Highly Heat-Resistant Aluminum Alloy "KS2000"

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Rotating/sliding components that operate at elevated temperatures, such as impellers and pistons, require aluminum alloys having a heat resistance higher than that of conventional aluminum alloys. Kobe Steel has optimized the additive elements to finely disperse precipitates that improve hightemperature properties, the homogenization conditions to finely disperse crystallized products and the conditions of plastic deformation to refine grain size. The optimizing of the composition and processing conditions resulted in the development of a new aluminum alloy, "KS2000," having an excellent heat resistance compared with the conventional 2618 alloy.

Introduction

Aluminum alloy has a density of approximately 2.7 g/cm^3, which is about 1/3 that of iron, along with high specific strength (strength/specific gravity), and is easy to process by various methods including casting, forging, rolling and machining. Exploiting these advantages, aluminum alloys are being used in accordance with the properties required for transportation equipment, such as railway vehicles, motor vehicles and ships, as well as for various machinery parts and engine parts. Among these, mechanical members that rotate at high speed or slide at temperatures above the ambient temperature employ aluminum alloys having high temperature properties; such members include impellers used in generators/compressors, vacuum-pump rotors and engine pistons. For example, Al-Cu-Mg-Fe-Ni based 2618 alloy is widely used as an aluminum alloy in high-temperature environments and is one of the typical heat-resistant aluminum alloys applied, for example, to turbocharger impellers of various sizes, ranging from automobiles to vessels.

In recent years, there has been a trend toward improving the fuel efficiency of transportation equipment, which has led to turbochargers having higher compressibility and a higher flow rate. As a result, turbines are required to rotate at speeds higher than those of the conventional products, and intake-side impellers, which produce compressed air, are exposed to higher temperatures and load-pressures, requiring an aluminum alloy with even higher heat resistance.

This paper introduces heat-resistant aluminum alloy, KS2000, which was developed to meet these needs.

1. Features of highly heat resistant aluminum alloy, "KS2000"

The heat resistant aluminum alloy designated as 2618 alloy is a widely-used wrought alloy registered with the Aluminum Association in 1954. This alloy is designated as RR58 in the UK and AU2GN in France and was used for the structural members of the Concorde supersonic airliner. Kobe Steel applied this alloy to a hydraulic-equipment housing in the late 1960s and has applied it to automotive pistons and turbocharger impellers, etc., since the 1980s. The alloy is still being widely used as a stock material for items produced at Kobe Steel's Daian plant.

As described above, Kobe Steel began the development of heat-resistant aluminum alloy around the year 2000 in response to the increasing need for an aluminum alloy with high-temperature resistance; this resulted in the development of KS2000.[1)-4)] Its features are as follows:

1) The optimization of additive elements such as Cu, Ag and Mg has allowed the fine dispersion of Ω-phase precipitates, which improve high temperature properties, enabling the improvement of high temperature strength and creep properties to an extent that exceeds those of 2618 alloy.
2) The refinement of constituents by optimizing homogenization conditions, as well as forging conditions, has led to the discovery of process conditions that improve high-temperature fatigue properties.

2. Creep properties

Turbochargers for marine engines and diesel generators continue to rotate under high loads. As a result, each impeller blade is subjected to a large stress generated by centrifugal force, while the temperature on the intake side increases to a figure between 100 and 200℃, causing a concern about creep deformation. Therefore, creep is a key characteristic of the material used for intake-side impellers.

The composition of the newly developed material, aimed at improving high-temperature strength, has been adjusted on the basis of the concept that the addition of Cu and Mg increases the density of fine Al-Cu based precipitates and the addition of Ag promotes the formation of precipitates having excellent high-temperature properties. **Table 1** shows typical compositions representing the features of 2618 alloy and KS2000. Also, **Fig. 1** shows the transmission electron micrographs of 2618 alloy and KS2000, both after T61 aging. Regarding the formation of precipitates from a supersaturated solid solution of Al-Cu-Mg based alloys, the precipitation process depends on the Cu/Mg ratio (weight ratio) of the alloys.[5] More specifically, the θ-phase precipitates when Cu/Mg > 8, the *S*-phase precipitates when Cu/Mg < 1.5, and the competitive precipitation of three phases, α, θ and *S*, occurs when 1.5 < Cu/Mg < 8. The 2618 alloy has a Cu/Mg ratio of approximately 2, and most precipitates are *S*'-phase. In the micrograph of 2618 alloy in Fig. 1 (a), *S*'-phase is observed extending in the $[1\bar{1}0]$ and $[00\bar{1}]$ directions.

