THERMOMECHANICAL BEHAVIOR AND MICROSTRUCTURE DEVELOPMENT

OF ALLOY 706

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Abstract

GE Power Systems uses large 706 forgings for their F series gas turbines. These forgings are the largest Superalloy forgings made in the world today and each forging can weigh as much as 13,500 Kg. The mechanical properties of a Alloy 706 forgings can be modified through changes in thermo-mechanical processing. It is important to understand the effects of each step in the process which would affect final microstructure. This paper presents the results of lab scale studies to analyze the microstructural evolution of Alloy 706 at each step of the process. The test conditions were selected based on the limitations for a full size forging used in GE gas turbines.

Superalloys 718, 625, 706 and Various Derivatives
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Introduction

The microstructure of Alloy 706 forgings has a significant effect on mechanical properties. Toughness and LCF life can be significantly improved through improvements in grain size. The grain size improvement can be achieved through proper selection of forging and heat treatment parameters. The main parameters are forge temperature, strain rate and strain. In addition pre-heat time, pre-heat up rate and cooling rate after forge can be important. Compression testing and heat treatment provide an inexpensive way of evaluating different sets of conditions and determining the optimum process for a specific microstructural goal. An additional objective of this study was to determine the flow stress data for Alloy 706 under different conditions of temperature, strain and strain rate. Such data is necessary for deformation modeling which can be used to develop correlation between microstructure and local deformation conditions. Modeling can also be used to determine the required forging loads for a specific process. This is important because the size of the GE gas turbine forgings is so large that press capacity is an important factor.

Procedure

The material used in this study was from a large billet. The billet was converted from a 950 mm diameter ingot which was triple melted (Vacuum Induction Melting + ElectroSlag Remelting + Vacuum Arc Melting). The chemistry of the ingot is given in Table 1.

Table I - Chemical Composition (Weight percent) of Material Used in Study

C	Si	Mn	S	P	Al	Ti	Nb	Cr	Ni	Fe
.03	.02	.05	.001	.008	.185	1.87	2.73	16.13	40.85	Balance

The isothermal compression testing was done by Wyman-Gordon in Houston. A closed loop servo-hydraulic machine was used for generating constant strain rates in compression. Three different specimen geometry's were used. They are shown in Figure 1. The Normal Specimen was the standard specimen used for generating most of the flow curves. Alternate Specimen was used for multiple upset testing and therefore is longer. A special specimen (Figure 1) of a double cone shape was designed to develop different strain contours within a single specimen. All specimens were heated for 20 minutes before testing. Heating was done in a clam shell furnace on the test fixture. The dies used for the testing was Titanium Carbide. The specimens were coated with Boron Nitride to provide lubrication. On completion of testing the specimens were removed and allowed to cool in air.

Results

The as-received microstructure (Figure 2) of the billet showed a uniform recrystallized microstructure of ASTM 0-1. The compression test specimens were all machined in such a way that the axis of the specimen would be parallel to the axis of the original billet.

Standard Specimens

Compression tests were done at temperatures from 815 °C to 1093 °C at 55 °C intervals. Tests were done at four different strain rates 1.0, 0.1; 0.01 and 0.001 per second for each temperature. The specimens were upset 50% (0.7 true strain). The nominal strain rate was kept constant throughout the test. The load displacement data acquired was converted to true stress and true

