P/M AF115 DUAL PROPERTY DISK PROCESS DEVELOPMENT

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AF115 is an advanced P/M turbine disk alloy developed by General Electric to satisfy the needs of advanced gas turbine engines for a high strength alloy capable of long term 1400F service. This paper reports the results of a program to develop an As-HIP process for moderate to highly stressed 1400F applications and also develop a selective forging thermo-mechanical process for a dual property AF115 disk for applications requiring ultra high tensile strength in the bore area and As-HIP 1400F creep strength in the disk rim.

INTRODUCTION/BACKGROUND

AF115 is a highly alloyed precipitation strengthened nickel-base superalloy designed to take advantage of the additional alloying capability provided by powder metal processing. The alloy was designed specifically for compressor and turbine rotating parts requiring high strength and exceptional 1400°F (760°C) creep capability.

The initial development (1) resulted in an AF115 composition which featured 55 volume percent γ', 10 weight percent W, plus Mo, and 2 weight percent Hf, all of which make the alloy essentially non-producible by conventional cast and wrought technology due to melting segregation problems.

The tensile and creep/rupture properties of Hot Isostatically Pressed plus solution heat treated and aged (As-HIP) AF115 were projected to result in significant performance or life improvements in many advanced gas turbine applications. Several applications, however, require AF115's creep capability in the rim of the disk together with tensile properties greater than that available in As-HIP AF115 in the bore. Previous studies at General Electric had shown that an increase in tensile strength at temperatures up to 1200°F (650°C) could be achieved in AF115 by a controlled hot working and heat treatment process termed thermo-mechanical processing (TMP). However, this increased tensile strength could only be gained at the expense of high temperature (1400°F) creep capability. This TMP capability has led to the dual property disk concept which involves producing an AF115 powder metallurgy forging preform by the HIP process, forging the bore area while leaving the rim area unreduced, cooling the forging rapidly from the press, and directly aging without a re-solution treatment. With this processing concept, it was anticipated that increased TMP'ed tensile properties would be obtained in the bore, while the As-HIP creep capability would be maintained in the rim. It was anticipated that this dual property processing concept would develop a combination of creep and tensile strength unattainable in any known uniformly processed alloy, and could eventually be applied to other alloys once the technology was demonstrated.

Program Scope

The objective of this program was to define the As-HIP and TMP dual property processes for producing AF115 turbine rotating parts. This task involved three principle areas of endeavor:

1) As-HIP Process Parameter Definition
2) TMP Process Parameter Definition
3) Half Scale Dual Property Disk Forging Development

All developments incorporated the AF115 chemistry modification listed and compared with the original chemistry in Table 1. The modified chemistry is reduced in hafnium primarily to raise the incipient melting point. This change is desirable, since it reduces the amount of Thermally Induced Porosity (TIP) that forms during solution heat treatment. The carbon level was lowered to maintain the carbide stability needed to prevent segregation of carbides to prior powder particle boundaries.

The definition of the As-HIP process encompassed the following processing variables: HIP time and temperature, solution temperature, quench media and section size.

The TMP processing study included forge temperature and reduction, section size and quench media. The half scale forging trials involved four attempts with variables in preform and die shape and forge reduction. The processing variables were screened in their ability to produce a sound part and in tensile and creep properties. The scope of this paper does not allow discussion of the effects of all processing variables on all properties. For a more comprehensive presentation see references 2-4.

RESULTS AND DISCUSSION

Powder Preparation

The powder utilized in this program was produced at Special Metals by vacuum induction melting an ingot followed by remelting and argon atomization. Two powder lots were produced from a single VIM ingot and were screened to a -60 mesh size. The chemistries of the powder lots produced are listed in Table 1, along with the original and low carbon chemistry limits. The powder was canned and compacted at Wyman-Gordon.

