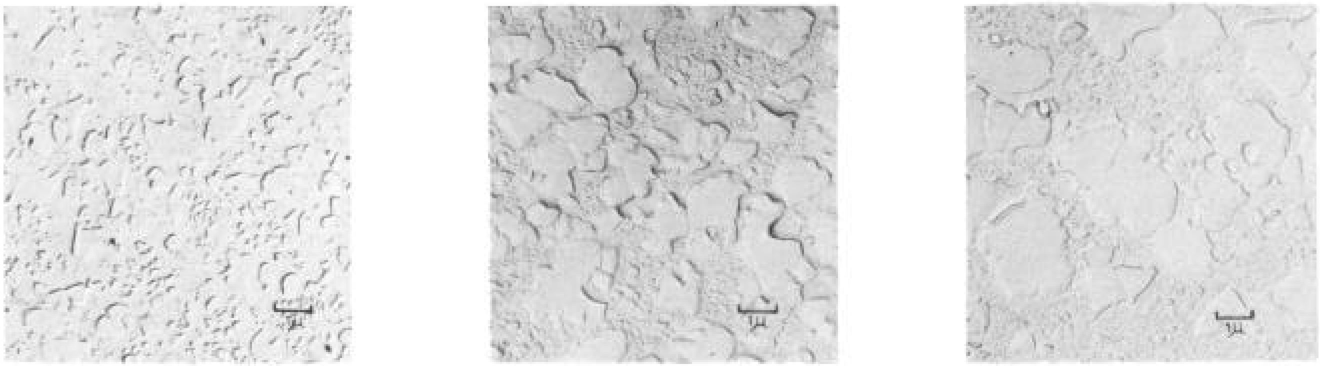


Figure 10: **WROUGHT ALLOY LOW CYCLE FATIGUE PROPERTIES**



7600X 698-4

2 INCH BAR

7600X 700-10

7½ INCH BILLET

7600X 700-7

4½ INCH BILLET

Figure 11: MICROSTRUCTURES OF PA101 EXTRUSIONS

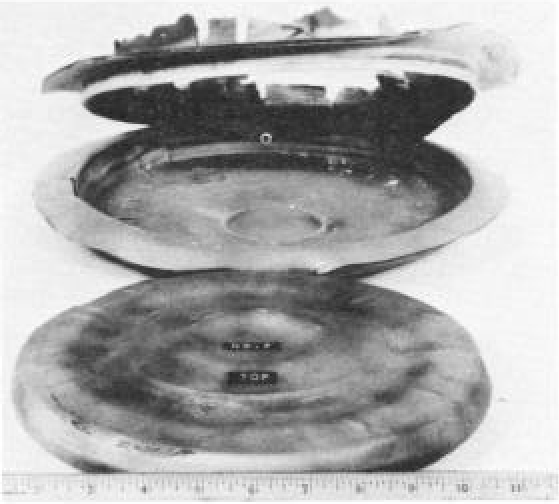
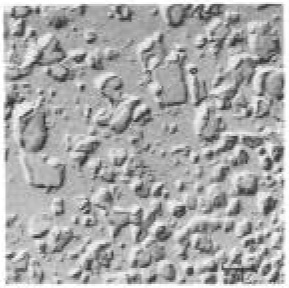
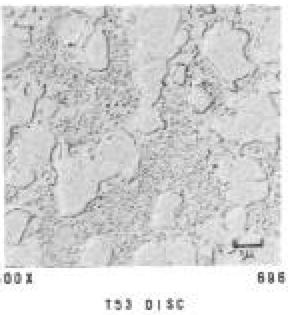


