Technologies for Process Design of Titanium Alloy Forging for Aircraft Parts

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Titanium alloys are widely used for aircraft parts, thanks to their high specific strength. It is important, in dealing with titanium alloy forgings, to control the history of temperature and plastic strain in order to obtain desired microstructures and mechanical properties. This paper introduces an example in which a process is designed using finite element method (FEM) analysis for β-processed forgings of a jet engine disk made of Ti-6246 alloy.

Introduction

Titanium alloys are superior to other metallic materials in specific strength (=0.2% proof stress / density). More than 50% of titanium alloy forgings used worldwide are for aircraft members requiring weight reduction and strength.[1)]

Supported by increasing passenger demand in recent years, the market for commercial aircraft is growing at a rate of 4 to 5% every year. Including replacement units, the demand for commercial aircraft is expected to more than double in the next 20 years.[2)] In addition, the quantity ratio of titanium alloy used per aircraft has increased lately, and the demand for titanium alloy forgings is on the increase.

On the other hand, titanium alloy is regarded as a difficult-to-forge material, and it is difficult to fill dies with the alloy to obtain the desired shapes. In addition, titanium alloy forgings for aircraft, in particular for rotating parts such as engine disks and shafts, are required to have high reliability. Thus the temperature, strain and strain rate during forging must be so controlled that the specifications for the material properties and quality inspection are satisfied.

Further, compared with other metallic materials, titanium alloys are poor in machinability, resulting in a high machining cost in addition to their high material cost. Hence, in order to expand the demand for them in aircraft and other applications, it is important from the aspect of forging technology to improve the yield through near-net shaping while securing quality.

This paper describes the forging technology of titanium alloy parts for aircraft.

1. Titanium alloy forgings used for aircraft

Titanium alloy forgings are used for various parts of airframe structures and engines. In the case of the Boeing 787, for example, titanium alloy accounts for approximately 15% of structural members, more than doubling the amount used for conventional aircraft. The amount (estimated) of titanium alloy used per unit has reached approximately 100 tonnes.[2)] This is because titanium alloy has a high compatibility with carbon fiber reinforced plastic (CFRP), which is used in large amounts in place of aluminum alloy to reduce airframe weight and thus to improve fuel economy. When joined with CFRP members, titanium alloy is less likely to cause galvanic corrosion and inhibits strain due to temperature change, since its coefficient of thermal expansion is similar to that of CFRP.

A titanium alloy commonly used for airframe structure parts is Ti-6Al-4V (acronym; Ti-64), which accounts for 80 to 90% of the titanium alloys generally used for aircraft. Ti-64 is the most widely used α-β alloy, having well balanced characteristics with an abundance of data and application history.

Meanwhile, among the airframe structure parts, aircraft legs, called landing gears, must be made of high-strength, high-toughness material that can support mid to large-sized aircraft, each weighing as much as 200 to 400 tonnes, and tolerate the impact at the time of landing. NiCrMo steel has been mainly used for this purpose; however, new titanium alloys are being adopted. For example, the Boeing 777 and Airbus A380 employ a high-strength titanium alloy, Ti-10V-2Fe-3Al, of near-β type (this alloy having a higher concentration of β-stabilizing element than other α-β alloys), and the Boeing 787 has adopted Ti-5Al-5Mo-5V-3Cr.[3)] Although these titanium alloys are more expensive than Ti-64, they are superior in forgeability and can be strengthened by solution and aging treatment after forging.