Heat Treat Study

The material for the heat treat study was HIP at 2175°F (1190°C) and 15,000 psi (100 MPa) for four hours into three 6 inch (150 mm) diameter logs. The logs were sliced to produce disks of thickness ranging from 1 inch (25 mm) to 4 inches (100 mm). The solution treatments ranged from 2000°F (1095°C) to 2175°F (1190°C) and the quench media included oil, forced air, and 1000, 1200, and 1400°F salt. Following solution treatment and quench, the disks were aged at 1400°F (760°C) for sixteen hours. Grain size was also introduced as a random variable as a consequence of HIP'ing the material, which had a 2180°F (1193°C) gamma prime solvus, at 2175°F (1190°C). As a result, approximately half the autoclave load exceeded the γ' solvus and underwent varying degrees of grain growth. The screening tests conducted on each of the eighteen conditions investigated included room temperature, 1200°F (650°C) and 1400°F (760°C) tensile and 1400°F/75 KSI (760°C/510 MPa) creep tests.

Of the three test temperatures evaluated, the room temperature tensile test showed the greatest sensitivity to heat treatment, and therefore will be discussed in greatest detail. The other temperatures generally followed the same trends, although to a lesser degree. The room temperature tensile data, tabulated in Table 2, shows a significant sensitivity to grain size which, in many cases, disguised the more subtle effects of heat treatment. In order to distinguish the heat treat effects, it was necessary to conduct a regression analysis of the data using an equation of the form:

$$\log X = B_0 + B_1 T^{-1} + B_2 \log GS + B_3 \log SS + B_4 T^{-2}$$

X = Property to be Analyzed

B_0-B_4 = Constants

T = Temperature

GS = ASTM Grain Size

SS = Section Size

Using this regression analysis, the tensile data was normalized to a standard sub-solvus grain size of ASTM 8 (.022 mm average diameter) and plotted in Figure 1 as a function of solution temperature and section size. The regression analysis fit the data very well as indicated by a standard deviation of 2.8% for ultimate and 1.5% for yield strength. The data indicate only a minor increase in ultimate tensile strength with solution temperature. This appears to be due to the fact that the increases in yield strength obtained through application of higher solution temperatures were accompanied by decreases in ductility. Ultimate strength, yield strength, and ductility were all affected by section size and, although not shown here, by quench media as well. Thus, it appears that tensile properties are more sensitive to cooling rate and the characteristics of the gamma prime formed than solution temperature and the amount of gamma prime available for hardening.

The creep data, tabulated in Table 2, shows an even greater dependence on grain size than the tensile properties. The regression analysis, in this case, was not successful in fitting the data with the accuracy needed to separate the effect of many of the variables such as quench media, solution temperature or section size. This is due to a standard deviation of $\pm$30% in life which overwhelmed many of the actual life differences. One significant difference obtained from the regression analysis was the 40% lower life obtained by the oil quench versus the other quench media. This difference is believed due to the extended quench delay (two minutes) applied to the oil quenched disks compared to the shorter delay (forty seconds) applied to the other quenched disks. The oil quenched disks were given a longer quench delay in order to simulate the delay encountered by the rim of the dual property disk while being transferred from the pre-heat furnace to the forge press and into the oil tank. It is believed that the longer quench delay resulted in loss of heat which effectively reduced the solution temperature and initial cooling rate.

As-HIP Property Improvement

The tensile properties demonstrated throughout the As-HIP portion of the program are signficantly superior to those previously produced in high carbon AF115. The data from selected conditions of this program are compared to the previous high carbon AF115 capability curve in Figure 2. The improvement in ultimate tensile strength is probably a result of the corresponding ductility improvement. The most dramatic improvements were made as a result of the elimination of the intermediate temperature (600°F, 313°C) ductility minimum which occurred in high carbon AF115. In the temperature range of the ductility minimum, a range which is critical to the capability of turbine disks, the modified chemistry and associated process modifications produced a 150% improvement in ductility and a 15% (30 KSI 200 MPa) increase in ultimate tensile strength. This was accomplished without loss in creep capability.

TMP Study

The material for the TMP study was HIP consolidated in three 8 inch (200 mm) diameter logs at conditions equivalent to those of the As-HIP heat treat study. The HIP logs were then sliced to thickness, machined to a 7.1 inch (180 mm) diameter and bored to form a 2.75 inch (70 mm) diameter bore. The donut shaped pancakes were then forged on 1700°F induction heated cast IN 100 dies. The forging parameters covered reductions from 20 to 43%, temperatures from 2000 to 2100°F (1095 to 1150°C), and section sizes from 2 to 3 inches (50 to 76 mm). Room temperature, 1200°F (650°C) and 1400°F (760°C) tensile and 1200°F and 1400°F creep properties were evaluated. The room temperature tensile and creep data are tabulated in Table 3. The creep life at 1200°F was equivalent or slightly better than the As-HIP properties, but the 1400°F creep life was, as expected, reduced to only 5 to 37% of typical As-HIP lives.

