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Manufacturing Technologies for Ti-6246 Alloy Aero Engine Disc Forgings

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In order to achieve both optimum fatigue strength and fracture toughness in the Ti-6246 β-processed disc, proper controls for final forging conditions were sought. The FEM analysis, which can provide both deformation and thermal analysis at the same time, was developed for the case of hammer forging. Applying the technology, actual forged discs were manufactured by using a counterblow hammer, and the estimation of their mechanical properties was performed.

Keyword: titanium(Ti), Ti-6246, a+β titanium alloys, β- processed forging, acicular a, thermo mechanical treatments, mechanical properties

1. Introduction

Various compressor parts of aero gas turbine engines are made of titanium alloys featured by their low weights and high strengths. In particular, compressor discs used as high strength titanium alloy up to 450 degrees centigrade or lower are made of such an alloy as Ti-6%Al-2%Sn-4%Zr-6%Mo (Ti-6246) alloy.
The microstructure forged in the α + β field temperature is equiaxed α grains in the transformed β phase with acicular α in the β matrix as shown in Figure 1(a). This microstructure suffers from poor fracture toughness and fatigue crack growth properties.
The β-processed forging has been applied to improve such properties. The microstructure consists of acicular α micro-structure as shown in Figure 1(b), and it shows superior properties in not only fracture toughness, but also in fatigue strength and creep properties. As for the fracture toughness, the β-processed discs are obtained 50MPa-m1/2 or more1,2) by comparison with α+β field forging discs as 30MPa-m1/2 level[3,4)].
In this research, the influence of forging temperatures and strains on mechanical properties was investigated from preliminary tests. The Finite Element Method (FEM) analysis, which can provide both deformation and thermal analysis at the same time, was developed for the case of hammer forging. In order to achieve both optimum fatigue strength and fracture toughness in the compressor discs, proper β-processed forging conditions such as forging temperature and number of hammer blows were determined, applying the technology. Actual forged discs were manufactured by using a counterblow hammer, and the evaluation of their mechanical properties was performed.

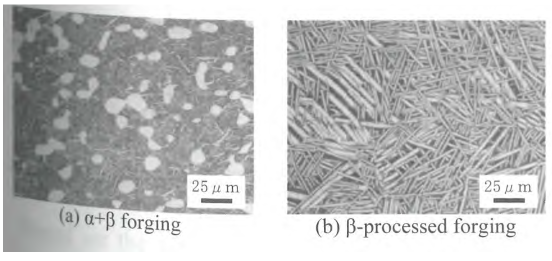

Figure 1. Microstructure of Ti-6246 forging

2. Proper Condition of a-processed Forging

2.1 Investigation for optimum temperature and strain from the microstructure.

For obtaining proper acicular α microstructure, a compression test at high temperatures was conducted using a specimen with 8 mm in diameter and 12 mm in length. The testing conditions are shown in Figure 2, where deformation temperatures and strains are varied, and the microstructures obtained were studied after heat treatments of solid solution followed by aging.
Figure 2 shows the proper range of deformation temperatures and strains. The upper horizontal axis shows equivalent strains calculated by the FEM analysis. Figure 3 shows microstructures in each region of temperature and strain. Regions; (a), (b), (c), (d) in Figure 2 correspond to those in Figure 3, respectively.
In the region (b) where the temperature is high, both ductility and fatigue strength are low, presumably because large recrystallized β grains are observed. In the region (c) where strain is low, both ductility and fatigue strength are also low. This is thought to be caused by thick and long grain boundary α. In region (d) where temperature is low and strain is high, the length of acicular α is rather short in the β grains and further grain boundary α has become considerably equiaxial. In this condition, fracture toughness is low, probably because crack propagation is easier as in the case of α+β temperature field forge.
In conclusion, the proper temperatures are between 800 and 1050 degrees centigrade and also there is the optimum strain range at the proper temperature as shown Figure 2.