KS2000, on the other hand, has a Cu/Mg ratio of approximately 20, which is in the region where θ'-phase generally precipitates; but KS2000 exhibits different precipitation behavior because of the addition of Ag. As shown in Fig. 1 (b), in addition to the θ'-phase extending in the $[1\bar{1}0]$ and $[00\bar{1}]$ directions, a new precipitation phase extending in the $[1\bar{1}\bar{2}]$ and $[\bar{1}1\bar{2}]$ directions is observed. This precipitation phase is called Ω-phase and is believed to increase the alloy's strength and heat resistance.[6),7)] Regarding the precipitation of Ω-phase, Hono proposed heterogeneous nucleation of Ag-Mg co-clusters on the basis of his analysis using a three-dimensional atom probe (3DAP), etc.[8)] More specifically, θ-phase and Ω-phase are thermodynamically equivalent; however, θ-phase grows incoherently with α-phase in non-specific directions, whereas Ω-phase is an equilibrium phase that homogeneously precipitates coherently with the {111} plane of the α-phase, in which Ag-Mg co-clusters serve as precursors. Thus, Ω-phase is considered to improve the high-temperature properties of the alloy, since it is an equilibrium phase having excellent stability at high temperatures and is coherent with the α-phase, as described above.

Fig. 2 shows the transmission electron micrographs of 2618 alloy and KS2000 after T61 artificial aging and subsequent exposure at 180℃ for 400 h. In the case of 2618 alloy shown in Fig. 2 (a), *S*'-phase is coarsened into a lath-like shape, indicating that the precipitation-strengthening effect of *S*'-phase has been decreased by the heating. On the other hand, in the case of KS2000 shown in Fig. 2 (b), there is no significant change in the size of Ω-phase from the T61 as-aged condition, despite some coarsening of θ'-phase. **Table 2** summarizes the yield strength of 2618 alloy and KS2000 at ambient temperature and after heating at 150℃ for 100h, along with their

Table 1 Typical chemical composition (wt.%)

Alloys	Fe	Cu	Mg	Ni	Ag
2618	1.0	2.5	1.5	1.0	—
KS2000	—	6.5	0.3	—	0.5

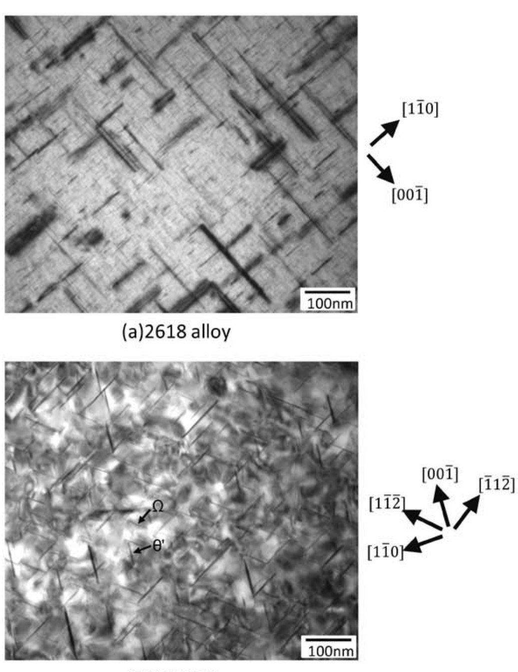

Fig. 1 Transmission electron micrographs after T61 artificial aging

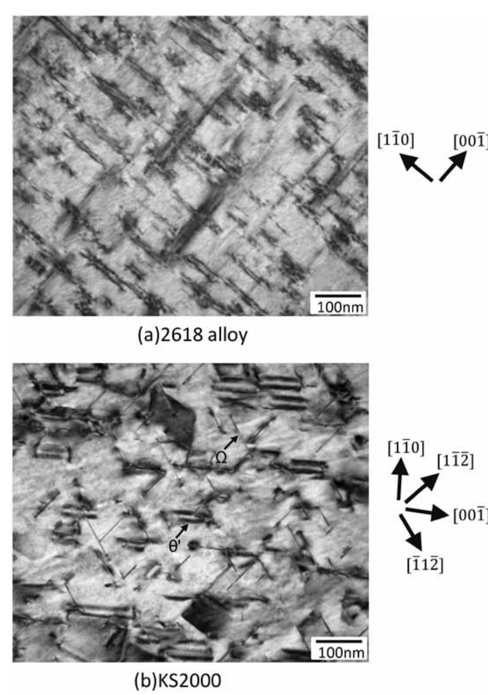

Fig. 2 Transmission electron micrographs after T61 artificial aging followed by exposure at 180℃-400h

Table 2 Properties of yield strength and creep of each alloy

Alloys		2618-T61	KS2000-T61
Yield strength (MPa)	RT	360	430
	150℃, 100h	330	375
Creep rupture time (h)	180℃, 235MPa	165	710

creep properties under the testing conditions of 180℃, 235MPa. As shown in Table 2, the creep-rupture time of KS2000 is longer than that of 2618 alloy. Thus, the *Ω*-phase, having high thermal stability, suppresses the intra-granular slip, enabling KS2000 to exhibit excellent high-temperature tensile properties and creep properties.