Regression analyses of similar form to that in the heat treat study were conducted on the TMP tensile data. The analyses provided a good data fit as indicated by a standard deviation of 1 and 2% for the respective ultimate and yield strength relationships. The results of the regression analyses are plotted in Figures 3 and 4. The most unusual aspect of the TMP tensile data is the increase in ultimate tensile strength that resulted from increasing the section size from 2 to 3 inches (50 to 76 mm). The increase corresponds with an increase in ductility in much the same manner as the As-HIP tensile data generated in the heat treat study. While it is doubtful that this ductility related strength improvement can be extrapolated indefinately, it does provide encouragement for the materials' capability in the thicker section sizes that are often required in turbine disks.

Analysis of the other TMP parameters indicates a modest decrease in strength with increasing forging temperature. For the dual property disk, however, the higher 2100°F (1150°C) forge temperature was selected due to concern that a lower forging temperature (which is also the rim solution treatment) would decrease rim creep properties. The data also showed a trend of higher strength and ductility with increasing forge reduction. The forge reduction could well be limited in the dual property disk by the forgeability constraints to be discussed in the section describing the half-scale disk development. These results do indicate that a modest 30% reduction at 2100°F is capable of producing a room temperature ultimate tensile strength of 250 KSI (1700 MPa) in a 2.5 inch (63 mm) section size component such as the half-scale dual property disk.

Half-Scale Dual Property Disk Forging Trials

Both the original and the subsequently modified die and preform configurations for the half-scale dual property disk forging trials are shown in Figure 5. The intended forging action is visualized by imagining the die contacting the preform at the hub and closing to the point of contact with the rim.

Four preform shapes were HIP at the standard 2175°F (1190°C) conditions, and two were machined to the original preform configuration. The top and bottom surfaces of the preforms were covered with one layer of lubricated cloth and a contoured sheet of 304 stainless steel. The cast IN 100 dies were induction heated to 1700°F (927°C) and the first preform (S/N 1224) was forged 40% at 2100°F (1150°C) and oil quenched directly off the forge press. Visual examination of the piece after cover removal revealed three radial cracks in the rim which extended to, but not into, the thicker hub area. The second preform (S/N 1226) was to be forged in the same manner except it was to be air cooled rather than oil quenched. However, it split radially from rim to bore soon after the dies contacted the preform, and the forging stroke was aborted before full reduction was reached. A comparison of the uncracked circumference of both parts showed the first piece, S/N 1224, to have expanded 8.2% before cracking while the second piece S/N 1226, expanded only 2.5%.

This difference in forgeability was eventually attributed to local contamination of the powder preform. Black light photomicrographs comparing the forging crack origin areas of the two disks are shown in Figure 6. Disk S/N 1226, the more severely cracked preform, appears to have failed in a "brittle" manner with little secondary cracking or void formation. However, disk S/N 1224 exhibited a considerable amount of ductility, as evidenced by the extensive void formation. The brittle failure in disk S/N 1226 is attributed to the presence of prior powder particle boundary contamination in the form of oxides which generally form when moisture or organic contaminants are present. Thus, there appeared to be two problems requiring attention before the second two disks were forged. The first involved examination of each preform to determine contamination level. This was accomplished by removing a chordal slice from a section of the rim and conducting an oxygen analysis and metallographic examination. Neither of the second two preforms showed any evidence of contamination. The second problem was to minimize the tensile strain induced in the rim during die closure, since the initial forging parameters obviously exceeded the materials' ductility limit. In order to reduce the tensile strain in the rim, it was necessary to minimize the amount of outward flow by either reducing the amount of metal forged or by encouraging more inward flow. With this in mind, the die and preform were modified as shown in Figure 5. The ID restraint in the die was removed to improve inward flow and the face of the die in the rim area was recessed to assure that it would not forge the rim OD. The height of the preform was reduced to diminish the total forging reduction from 40 to 30%. An additional radius was cut into the outside diameter of the hub area to reduce the amount of metal forged and to allow the metal in the outside diameter of the hub to provide restraint against outward flow instead of participating in it, as had been the case in the first two trials. In addition, a mild steel belly band was fitted around the rim of the disk and held in place by tack welding to the stainless steel covers. The ring was not put in place to provide restraint, but to provide thermal insulation to keep the rim from cooling too rapidly, since it is otherwise exposed in this type of open die configuration.