Figure 12: PA101 T53 DISC FORGING WITH CAN



7600X 696-7

5 INCH DIAMETER PANCAKE



7600X 696-2

T53 DISC

Figure 14: MICROSTRUCTURES FOR PA101 PANCAKE AND T53 DISC FORGINGS

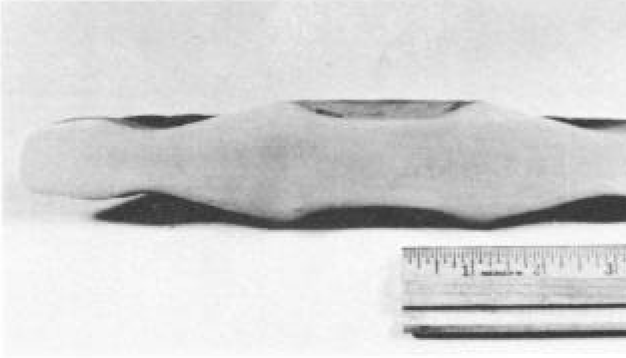


Figure 13: MACROETCHED CROSS SECTION OF A PA101 T53 FORGING

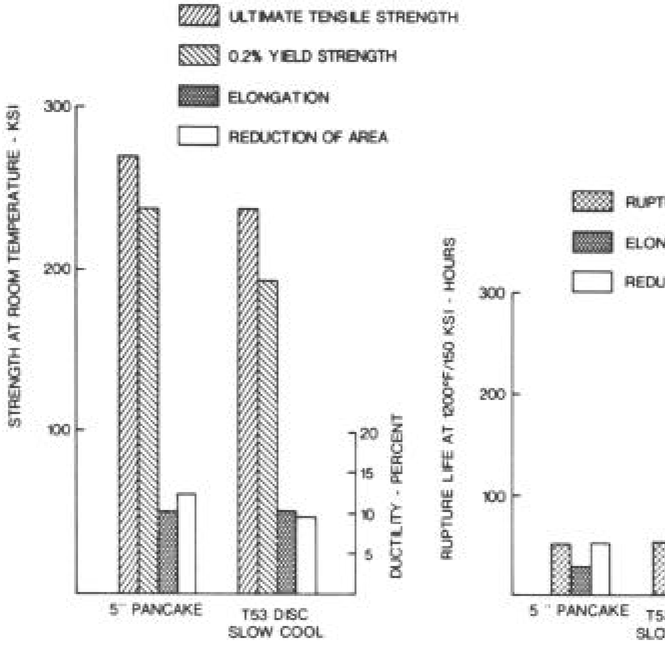


Figure 15: TENSILE AND STRESS RUPTURE PROPERTIES OF 5 INCH PANCAKE AND T53 DIS

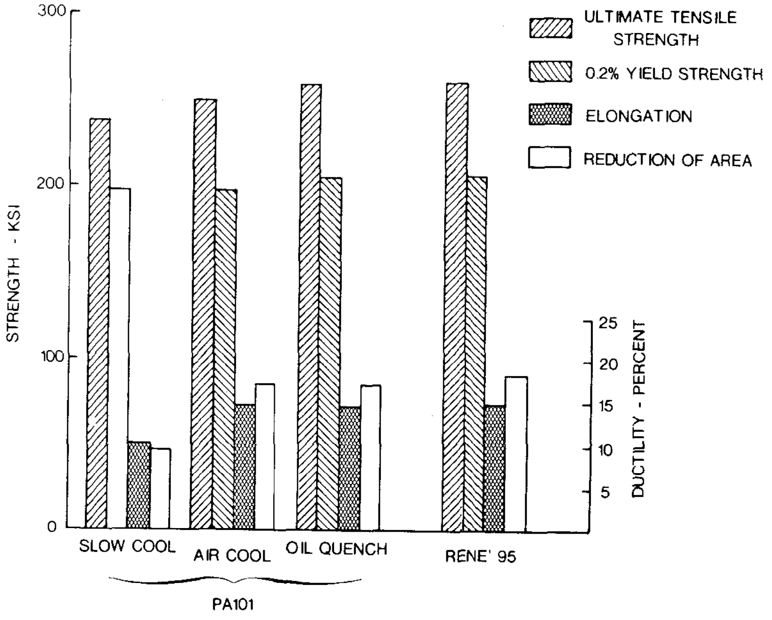