In aircraft engines, titanium alloys find many applications for fans and compressor parts used at temperatures of 590℃ or lower.[2)] Ti-64 alloy is used for fan disks and low-pressure compressor disks. For mid-pressure compressor disks, Ti-6Al-2Sn-4Zr-6Mo (Ti-6246) alloy and Ti-5Al-2Sn-2Zr-4Cr-4Mo (Ti-17) alloy, both near-β type, solutioned and aged, are used. For high-pressure compressor disks, which are exposed to higher temperatures, forgings made of heat-resistant titanium alloys are used. These alloys include Ti-5.8Al-4Sn-3.5Zr-0.7Nb-0.5Mo-0.35Si alloy (IMI834), which is near-α type (an α-β alloy containing a smaller amount of β stabilizing elements). For rotating bodies such as fans, compressor disks, shafts, and blades, various high-level characteristics are required, including ease of defect detection by ultrasonic testing (UT), in addition to static strength, fatigue strength and fracture toughness.4)

2. Characteristics of titanium alloys in hot forging

As shown in **Fig. 1**, titanium alloys are roughly classified into three categories depending on the types of additional elements and their amounts: namely, α alloy, α-β alloy and β alloy.5) The α-β alloys are most commonly used. All these alloys are composed of two phases, i.e., an α-phase with a close-packed hexagonal structure and a β-phase with a body-centered cubic structure. These phases greatly affect the forgeability and mechanical properties of the alloys, depending on their amount, size and morphology. In general, a higher content of β stabilizing elements, such as Mo, V, Cr and Fe, increases the amount of β phase and improves forgeability. An excessively large amount of β stabilizing elements, however, lowers the β transus temperature (i.e., the transition temperature between the α+β dual phase region and β single phase region), raising the flow stress for α-β forging (a method for forging in the α+β dual phase region), increasing the forging load required. Hence, the alloy type and forging method must be selected and combined appropriately depending on the applications and required characteristics.

Fig. 2 shows, as examples, stress-strain curves obtained during the hot working of the cylinder compression testing of a titanium alloy and commonly used steel. Steel generally exhibits work-hardening behavior, while titanium alloy shows a decline in the flow stress value as the strain increases, especially for deformation at a high strain rate. A material that shows work-softening behavior as described above exhibits a decline in flow stress at the portion where deformation first occurs, and this portion continues to deform preferentially during further processing. This results in inhomogeneous strain distribution inside forgings and, in the case of die forging, makes it more difficult to fill the dies. Furthermore, titanium is a material with relatively low thermal conductivity, which maintains and enhances the temperature distribution due to the inhomogeneity of strain during processing, making the temperature distribution also inhomogeneous, in addition to the strain distribution.

A typical production process for titanium alloy forgings is shown in **Fig. 3**, in which the post-forging heat treatment is usually conducted at a temperature

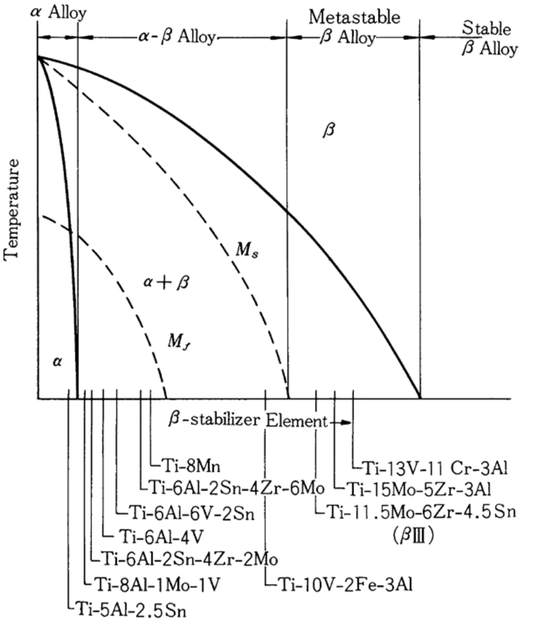
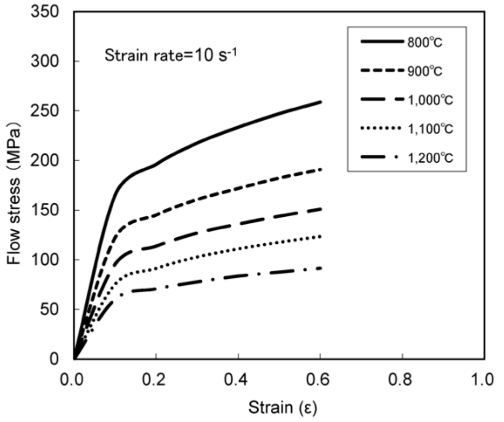
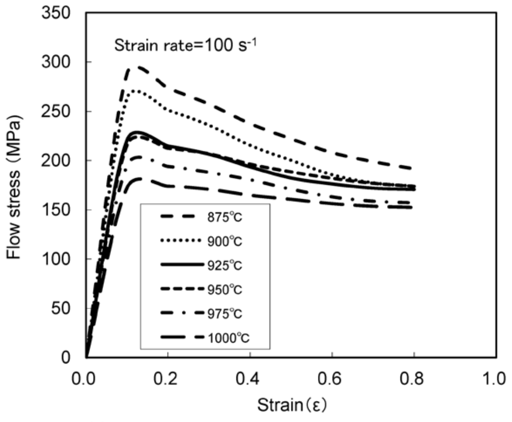