2.2 Influence of strain on material characteristic

Pancake forgings with 230mm in diameter and 80mm in length, which were given reduction in height of 33% and 67%, were produced. Heating temperature and die temperature were 1000 degrees centigrade and 850 degrees centigrade, respectively. After the forging, tensile test specimen blanks were cut out in the tangential direction at a half thickness, a quarter thickness, and 10 mm depth from the pancake surface. And then they were solution treatment and age (STA) heat treated in the α+β field : Solution at 930 degrees centigrade for 1 hour, air cool (AC) and aging

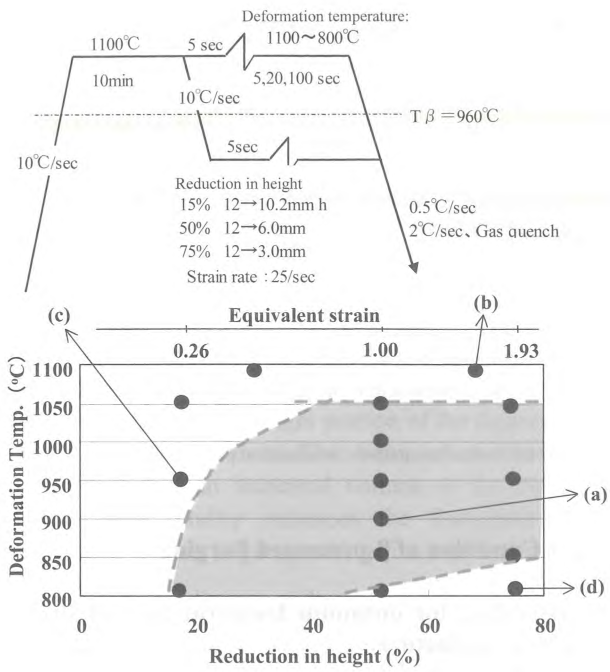

Figure 2. Influence of temperature and strain on microstructure of β-processed forging

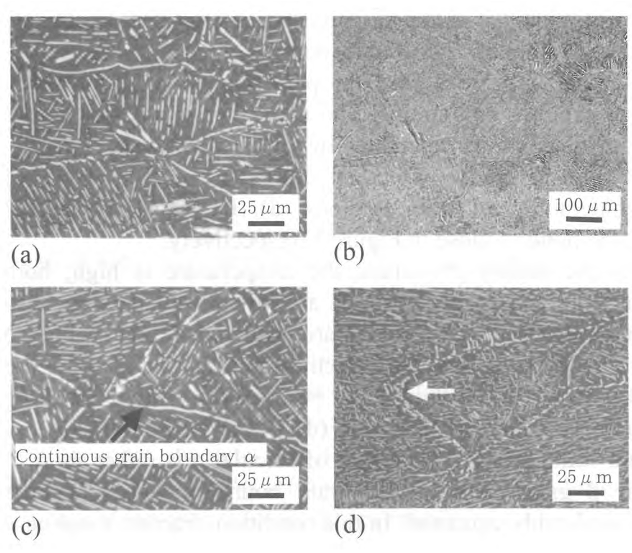

Figure 3. Microstructure of Ti-6246 β processed forging

at 595 degrees centigrade for 8 hours, AC followed by tensile testing at room temperature (RT).

Figure 4 shows the mechanical properties with equivalent strain calculated by the FEM analysis at the locations where the specimens were cut out for the two cases of the pancake forging. Tensile strengths is not affected by the equivalent strain, but the reduction of area (RA) improves until the equivalent strain reaches 0.5, and then they are followed by a constant value of ductility. Less elongation improvement with strain is observed. Therefore, a conclusion is drawn here that equivalent strain of at least 0.5 or more is necessary to obtain high ductility.

Figure 5 shows the influence of equivalent strain on cycles to failure in low-cycle fatigue (LCF) testing. It can be seen that fatigue life has the tendency to improve with the increase of equivalent strain.

It can be supposed that the LCF strength may have a good relationship to the ductility even in the β-processed material. But, clearer relationships between them are thought to be needed from the point of more detailed microstructural analysis.

Fracture toughness at room temperature are shown in Table 1. The pancake of 33% reduction in height with low forging strain indicates a slightly higher fracture toughness than the pancake of 67% reduction. This seems to reflect the fact that material with lower strain offers longer zigzagged crack paths than that with higher strain even in the β-processed case.