The first of the second two modified preforms was forged with the new die configuration, but also cracked for two apparent reasons: a stress concentration in the rim (remaining from removal of the previously mentioned chordal slice); and an accidental increase in the forge reduction from the intended 30% to 35%. The last preform (S/N 1225) was forged to the planned 30% reduction at 2100°F and successfully oil quenched directly from the press. The amount of rim expansion was lowered from 8.2% in the first forging to 3.2% in the S/N 1225, indicating a very significant reduction in the amount of strain produced in the rim.

The tensile and creep properties of the successfully forged sub-scale dual property disk (S/N 1225) are presented in Table 4. The bore tensile strength of 252 KSI (1738 MPa) is in good agreement with that obtained in the TMP study. The rim tensile strength is, as anticipated, lower than the bore strength and more typical of the capability demonstrated in the As-HIP study. The 1400°F creep life at the rim varied from 120% to only 15% of the expected As-HIP creep capability. This variation is believed to result from deviations in the initial cooling rate and the amount of heat lost in the rim while transferring the disk from the preheat furnace to the forge press to the oil quench tank. A similar creep life reduction was encountered in the oil quench portion of the heat treat study which was meant to simulate the rim of the dual property disk. In both cases the disks were delayed prior to quenching and, as a result, lost creep capability. Thus, the key to better creep capability in the rim of the dual property disk is to maintain the 2100°F solution temperature until the quench. This, it is believed, can be accomplished through better thermal insulation of the rim during transfer (to be stripped just before quench) and by reducing the handling time.

SUMMARY AND CONCLUSIONS

The main goal of this investigation was achieved: process parameters were defined for subsequent application to full scale AF115 "As-HIP" and "TMP dual property" turbine disks. Specific conclusions drawn from the data are summarized below:

1. The low carbon AF115 chemistry with a modified HIP/heat treatment resulted in significant increases in both tensile strength and ductility.
2. Thermal Mechanical Processing of AF115 can produce ultimate tensile strengths in excess of 250 KSI, with good intermediate temperature creep strength but at the expense of high temperature creep strength.
3. A dual property AF115 disk can be produced utilizing selective thermal mechanical processing. However, care must be taken to minimize the forging tensile strain induced in the rim to avoid cracking.
4. Optimum creep properties in the rim of the dual property disk will require processing which minimizes heat loss during transfer of the preform from the preheat furnace to the forging press to the quench tank.

ACKNOWLEDGEMENTS

The author would like to acknowledge the financial support of the U.S. Air Force Materials Laboratory and the guidance of Mr. Kenneth Kojola who helped make this program possible. The author would also like to thank his co-workers at General Electric and personnel at Wyman-Gordon, Inc. for their advice and support on this program.

REFERENCES

1. Bartos, J.L., "Development Of A Very High Strength Disk Alloy For 1400°F Service", Technical Report # AFML-TR-74-187 on Contract F33615-72-C-1797, December, 1974.

2-4. Carlson, D.M., "Advanced Superalloy Dual Property Turbine Disk", Interim Technical Reports on Contract F33615-77-5253, October, 1978, April 1979 and October, 1979.

TABLE I AF115 CHEMISTRY LIMITS/ANALYSIS

MAJOR ELEMENTS, WEIGHT PERCENT

	C	Cr	Ti	Al	B	Zr	Co	Mo	W	Hf	Cb
ORIGINAL LIMITS	.13-.17	9.95-11.45	3.6-4.2	3.5-4.1	.015-.025	.03-.07	14.5-15.5	2.6-3.0	5.6-6.2	1.7-2.3	1.5-1.9
MODIFIED LIMITS	.03-.07	9.95-11.45	3.6-4.2	3.5-4.1	.015-.025	.03-.07	14.5-15.5	2.6-3.0	5.6-6.2	.55-.95	1.5-1.9
CHEMICAL ANALYSIS	.045	10.9	3.67	3.78	.016	.05	15.0	2.8	5.65	.70	1.72