Fig. 1 Phase diagram of titanium alloy 5)



(a)Steel S25C at strain rate 10 s^{-1}



(b)Titanium alloy Ti-6246 at strain rate 100 s^{-1}

Fig. 2 Schematic illustration of flow stress curves at high temperatures

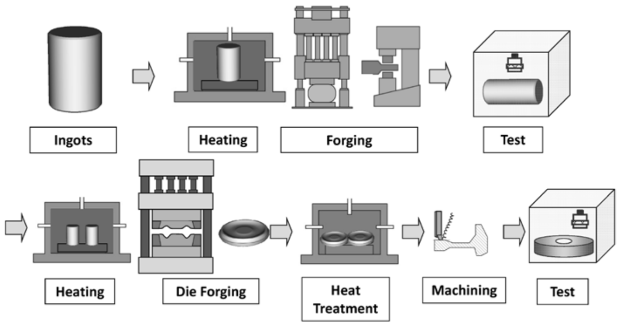


Fig. 3 Schematic illustration of titanium forging process

equal to or lower than the β transus temperature. Therefore, the as-forged conditions of the microstructure greatly influence the microstructural morphology and, consequently, the characteristics of the final product. Therefore, in the case of titanium alloys, it is extremely important, not only to obtain the product shapes, but to control the temperature, strain, and strain rate during forging, and the cooling rate after forging, and thus to achieve the desirable microstructures and characteristics.

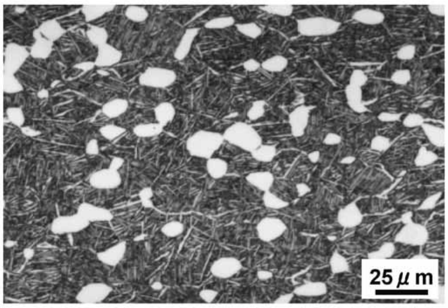
The next section focuses particularly on the influences of temperature and strain during forging and introduces the concept of process design for titanium forgings and the technologies required for the process, giving concrete examples.

3. Hot-forging technology for titanium alloys

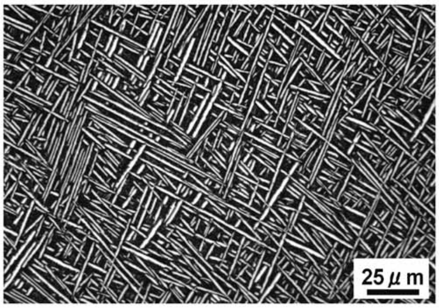
3.1 β-processed forging of Ti-6246 alloy disks for aircraft

As described above, titanium alloy, as a lightweight material with high strength, is widely used for the compressors in aircraft jet engines. Above all, high reliability is required for the rotating disks, each with moving blades attached to its circumference, and these are, therefore, made of forgings. The material properties required for these disks include high fatigue strength and excellent toughness. Ti-6246 is one such alloy that is in use.