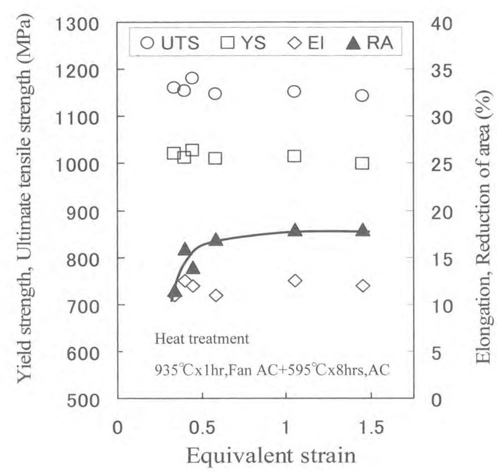

Figure 4. Influence of forging strain on tensile properties of Ti-6246 β-processed forging (at RT)

Table 1. Fracture toughness of β-processed forging (at RT)

Reduction in height (%)	33	67
Fracture toughness ($MPa\text{-}m^{1/2}$)	69.9	64.5

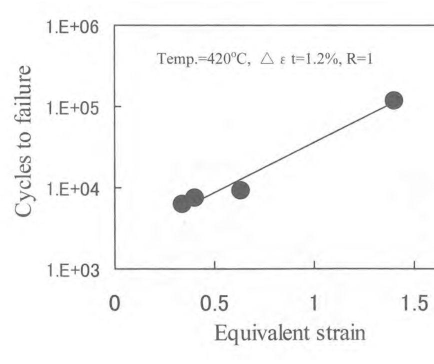

Figure 5. Influence of forging strain on LCF life of Ti-6246 β-processed forging

3. Numerical analysis for β-processed Forging

3.1 Flow stress value of Ti-6246

Figure 6 shows stress-strain curves of Ti-6246 obtained by conventional compression tests using round bars. Work-softening seems to appear at a relatively low temperature. This can be considered to be resulted from temperature changes caused by heat build-up during the deformation. But, it is necessary to get deformation resistance at a constant temperature for the theoretical analysis. To cope with this problem, the following measures were taken.

The equation of the stress σ and strain ε was assumed as equation (1).

$$\sigma = A(T) \times (1.0 + F \cdot \varepsilon^{n}) \qquad (1)$$

Where, *A(T):* initial flow stress (a function of temperature and strain rate), *n:* work-hardening exponent, and *F:* coefficient Initial flow stress *A(T)* is determined referring to the yield point of a conventional stress-strain curve at a low strain region, where heat build-up is less. Next, in order to determine the work-hardening exponent *n* and coefficient *F,* a deformation-temperature-coupled analysis was conducted to make good agreement with stroke-load curves in the compression test. By substituting these values for the equation (1), stress-strain curves were calculated at various temperatures, strain rates, and strains as shown in Figure 7. Stress-strain curve from above mentioned method proved Ti-6246 was a tendency of work-hardening.

3.2 Numerical analysis for hammer forging

To control the material property through the β-process of Ti-6246 alloy, it is important to estimate the strain and temperature history distribution on the deformed material. The isothermal flow stress values were applied to deformation-temperature-coupled analysis of Ti-6246 forging process. In the analysis, the relation between the temperature, strain, strain rate and flow stress value are input to the FEM code as the data of a table form. As heat build-up of material in the analysis, plastic deformation energy is converted into the thermal energy and the temperature is calculated. Figure 8 shows analytical results of temperatures and strains during forging. The analysis conditions used blow energy, energy efficiency and blow intervals measured at the practical forging. The temperature ranges were between 800 and 1050 degrees centigrade within the proper range though the lower side of the material was slightly cooled by contacting the die in the forging processes. Further, the forging equivalent strains were sufficiently higher values than 0.8.