3. High-temperature fatigue properties

Turbochargers are used not only in ships and generators, but also in automobiles. Unlike the turbochargers in ships and generators, which continue to rotate under steady-state conditions, automotive turbochargers are subjected to significant variations of rotation in coordination with the engine output set by accelerator operation. Therefore, their impellers are exposed to stress variations and stress amplitudes associated with acceleration and deceleration, thus calling for fatigue strength at high temperatures. Thus, the materials used for rotating bodies are required to have not only creep properties, but also a certain level of high-temperature fatigue properties.

As described in the previous section, KS2000 contains a larger amount of Cu and a decreased amount of transition elements such as Fe and Ni. In addition, the composition with added Ag has improved the creep properties, thanks to the precipitation of the *Ω*-phase. In terms of fatigue strength, however, KS2000 has been found inferior to 2618 alloy at both ambient and high temperatures as long as the alloy is simply forged and heat-treated after casting. The following reasons are considered: i) KS2000 contains Cu in an amount exceeding the maximum solubility limit, resulting in the coarsening of constituents, which provide origins of fatigue fracture; and ii) coarse crystal grains are formed due to the small amount of transition element, which is a factor reducing fatigue strength.

Considering the high temperature applications of KS2000, it is required to achieve fatigue properties that are at least equivalent to those of 2618 alloy, while maintaining the creep properties that have been obtained. To this end, as described in the following section, optimum manufacturing conditions have been devised to improve the high-temperature fatigue properties of KS2000.

3.1 Refinement of constituents

Fig. 3 shows scanning electron micrographs of 2618 alloy and KS2000, in which the latter was subjected to axial fatigue testing before the constituents were refined, and each micrograph was captured around the starting point of the fatigue fracture in axial fatigue tests. In 2618 alloy, the fracture originates in a cleavage crack, an indication of intra-granular fracture, whereas in KS2000, the origin has turned out to be a constituent particle. **Fig. 4** shows the optical micrographs of both fatigue test samples. In KS2000, the constituents are larger than those in 2618 alloy and their distribution is inhomogeneous. In addition, energy dispersive X-ray spectroscopy (EDX) has shown that the constituents observed in KS2000 are Al-Cu based. According to Kuroki et al., refining the eutectic Si/Fe-based compound in an aluminum alloy casting improves the fatigue strength.[9] Against this backdrop, a study was conducted to refine constituents by raising the temperature of homogenization so as to dissolve Al-Cu base constituents into the matrix phase. In the case of Al-Cu based alloys, including KS2000, excessively high soaking temperature results in eutectic melting. Therefore, the soaking temperature has been optimized on the basis of Thermo-Calc, a thermodynamics equilibria calculation software, and the results of a heating test performed on small test pieces. The reduction of constituents has

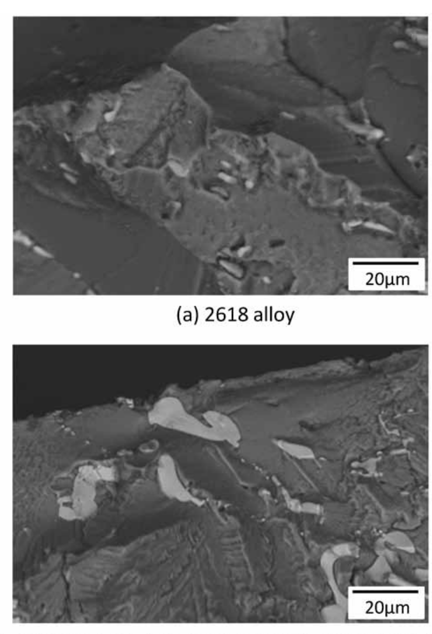

Fig. 3 Scanning electron micrographs around starting point of fatigue fracture of axial fatigue tests