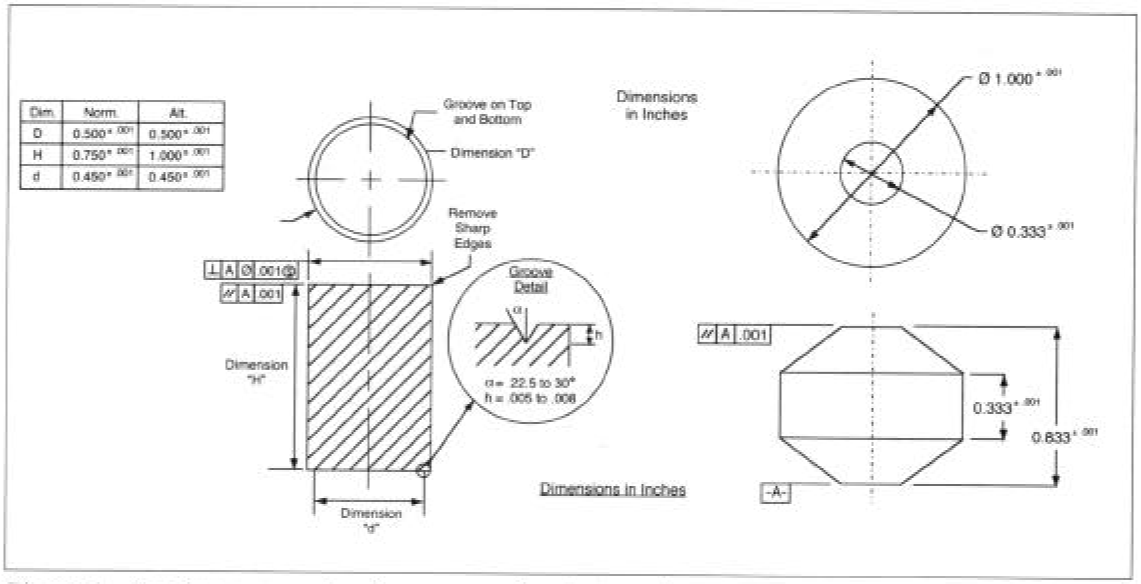

Figure 1 - Specimen geometry for compression test specimens.

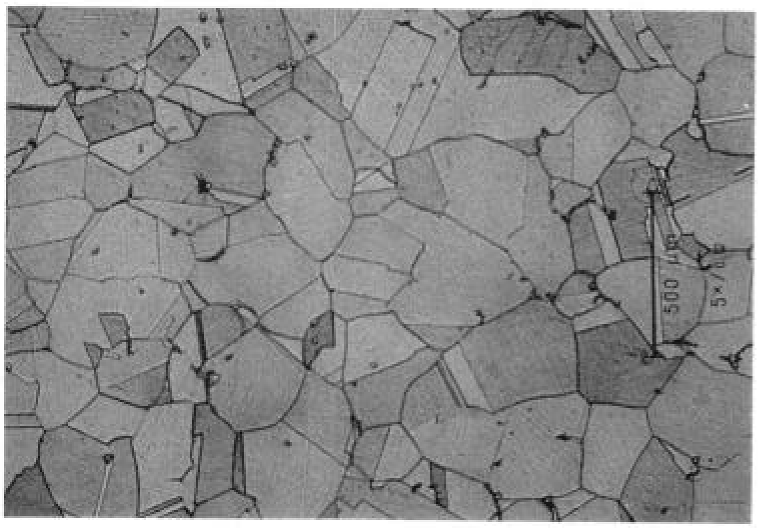

Figure 2 - Initial microstructure of compression test specimen.

strain after correcting for tooling deflection and lubricant film compaction. The flow stress data was adjusted to account for specimen temperature rise during deformation due to adiabatic heating. Correction was done based on the assumption that 90% of the strain energy is converted to heat. The temperature rise was calculated from:

$$\Delta T=\{\{1/(\rho\ Cp)\}\int \sigma\delta\varepsilon\}0.5f$$

where ρ = density; Cp = specific heat ; f=dissipation factor defined as:

$$f=0 \text{ for } \varepsilon<0.001/\text{sec};\ f=(1/3)\log\varepsilon+1 \text{ for } .001<\varepsilon<1;\ f=1 \text{ for } \varepsilon>1$$

Most of the flow curves were observed to be essentially flat and did not show any evidence of flow softening through dynamic recrystallization. A contour plot of flow stress at 0.001/sec strain rate is shown in Figure 3. The variation in flow stress with temperature was similar for

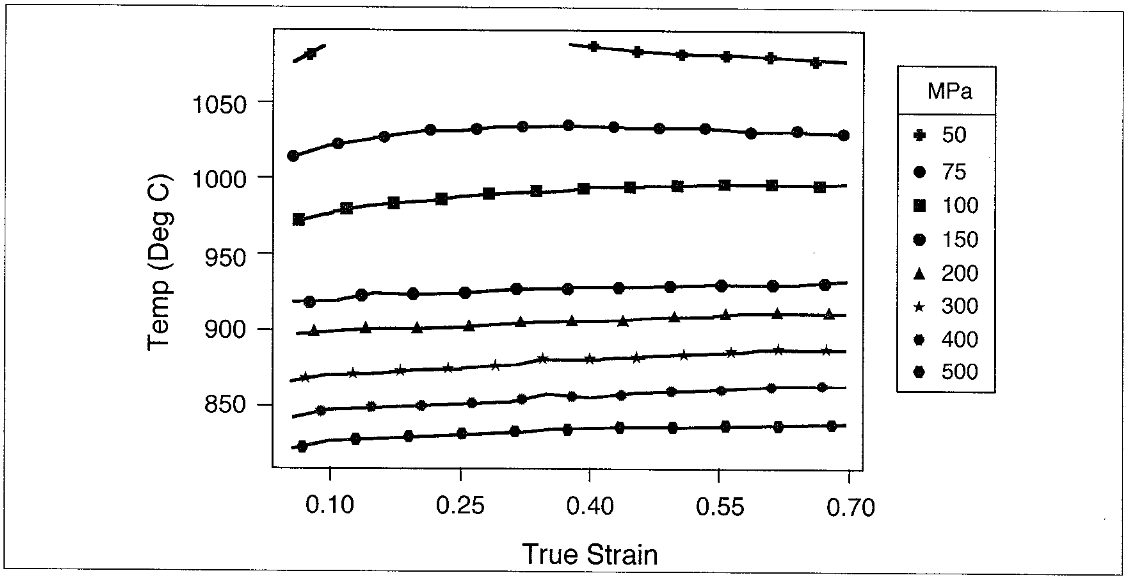

Figure 3 - Flow Stress Plot of 706 at a strain rate of 0.001/sec.