The method of forging in a temperature region equal to or lower than β transus temperature ($\alpha+\beta$ region) is called "$\alpha+\beta$ forging". The $\alpha+\beta$ forging yields a microstructure in which elongated α grains are segmented and equiaxed by reheating, which results in a dual phase structure of $\alpha+\beta$ consisting of equiaxial α grains and a matrix consisting of fine acicular α (**Fig. 4**(a)). This microstructure, however, has the problem of low fracture toughness. One production method for alleviating the problem is a forging process involving heating in the β region (hereinafter referred to as "β-processed forging") prior to forging. In this process, the α phase precipitates very little during forging, precipitating mainly during the post-forging cooling. This results in an acicular microstructure occupying the entire body as shown in Fig. 4 (b), which achieves high fracture toughness. A conventional disk forged in the $\alpha+\beta$ region has a fracture toughness around 30 MPa $m^{1/2}$ at room temperature.6), 7) On the other hand, a β-processed forged piece has a fracture toughness of 50 MPa $m^{1/2}$ or higher.8), 9)



(a) α - β forging



(b) β processed forging

Fig. 4 Microstructure of forged Ti-6246

Meanwhile, in β-processed forgings, the heating in the β region before forging causes the microstructure to transform, which almost eliminates the influence of the prior processing history. Therefore, the characteristics of forged pieces are affected significantly by the temperature and processing strain during the final forging. Hence, the conditions for β-processed forging must be highly controlled to achieve appropriate material properties.10)

3.2 Appropriate conditions for β-processed forging: microstructure

The concept of β-processed forging is based on the concept of suppressing continuous grain boundary α, the phase that decreases ductility and fatigue strength, and promoting acicular α, the phase that increases fracture toughness. These objectives are achieved by suppressing the preferential precipitation of α phase at the grain boundaries from work hardened β phase so that the acicular α phase precipitates throughout the entire body.

Fig. 5 shows the range of process conditions

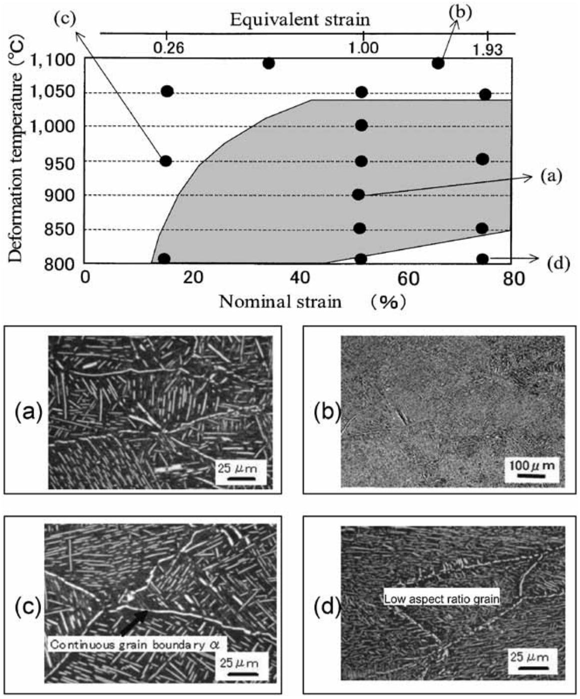


Fig. 5 Influence of temperature and strain on microstructure of Ti-6246, β-processed forging

based on microstructures. In the graph at the top of Fig. 5, the vertical axis represents the processing temperature and the horizontal axis represents the compression ratio. In order to take into account the inhomogeneous strain during the experiment, an upper horizontal axis is provided with equivalent strain of the microstructural area observed (at the thickness center and 1/2 radius), in which the equivalent strain was determined by FEM analysis. Fig. 5, at the bottom, includes microstructures obtained by the typical process conditions of the experiment. Condition (b) at a high temperature results in coarse β grains generated by recrystallization. Condition (c), with a small processing strain despite the relatively low temperature, results in a microstructure in which continuous grain boundary α remains. Condition (d), at a relatively low temperature with a large processing strain, results in acicular α that has a small aspect ratio (ratio of length to width) and is more equiaxed. Once the intragranular α is equiaxed as described above, the resulting microstructure becomes similar to that of a piece forged in the α+β region, which results in low fracture toughness and a high crack-propagation rate.