Figure 16: **ROOM TEMPERATURE TENSILE PROPERTIES FOR PA101 AND RENE' 95 DISC FORGINGS**

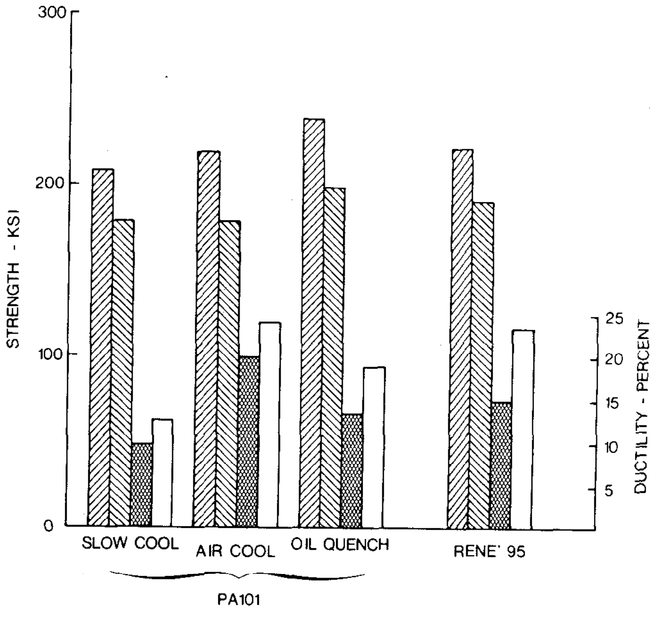


Figure 17: **1200°F TENSILE PROPERTIES FOR PA101 AND RENE' 95 DISC FORGINGS**

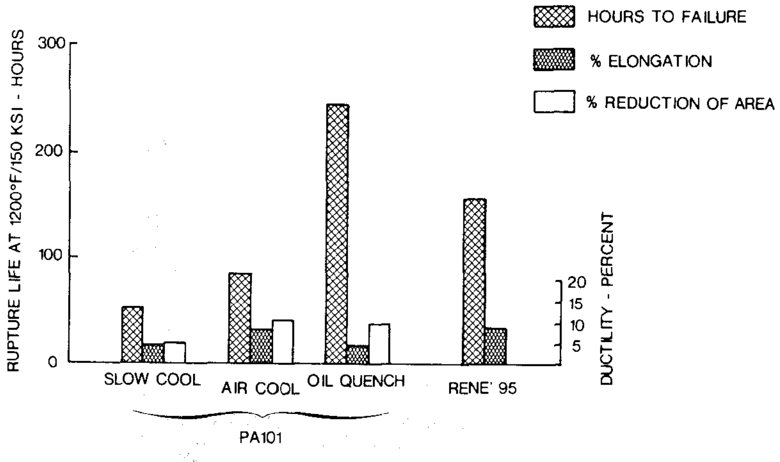


Figure 18: **STRESS RUPTURE PROPERTIES OF PA101 AND RENE' 95 DISC FORGINGS**

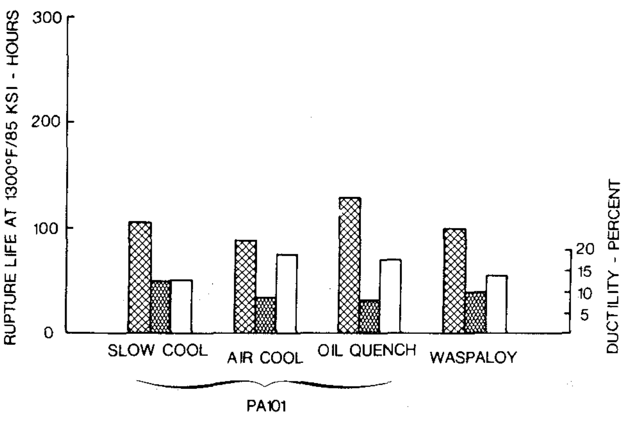
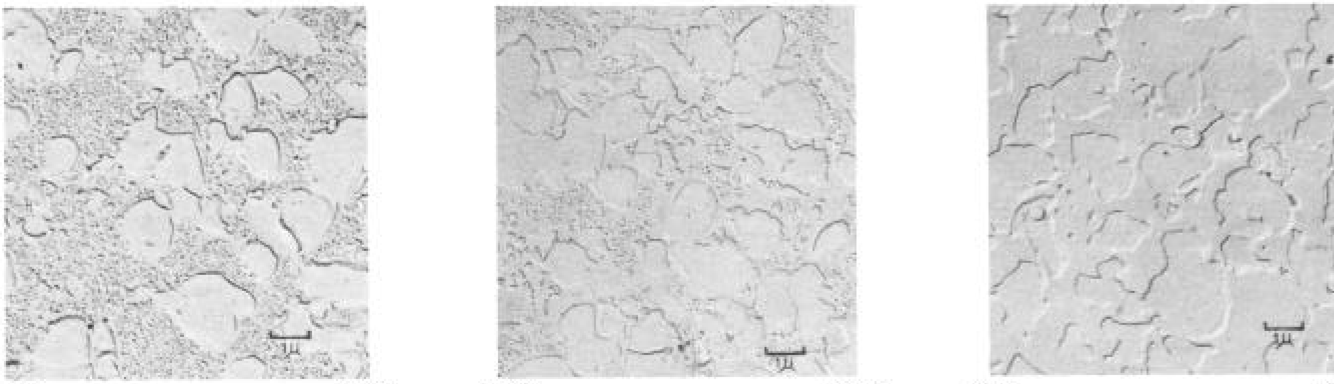