TABLE II AS-HIP HEAT TREAT TENSILE/CREEP RESULTS

R.T. TENSILE, 1400°F/75 KSI/.2% CREEP LIFE

Solution Temp. (°F)	Quench Media	Section Size (in)/(mm)	ASTM G.S.	UTS (KSI)	.2 YS (KSI)	% El	% RA	Creep Life (Hrs)
2050	1000°F Salt	2	6	229.1	155.5	17.7	19.6	81.1
2100	1000°F Salt	2	8	239.8	161.0	20.5	21.3	62.6
2100	1200°F Salt	2	8	234.9	154.7	20.1	19.6	91.3
2150	1200°F Salt	2	8	233.6	160.8	19.0	21.3	106.7
2175	1200°F Salt	2	5	219.8	162.3	15.4	18.2	167.0
2150	1400°F Salt	2	8	236.4	159.0	19.9	21.3	70.5
2175	1400°F Salt	2	7	215.6	158.3	15.6	18.2	130.5
2000	Oil	2	8	237.0	164.2	17.6	17.6	34.0
2050	Oil	2	5	223.1	158.8	15.7	16.5	90.2
2100	Oil	2	6	226.6	164.6	14.7	16.2	48.6
2050	RAC	2	6	222.4	151.9	16.4	16.8	100.2
2100	RAC	2	8	241.9	163.6	18.8	20.7	66.5
2150	RAC	2	6	229.5	156.9	17.0	18.2	121.6
2150	1200°F Salt	1	8	236.4	169.0	15.7	17.9	74.9
2150	1400°F Salt	1	6	227.3	158.7	16.6	18.8	152.8
2150	1000°F Salt	4	8	236.7	161.3	18.5	19.3	78.8
2150	1200°F Salt	4	5	219.6	153.9	16.2	18.2	121.3
2150	1400°F Salt	4	8	208.7	155.6	11.8	14.5	41.0

TABLE III TMP STUDY TENSILE/CREEP RESULTS

Forge Red. %	Quench	Forge Temp. (°F)	Section Size (in)	UTS (KSI)	.2 YS (KSI)	% El.	% RA	Creep 1400°F/75 KSI .2% Life	Creep 1200°F/140 KSI .2% Life
34	Oil	2000	2.36	254.1	194.8	12.7	14.6	6.0	298
41	Oil	2000	1.96	249.3	191.4	12.3	14.6	17.5	287
43	Oil	2000	2.80	265.5	198.4	20.0	21.0	5.5	79
33	Oil	2050	2.40	251.7	189.4	13.6	14.6	17.0	240
42	Oil	2050	2.89	264.6	194.2	18.4	21.3	9.8	343
40	Oil	2050	1.98	251.9	199.6	13.2	16.2	7.0	252
30	Oil	2100	2.50	256.2	191.5	18.0	16.2	31.0	280
34	Oil	2100	2.38	251.1	187.9	12.9	14.6	36.0	352
42	Oil	2100	2.90	258.3	186.8	21.3	25.9	30.0	174
41	Oil	2100	1.96	250.5	189.9	13.6	15.4	20.4	375
20	Oil	2000	2.95	258.4	183.6	17.9	18.2	33.0	646
40	Air	2100	3.03	257.7	195.2	15.8	18.5	50.0	260
30	Air	2100	2.52	245.3	171.1	18.1	19.6	37.0	352

TABLE IV SUBSCALE DUAL PROPERTY DISK (S/N 1225) PROPERTIES

Property	Location	UTS (KSI)	.2% YS (KSI)	% El	% RA
R.T. Tensile	Bore	251.8	177.4	16.3	17.1
800°F Tensile	Bore	233.7	163.5	18.8	18.2
1200°F Tensile	Bore	219.8	158.0	20.0	22.8
R.T. Tensile	Rim	239.3	159.5	18.0	19.7
1400°F Tensile	Rim	174.0	158.5	7.0	9.7

Creep Condition	Location	.2% Creep Life (Hrs)
1200°F/140 KSI	Bore	220
1200°F/140 KSI	Bore	390
1400°F/75 KSI	Rim	15
1400°F/75 KSI	Rim	120

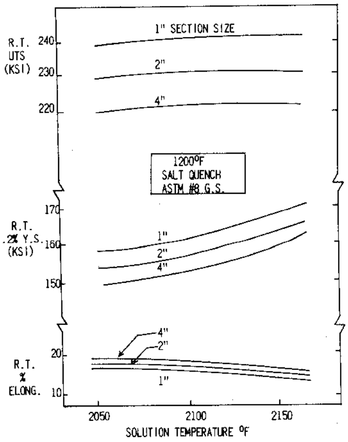


FIGURE 1: THE EFFECT OF SOLUTION TEMPERATURE AND SECTION SIZE ON AS-HIP AF115 TENSILE PROPERTIES.