4. Evaluation of actual trial-forged disc

Based on the knowledge obtained as above described, a disc with an outside diameter of 730mm and maximum thickness of 115mm was actually hammer forged. 5 ton

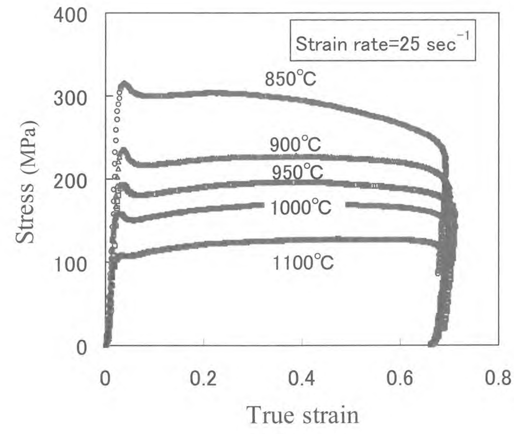

Figure 6. Stress-strain curves of Ti-6246

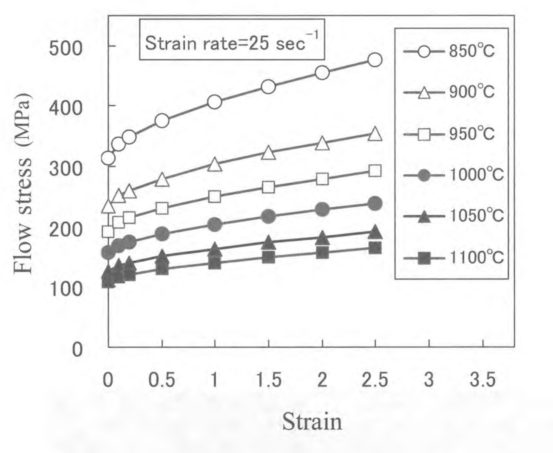

Figure 7. Isothermal flow stresses of Ti-6246

ingot that in-house melted by Vacuum Arc Remelting (VAR) method was forged in β region and α+β region, and then the round billet with a diameter of 305mm in an α+β condition was manufactured.

Table 2 shows chemical composition of billet material used in this test.

First, perform was forged by the press after heating to the α+β field, and then final forging carried out by hammer after heating to the β field.

The heat treatment such as solution and aging was carried out after forging, followed by non destructive testing and cut up testing.

Figure 10 shows the cross section macrostructure of the forging. It was confirmed that a good microstructure and material flow were obtained as anticipated.

Tensile test results at RT are shown in Figure 9. Elongation and RA in the internal position of the disc are higher than those in the outer position, because the strain in the internal position is higher than that in the outer position. However, the lowest elongation and RA were obtained to be 6% and 10% or more.

LCF test results are shown in Figure 11. As for the LCF strengths, good values are obtained on the whole positions in the disc.

Fracture toughness are shown in Table 3. Enough value was obtained at both RT and 450 degrees centigrade.