Figure 19: **STRESS RUPTURE PROPERTIES OF PA101 AND WASPALOY FORGINGS**



7600X SLOW COOL 696-3

7600X AIR COOL 696-10

7600X OIL QUENCH 6

Figure 20: AS-FORGED PA101 MICROSTRUCTURES

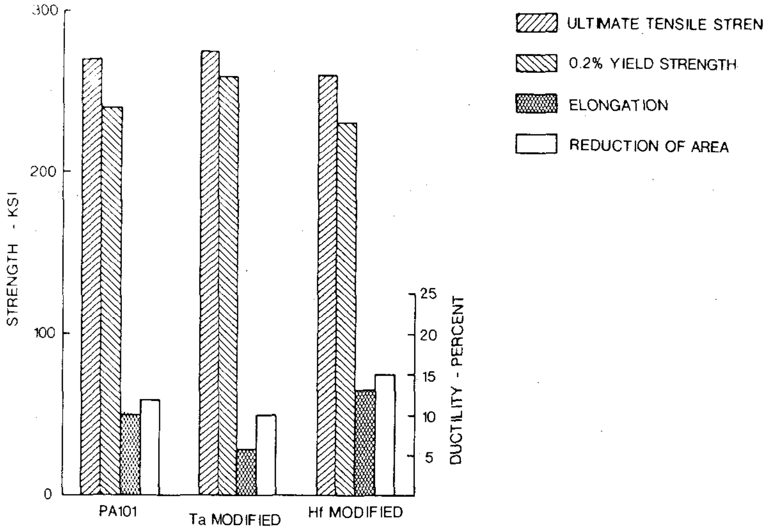


Figure 21: **ROOM TEMPERATURE TENSILE PROPERTIES FOR PA101 CHEMISTRY MODIFICATIONS**

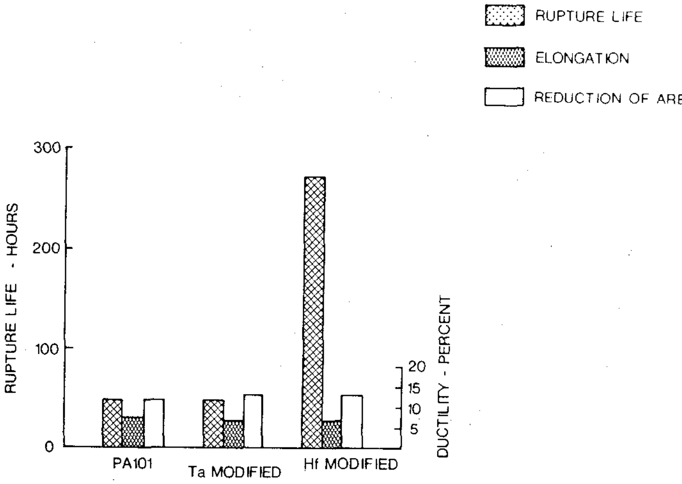


Figure 22: **STRESS RUPTURE PROPERTIES AT 1200°F/150 KSI FOR PA101 CHEMISTRY MODIFICATIONS**

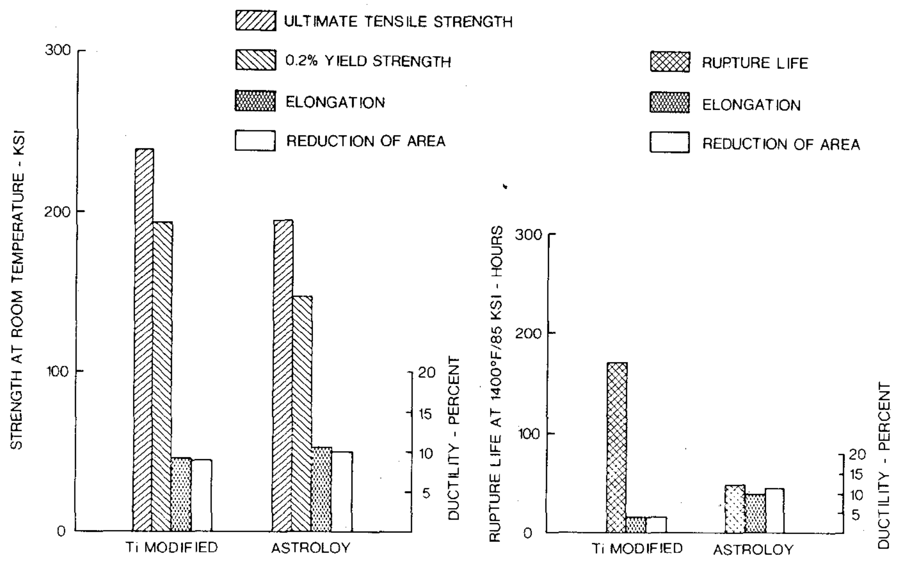


Figure 23: **TENSILE AND STRESS RUPTURE COMPARISON OF TITANIUM MODIFIED PA101 AND ASTROLOY**