the other strain rates. At high strain rates the lower temperature curves showed a decrease with increasing strain. This decrease in flow stress is definitely not due to dynamic recrystallization because the as-deformed specimens at these conditions did not show any recrystallized grains. The drop is therefore because of softening due to adiabatic temperature rise of the specimen. This is not observed at the higher temperatures because the decrease in flow stress with increase in temperature is less significant at the higher temperatures.

The compression test specimens were sectioned and evaluated for microstructure. Selected samples were given a solution treatment at 898 °C, 927 °C or 954 °C for 4 hours and air cooled. Table 2 summarizes the microstructures observed in the as-forged and solution treated conditions. The only condition that achieved a 100% recrystallized microstructure in the as-upset condition is the 0.001/sec test done at 1093 °C. The 1.0/sec showed only partial recrystallization in the as-upset condition. However the recrystallized grain size for 0.001/sec test was significantly coarser than the higher strain rates. This is probably because the slow strain rate test takes long enough to permit some static and metadynamic recrystallization. No dynamic recrystallization was observed at 982 °C and below. This is in contrast to Alloy 718 where dynamic recrystallization at 982 -1010 °C is used to produce a very fine grain size (ASTM 8-10). Static recrystallization was complete for all test specimens at 954 °C. No recrystallization was observed at 926 °C and below. The statically recrystallized grain size after 4.0 hours at 954°C was a uniform ASTM 4 , irrespective of the forging temperature.

Variable Strain Specimen

A second set of specimens were used to determine the minimum strain required to induce static recrystallization on solution treatment. These had a very specific 'double cone' geometry as shown in Figure 1. This geometry was developed by Wyman-Gordon to develop different strains within the same specimen. A nominal upset of 38% produces strains of 0.6 at the center and 0.2 at mid-radius. For a 23% nominal upset the center develops strains of 0.3 at the center and 0.15 at mid-radius. Only 6 tests were done on these double cone type specimens. They were all done at 1037 °C. Three strain rates 0.001/sec, 0.01/sec and 0.1/sec each were done to two different nominal strains. Sections from these samples were given solution treatment at 964 °C, 982 °C or 1037 °C.

Table II - Microstructure of Compression Test Specimens (0.7 True Strain)

Test Temp °C	Strain Rate	As-Upset Microstructure	Heat Treated Microstructure
1093	.001	100% ASTM 4-5	954 °C/4hrs - No Change
	.01	10% Recrystallized Necklace	954 °C/4hrs - 100% ASTM 4
	.1	50% ASTM 6	927 °C/4hrs - 80% ASTM 4
	1.0	60% ASTM 6	-
1037	.001	20% Recrystallized Necklace	-
	.01	5% Recrystallized Necklace	954 °C/4hrs - 100% ASTM 4
	.1	5% Recrystallized Necklace	898 °C/4hrs - No Change
	1.0	5% Recrystallized Necklace	-
982	.001	5% Recrystallized Necklace	-
	.01	No Recrystallization	954 °C/4 hrs - 100% ASTM 4
	.1	No Recrystallization	927 °C/4 hrs - G.B. Eta No Recrystallization
	1.0	No Recrystallization	-
927	.001	No Recrystallization	-
	.01	No Recrystallization	954 °C/4 hrs - 100% ASTM 4
	.1	No Recrystallization	898 °C/4 hrs - G.B. Eta No Recrystallization
	1.0	No Recrystallization	-
871	.001	No Recrystallization	-
	.01	No Recrystallization	954 °C/4 hrs - 100% ASTM 4
	.1	No Recrystallization	927 °C/4 hrs - G.B. & I.G. Eta No Recrystallization
	1.0	No Recrystallization	-
815	.001	No Recrystallization	-
	.01	No Recrystallization	954 °C/4 hrs - 100% ASTM 4
	.1	No Recrystallization	898 °C/4 hrs - G.B. & I.G. Eta No Recrystallization
	1.0	No Recrystallization	-

Examination of the micro-structures has provided some very useful characteristics of this alloy for upsetting at 1037 °C. they are:

1. A minimum strain of approximately 0.15 at 1037 °C is required to achieve full static recrystallization when subsequently heat treated at 954 °C.
2. The statically recrystallized grain size increases from ASTM 4 to ASTM 1 with solution treatment temperature from 954 °C to 1037 °C (4 hours hold time)
3. The grain size decreases with increasing strain for solution treatment temperatures of 954 °C and 982 °C. The effect of strain is not observable for 1037 °C solution treatment.
4. The grain size also decreases with increasing strain rate for the 954 °C and 982 °C solution treatment. No effect of strain rate can be observed at 1037 °C.
5. No evidence of abnormal grain growth was observed for deformation at 1037 °C

Multiple Upsets

As mentioned earlier the specimens for the double upsets were slightly different in geometry. They were 25.4 mm long and 12.2 mm in diameter (Figure 1). They were longer because they were double upset. The strain at each step was limited to 0.35 because this would be representative of the low strain area in a large gas turbine forging. Two specimens were given a controlled cool from the first forge temperature (1037 °C) to the second forge temperature of 982 °C.

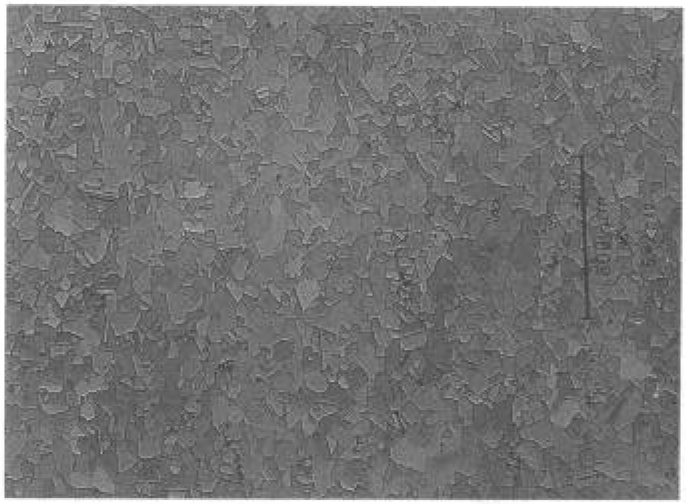

Figure 4 - As-upset microstructure of specimen given a multiple upset with a hold time after final upset of 15 minutes.

After the second upset one specimen was solution treated at 954 °C and the other was solution treated at 927 °C. Solution treating at 954 °C produced a uniform grain size of ASTM 5 while solution treating at 927 °C produced a partially recrystallized grain structure.

Multiple Upset + Hold Time

A specimen was upset at 982 °C, recrystallized at 982 °C for 2 hours, upset again at 982 °C and held for 15 minutes. A fully recrystallized ASTM 6 (Figure 4) was obtained. A similar upset sequence with a 30 minute hold time produced a uniform grain size which was somewhat coarser (ASTM 5.5). These were the finest grain structures that were obtained from the study.

Discussion

The flow stress for Alloy 706 is observed to be similar to many superalloys. Flow softening was observed due to adiabatic heating for the 815 °C and 871 °C tests. No flow softening was observed for the other tests. The flow stress of the alloy became very high with decreasing temperature.

Dynamic recrystallization to 100% was not observed for the test conditions used here. Alloy 706 differs from Alloy 718 in this behavior because full dynamic recrystallization is possible in 718[2]. It is expected that processes like rolling and hammer forging which develop high strain rates could induce full dynamic recrystallization. But such processes cannot be easily applied to large gas turbine forgings.

The recrystallized grain size was observed to be mainly a function of recrystallization temperature. The lower limit however for 100% static recrystallization on heat treatment appeared to be 954 °C. The statically recrystallized grain size was independent of upset temperature. However a low forging temperature would be preferred for large parts because possible grain growth during cool down after forging.

The hold time process is a method of avoiding excessive grain growth. A direct heat treatment after forging would minimize the time for heat up of large parts and thereby reduce grain growth.

The multiple upset technique uses the idea that static recrystallization initiates at deformed grain boundaries. A finer initial grain size has a higher grain boundary area per unit volume and therefore has more nucleation sites for subsequent recrystallization into a finer grain size.

Conclusions

The following are the main conclusions of the study.

1. The grain size after heat treatment is dependent only on the solution temperature and is independent of the deformation temperature.
2. A minimum strain of 0.15 at 1037 °C is needed to achieve full static recrystallization when subsequently heat treated above 954 °C.
3. Multiple upsets with decreasing temperatures and intermediate recrystallization can improve the grain size of Alloy 706.
4. The grain growth of Alloy 706 is very rapid above 1093 °C. However at 982 °C it takes more than 30 minutes at temperature for grains to start growing. Lower forging temperatures are therefore recommended.
5. Forging below the ETA solvus does not produce the results as in Alloy 718. Dynamic recrystallization is not complete.

Acknowledgements

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