On the other hand, when processed under a condition in the shaded area of Fig. 5 (top), the grain boundary α becomes discontinuous, showing an acicular microstructure with a large aspect ratio (i.e., with an elongated shape) inside grains, as represented by microstructure (a) of Fig. 5 (bottom), which improves fatigue characteristics.[10]

3.3 Appropriate conditions for *β*-processed forging: material properties

The influence on the material properties has been studied in addition to the relationship between metallographic structure and the forging conditions described above. First, compression forming was performed under conditions including a heating temperature of 1,000℃, die temperature of 850℃, and reduction ratios of 33% and 67% to prepare the forged pieces, each of which had a solid cylindrical shape with an outer diameter of ϕ230mm and a thickness of 80mm. Their mechanical properties were studied. This paper describes the results of a tensile test and fatigue test whose results were significantly affected by strain. It should be noted that, in the current test range, the fracture toughness value at room temperature was 50 MPa $m^{1/2}$ or higher, regardless of the amount of strain.

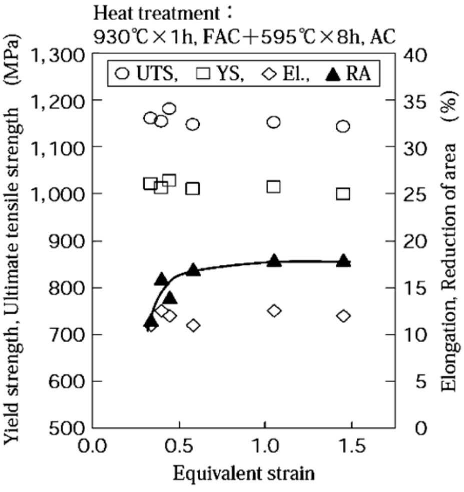
Tensile specimens were cut out from each forged piece at its thickness center (1/2t), 1/4t and 10mm from the surface layer, such that the tensile axis of each specimen lay in a tangential direction. These specimens were solution treated at 930℃ for 1 hr and aged at 595℃ for 8 hrs before the test.

Fig. 6 (a) shows the tensile property at room temperature for each equivalent strain. The equivalent strain was determined by FEM analysis for each specimen position of the forged pieces compressed with ratios of 33% and 67%. The ultimate tensile strength (UTS) and yield strength (YS) show no influence of equivalent strain; however, the reduction of area (RA) is decreased at an equivalent strain of 0.5 or lower. Hence, an equivalent strain of 0.5 or greater must be applied to secure sufficient ductility.

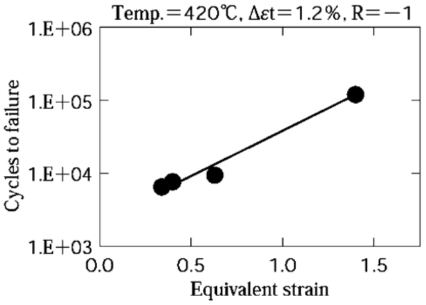
Fig. 6 (b) shows the influence of equivalent strain on the failure life of low cycle fatigue (LCF), an important characteristic for materials used in jet-engine disks. The failure life tends to improve as the equivalent strain increases. Small equivalent strain leads to low ductility. Further, in a microstructure that has continuous grain boundary α as a result of a small equivalent strain in forging, dislocations caused by applied stress tend to accumulate on grain boundary α, facilitating the generation of fatigue cracks along grain boundary α. These are considered to have caused the shortening of the fatigue life.

