Grain Boundary Precipitates and Mechanical Properties of Alloy706

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Abstract

Effects of cooling rate from solution treatment temperature on mechanical properties and microstructures of a large Alloy 706 disk forging has been investigated.

The precipitation of delta and eta phases occurred at the grain boundaries with an increase of cooling rate from solution treatment temperature. The morphology changes of from globular type to cellular type and coarsening of precipitates were observed with decreasing the cooling rate. The mechanical properties at room temperature such as yield strength, tensile strength, elongation, reduction in area and absorbed energy increased with increasing the cooling rate from solution treatment temperature.

Same tendency was observed in the yield and tensile strength at elevated temperatures, although ductilities at 650 °C slightly decreased with increasing the cooling rate.

Creep rupture time at 650 °C under 690 MPa extended with increasing the cooling rate from solution treatment, while creep rupture ductility decreased with increasing cooling rate.

These results were closely associated with the precipitation behavior of delta and eta phases at grain boundaries.

Introduction

Current Alloy 706 has been used for a heavy duty industrial gas turbine. In Alloy 706, there are two types of aging treatment, originally developed by International Nickel Company. A three-step aging process is used for application where high temperature creep rupture ductility is required, and a two-step aging process is employed when tensile and impact properties are required. In general, Alloy 706 for a gas turbine disk has been used at the temperature ranges lower than creep temperature range, therefore the two-step aging process has been applied. Since a large forging such as a gas turbine disk has a heavy thickness of more than 300mm, the cooling rates from solution treatment temperature differ with locations, and they affect the mechanical properties.

This paper describes the effect of cooling rate from solution treatment temperature in relation to microstructures and mechanical properties including creep rupture properties.
Table I  Chemical compositions of Alloy 706 used (wt %)

<table>
<thead>
<tr>
<th>Alloy</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Ni</th>
<th>Cr</th>
<th>Ti</th>
<th>Al</th>
<th>Nb</th>
<th>B</th>
<th>Fe</th>
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<tbody>
<tr>
<td>A</td>
<td>0.016</td>
<td>0.10</td>
<td>0.27</td>
<td>0.004</td>
<td>0.004</td>
<td>40.03</td>
<td>16.02</td>
<td>1.57</td>
<td>0.28</td>
<td>3.07</td>
<td>0.0030</td>
<td>Bal</td>
</tr>
<tr>
<td>B</td>
<td>0.008</td>
<td>0.09</td>
<td>0.07</td>
<td>0.006</td>
<td>0.001</td>
<td>41.19</td>
<td>15.81</td>
<td>1.66</td>
<td>0.15</td>
<td>2.82</td>
<td>0.0033</td>
<td>Bal</td>
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</tbody>
</table>

Table II  Simulated heat treatment of Alloy 706 used

- Solution treatment: 990°C - 3h
- Cooling rate: 1050, 580, 240, 100, 20°C/h
- Aging: 730°C - 10h (furnace cool to 620°C)
  620°C - 8h (air cool)

Figure 1  TTT diagram and Vickers hardness of Alloy 706
Material and Experimental Procedure

Chemical compositions of the materials are shown in Table I. Alloy A was a small ingot weighting about 1000 kg which was melted by an induction furnace and electroslag remelting (ESR). After melting, the ingot was forged and heat treated subsequently was subjected to tests for the TTT diagram. Alloy B was taken from rim portion of a large disk forging with 1900 mm in diameter and 310 mm in thickness. The disk was made by a 10 ton ingot which was melted by a vacuum ladle refining and ESR process followed by forging operation using a 13000 ton capacity press. After forging, the rim material was removed from the disk to study the effect of cooling rate from solution treatment temperature. The simulated heat treatments shown in Table II were employed to the test blocks. Tensile and Charpy impact tests were carried out at room temperature. High temperature tensile tests were performed at temperatures of up to 650°C. Creep rupture test at 650°C under 690 MPa was conducted using combination (smooth and notched) specimens. Microstructural study of the various specimens was conducted using optical, scanning electron and transmission electron microscopies.

Results and Discussion

Time-Temperature Transformation

Prior to study the effects of cooling rate on mechanical properties, the precipitation behavior of Alloy 706 was studied. The time-temperature-transformation (T-T-T) behavior was studied by SEM/EDX, and optical microscopy and hardness for Alloy A. Test specimens were solution treated at 990°C followed by rapid quenching and aged at various temperatures. Figure 1 shows T-T-T diagram and hardness of Alloy 706. Present T-T-T diagram is similar to previous reports. Laves, delta, eta, gamma prime, and gamma double prime were observed in this work. Peak hardness was observed at around 700°C. Coarsed delta and/or eta precipitates exist over 800°C and it leads to decrease in hardness.