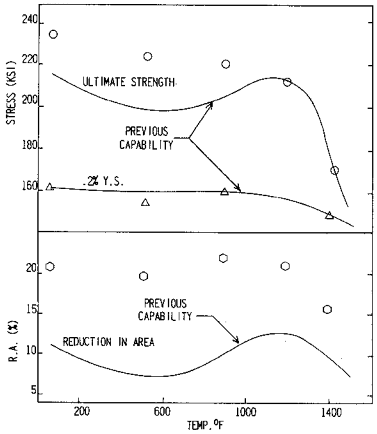


FIGURE 2: LOW CARBON AS-HIP AF115 TENSILE PROPERTIES AS A FUNCTION OF TEMPERATURE (2" SECTION SIZE)

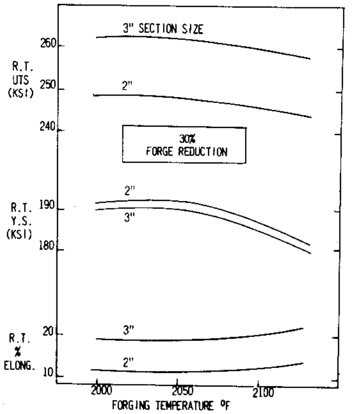


FIGURE 3: EFFECT OF FORGE TEMPERATURE AND SECTION SIZE ON TMP AF115 TENSILE PROPERTIES

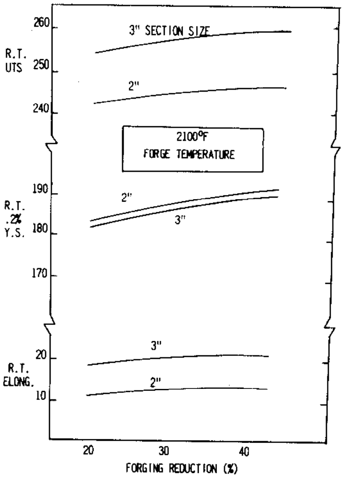


FIGURE 4: EFFECT OF FORGE REDUCTION ON TMP AF115 TENSILE PROPERTIES

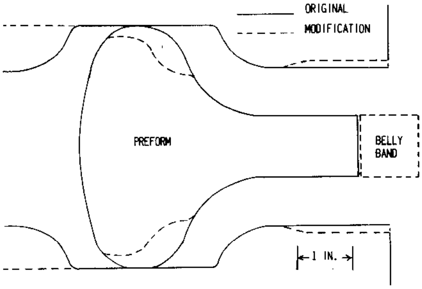
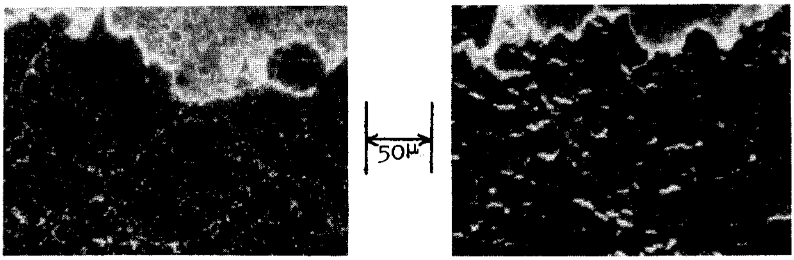


FIGURE 5: ORIGINAL AND MODIFIED DIE AND PREFORM CONFIGURATION



BRITTLE FAILURE
ALONG PPB

DUCTILE FAILURE,
NO PPB

FIGURE 6: BLACK LIGHT PHOTOMICROGRAPHS COMPARING THE BRITTLE AND DUCTILE FAILURES OF FORGINGS 1226 AND 1224 RESPECTIVELY.