3.4 Process design based on analysis technology of *β*-processed forging

As described above, to determine a forging process for obtaining a targeted disk shape while



(a) Tensile properties



(b) Low cycle fatigue life

Fig. 6 Influence of forging strain on tensile properties of Ti-6246, β-processed forging

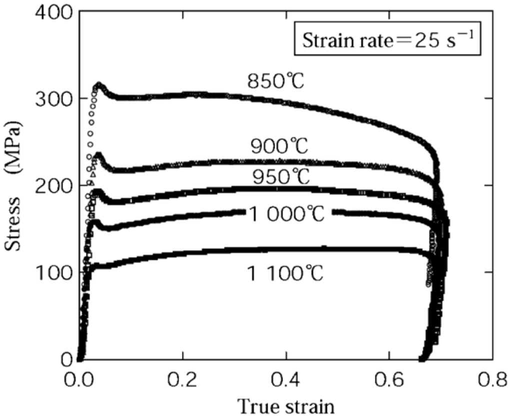


Fig. 7 Stress-strain curves of Ti-6246 as measured

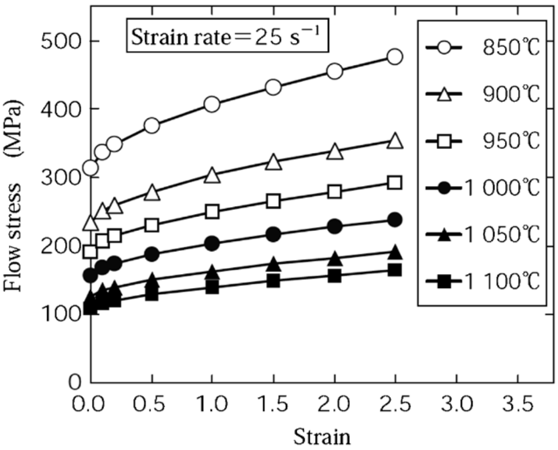


Fig. 8 Isothermal flow stress of Ti-6246

controlling the temperature and strain in appropriate condition ranges, it is indispensable to predict the temperature and strain using deformation-temperature coupled FEM analysis. One of the important factors in performing this FEM analysis with high accuracy is the processing of flow stress data used in the FEM analysis.

The stress-strain curves of Ti-6246 were prepared on the basis of load-stroke measurement during cylinder compression testing. The results are shown in **Fig. 7**, which presents work softening, particularly at low temperatures, as described previously. In reality, however, the specimen temperature increases due to the generation of processing heat. Therefore, these results include the influence of the temperature change. In the deformation-temperature coupled analysis by FEM, the generation of processing heat is calculated separately; hence it requires flow stress values under constant temperature (isothermal) conditions, and the following technique was used to remove the influence of temperature rise due to the generation of processing heat.

First, the relationship between the flow stress σ and strain ε was assumed to be expressed as Equation (1):

$$\sigma = A(T)\times(1.0+F\varepsilon^{n}) \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (1),$$

wherein $A(T)$ is the initial flow stress value (a function of temperature T and strain rate), n is the work hardening index, and F is a coefficient.

In the low strain region, there is little influence from processing heat generation. Therefore, the yield points of the stress-strain curves shown in Fig. 7 were used to establish data for the dependence of flow stress on temperature and strain rate, and thus to determine $A(T)$ of Equation (1). Next, deformation-temperature coupled analysis was conducted such that the stroke-load curves of the compression test coincide with the analysis results. Thus, the work hardening index n and coefficient F were optimized. Equation (1), obtained as above, enables the calculation of the isothermal flow stress in terms of temperature, strain rate and strain, as shown in **Fig. 8**.