Effect of cooling rates on microstructure

Figure 2 shows SEM photographs of as solution treated microstructure with different cooling rates from solutioning temperature of 990°C for Alloy 706. It was found that the amount and size of precipitates at grain boundaries increase with decreasing cooling rate. The precipitation of eta and delta phases predominantly occurred to grain boundaries on the way to cooling from solutioning temperature. These intergranular precipitates become larger as the cooling rate become slower, and these seem to be grown eta and delta phases. Figure 3 shows SEM photographs of the Alloy 706 which was cooled with various rates from solution temperature of 990°C and aged. In comparison with the microstructures shown in Figure 2, the finer r' and r'' phases which precipitated by aging were observed within grains. Figure 4 shows TEM photographs and analysis results by EDX of the alloy which
Figure 2  Scanning electron micrographs of as solution treated specimens cooled with various rates from solution temperature in Alloy 706.
Figure 2  Scanning electron micrographs of as solution treated specimens (continue) cooled with various rates from solution temperature in Alloy 708
Figure 3. Scanning electron micrographs of specimens cooled with various rates from solution temperature and aged in Alloy 706

a) Cooling rate: 1000°C/h
b) Cooling rate: 240°C/h
c) Cooling rate: 20°C/h
Precipitates 1 and 4 are seemed to be eta phase.
Precipitates 2 and 3 are seemed to be delta phase.

Figure 4 Transmission electron micrograph and EDX analysis of specimens cooled with 100°C/h from solution temperature and aged
Figure 4. Transmission electron micrograph and EDX analysis of specimens (continue) cooled with 100°C/h from solution temperature and aged
was cooled at the rate of 100 °C/h from solution treatment temperature and aged. It appears that the precipitates which are present at grain boundaries are delta and eta phases from above result and Heck's result. 6)

**Tensile and Impact Properties**

Mechanical properties were studied to the Alloy 706 with various cooling rates shown in Table II. The grain size of the specimens which was subjected to solutioning and aging treatments was 3 in ASTM GS No. Tensile and Charpy impact tests were performed at room temperature and the elevated temperature tensile tests were performed at 482°C and 650°C on different cooling rates from solution treatment temperature followed by aging. The effect of cooling rate on tensile and Charpy impact properties at room temperature are shown in Figure 5.

The 0.2% yield strength and tensile strength at room temperature increase with increasing cooling rate. In addition, small amount of increase in elongation, reduction of area and Charpy absorbed energy were recognized. Tensile properties at 482°C and 650°C on various cooling rates are shown in Figure 6. The 0.2% yield strength and tensile strength exhibited same tendency with room temperature properties. There are no effects of cooling rate on the ductilities at 482°C. On the other hand, those at 650°C slightly decrease with increasing cooling rate. The degradation cause of 650°C tensile ductility is because fine precipitation takes place during the tensile test and it strengthens the grains.

**Creep Rupture Properties**

Figure 7 shows creep rupture properties at 650°C under 690 MPa on the different cooling rates from solution temperature. Creep rupture time extended and rupture ductility decreased with increasing cooling rate. Notch detrioration are found in case of the cooling rate which exceeds 300 °C/h. The cooling rate which shows good balance of creep strength and creep ductility is 50~200 °C/h in average. As shown in Figure 3, no grain boundary precipitation occur during cooling from solution treatment temperature at the cooling rate of 1050°C/h and consequently, precipitation elements such as Nb and Ti are keeping in the matrix without precipitation. Thus the coherent and fine precipitation into grains occurred during aging. The grains aretherefore strengthen more greater than the grain boundaries. As a result, the grains are difficult to deform and results in brittle fracture from triple point of grain boundary. The globular eta and delta phases are present in the case of cooling rate of 240 °C/h. The size of precipitates was approximately less than 0.3 μm in diameter. This precipitation behavior caused a rise of rupture ductility. The microstructure of the material with a cooling rate of 20°C/h, which provides the lowest creep rupture strength showed the film and cellular eta and delta phases at the grain boundaries and the coarse precipitates in grains are present. The precipitates grew from globular type to cellular typeand became coarse with increasing cooling rate. The precipitation of coarse andtable eta and delta resulted in a small amount of coherent r' and r''precipitates and the denuded zone was formed near the grain boundaries. 7) Grain size of the present test
Figure 5 Room temperature mechanical properties with various cooling rate of Alloy 706

Figure 6 Elevated temperature tensile properties with various cooling rate of Alloy 706

Figure 7 Creep rupture properties with various cooling rate of Alloy 706
specimen is relatively larger. The effect of grain size on creep rupture properties is also important. If the finer grain materials are tested, it seems that higher rupture strength and ductility will be obtained.

Conclusions

Effects of cooling rate from solution treatment temperature on mechanical properties and microstructures of a large Alloy 706 disk forging has been investigated. The results obtained are as follows.

1. The number and size of precipitates at the grain boundaries increased with increasing cooling rate from solution treatment temperature. Microstructural observations showed that mixed delta and Eta phases were present at the grain boundaries. The morphology of precipitates grow from globular type to cellular type and coarsened with increasing cooling rate.

2. The strength at room temperature increased with increasing cooling rate from solution treatment temperature. In addition, the same tendency were observed in elongation, reduction of area and Charpy absorbed energy.

3. The strength at elevated temperatures also increased with increasing cooling rate although the ductility at 650 °C was slightly decreased with cooling rate.

4. Creep rupture time at 650°C under 690 MPa extended with increasing cooling rate, while creep rupture ductility decreased with increasing cooling rate. The notch detrioration took place in the case of the cooling rates which exceed 300°C/h. It is concluded optimum cooling rate was between 50 °C/h and 200°C/h.

References