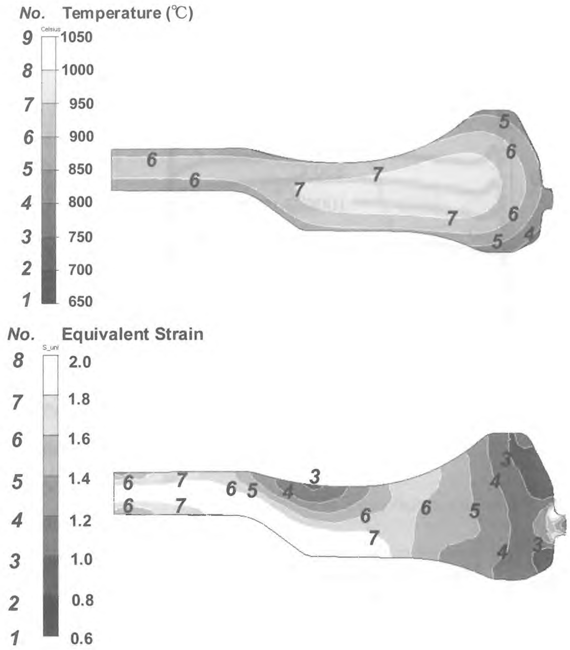

Figure 8. Results of calculation of temperature and strain during disc forging

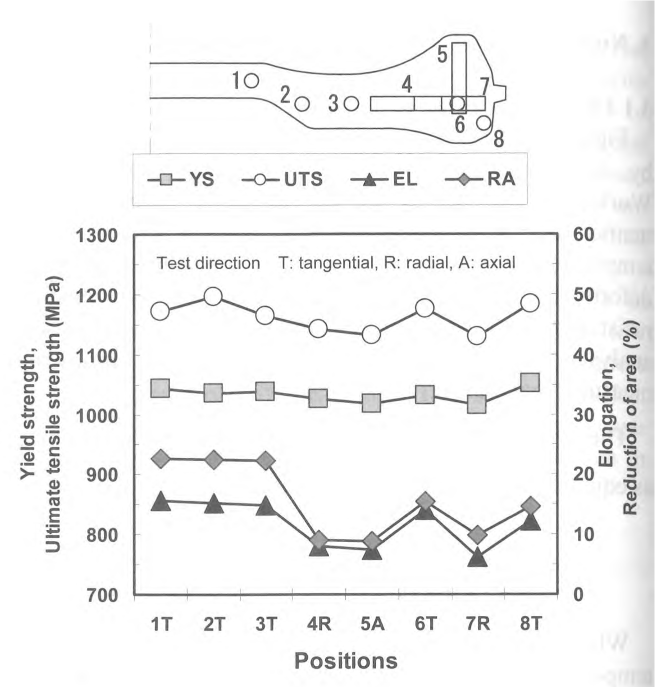

Figure 9. Results of tensile test of disc forging (at RT)

Table 2. Chemical composition of Ti-6246(mass%)

Position	Al	Sn	Zr	Mo	Fe	O	C	N
TOP	6.19	2.06	4.22	5.85	0.072	0.11	<0.005	0.0055
BOT	6.23	2.04	3.99	5.98	0.064	0.12	<0.005	0.0064

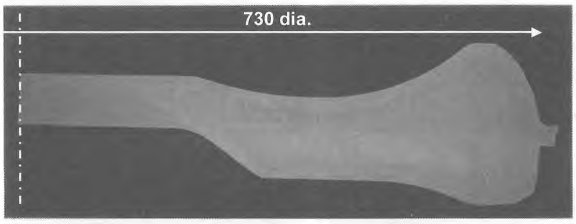

Figure 10. Macrostructure of β-processed disc forging

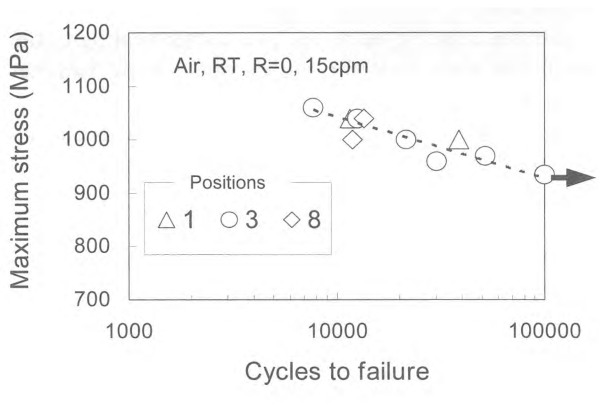

Figure 11. Results of LCF test of disc forging

Table 3. Results of fracture toughness test

Position	Temperature (°C)	Fracture toughness ($MPa\text{-}m^{1/2}$)
3	20	74.0
6	450	81.2

As a summary, these experimental results were well consistent with theoretical predictions.

5. Conclusion

The manufacturing technologies of β-processed forging were developed for Ti-6246 alloy aero engine disc forgings as follows.

1) The forging conditions for the good structure andproperties are a range of 800 to 1050 degrees centigrade in the deformation temperature and 0.5 or more in the equivalent strain.
2) The analysis technology of a hammer forging was verified to be able to do an accurate prediction by optimizing the boundary condition and flow stress value in the deformation-temperature-coupled analysis.
3) Good properties of the actual trial-forged discs proved the validity of these technologies.

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