An FEM analysis adopting the isothermal flow stress data was conducted to design the process for forging actual disks with a diameter of approximately 700mm. **Fig. 9** shows the analysis results for shape and temperature/equivalent-strain distributions after forging under the conditions determined for β-processed forging, as well as the historic temperature/equivalent-strain during

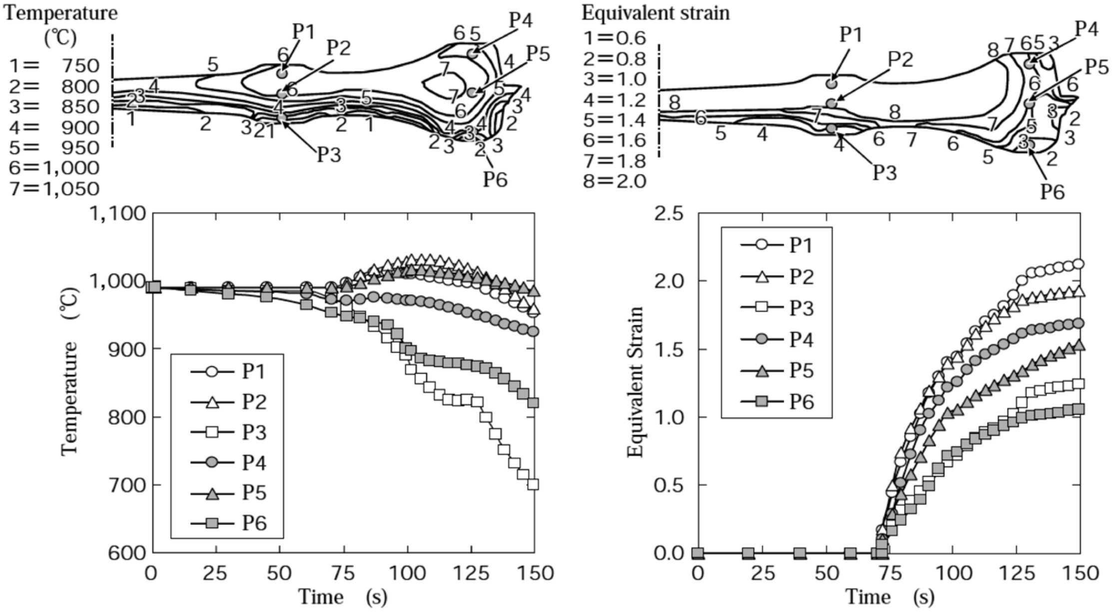


Fig. 9 Calculated results of temperature and strain during disk forging

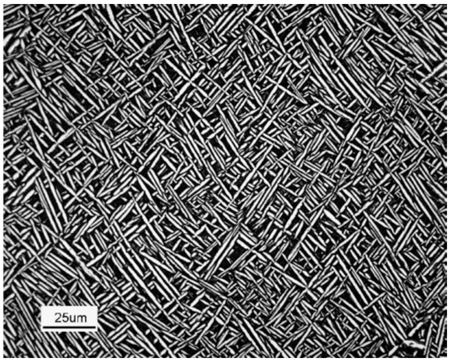


Fig.10 Microstructure of β-processed disk forging

forging at each location in the forgings. At each location, the deformation was completed within a range of appropriate conditions determined from the aspects of microstructures and material properties.

The process design technology, as described above, was adapted for prototype forgings, a typical micrograph of which is shown in **Fig.10**. The microstructure with acicular α, as shown, has achieved a high fracture-toughness value exceeding 50 MPa $m^{1/2}$ at room temperature.

Conclusions

This paper has introduced a forging technology featuring titanium alloy forgings, with a focus on the example of disks forged for aircraft engines. Titanium is a material difficult to process, since it requires the precise control of temperature and strain to create the desired microstructures and material properties. This, on the other hand, means that the material has the potential to make this forging technology stand out from others.

In Japan, a long-waited giant press with a 50 thousand tonne capacity started to operate in 2013 at Japan Aeroforge, Ltd. This press is expected to further increase the production volume of titanium alloy forgings for aircraft in Japan.

To that end, Kobe Steel is striving to establish analysis technologies that enable the highly accurate prediction of not only the shape and temperature, but also microstructures and material properties after forging and to achieve further advances in the forging technology for difficult-to-process materials as typified by titanium.

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