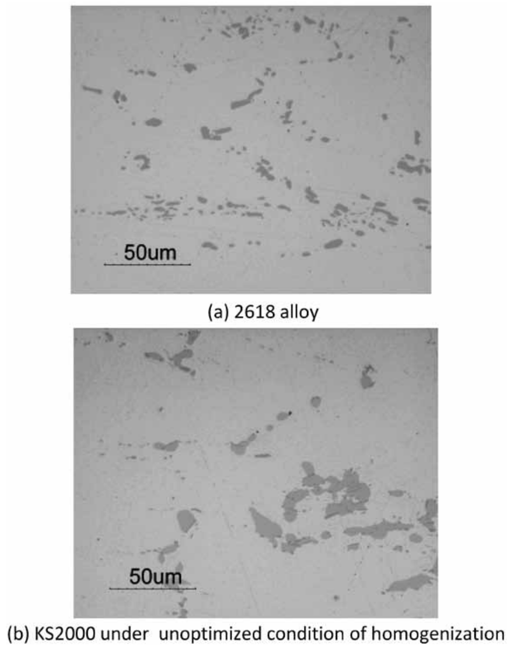

Fig. 4 Optical micrographs of fatigue testing sample

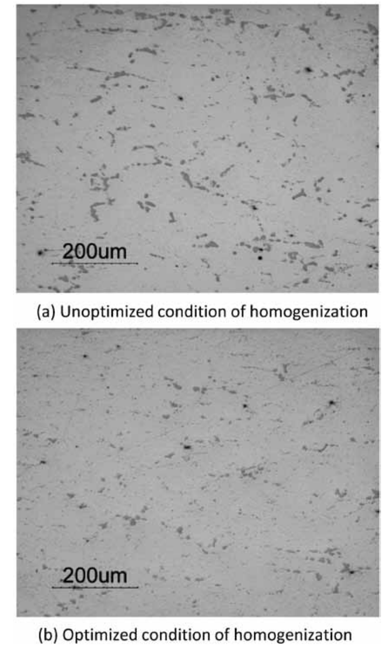

Fig. 6 Optical micrographs of KS2000 forging

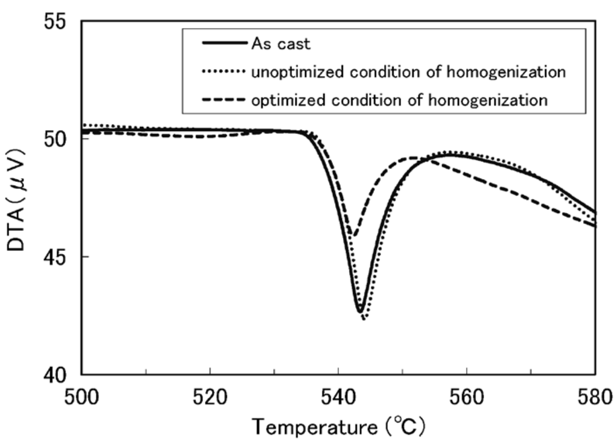

Fig. 5 Differential thermal analysis in each material condition

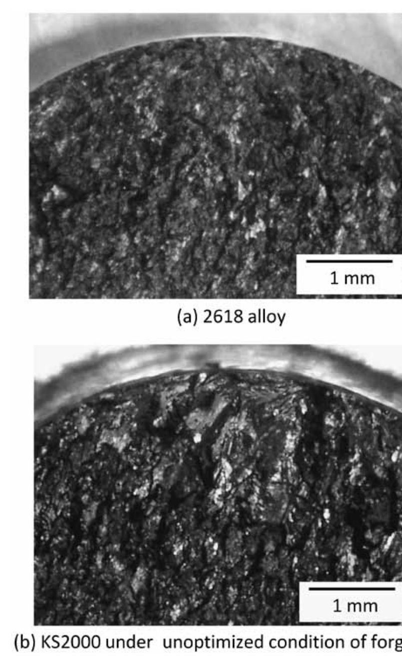

Fig. 7 Fractograph in rotary bending fatigue tests

been evaluated by differential thermal analysis. **Fig. 5** shows the results of differential thermal analysis performed on the as-cast sample, along with the samples from before and after the soaking temperature optimization. The endothermic peak before soaking temperature optimization is not much different from the peak for the as-cast, and the endothermic peak is decreased by the optimization of the soaking temperature. This indicates that a certain portion of Al-Cu based constituents has dissolved into the matrix phase, decreasing the constituents. **Fig. 6** shows the optical micrographs of KS2000 forgings before and after the optimization of the soaking temperature. In comparison with Fig. 6 (a), before the optimization, Fig. 6 (b), after the optimization, shows more disrupted networks of constituents, which are reduced in size. Therefore, it has been clarified that appropriate adjustment of soaking temperature enables the distribution control of Al-Cu based constituents.

3.2 Refinement of crystal grains

Rotary bending fatigue tests were conducted on a 2618 alloy test sample and KS2000 test sample, the latter having refined constituents as described in the previous section. **Fig. 7** shows the fatigue fracture surfaces of these samples. It is shown that both the alloys exhibit cleavage cracking, with KS2000 exhibiting more remarkable cleavage cracking.

Fig. 8 shows the optical micrographs of crystal grains. Some of the crystal grains of KS2000 are larger than 1mm, while the grains of 2618 alloy fall between approximately 100 and 200 μm. Hatanaka et al. studied the relationship between the crystal grain and fatigue strength of Al-2.4Mg alloy and showed that refined crystal grains improve fatigue strength.[10] It is generally believed that, in the high-cycle range of a fatigue test performed with low stress, the propagation of micro-cracks smaller than 1mm is a major factor in the fatigue. Suresh concluded that such micro-cracks are greatly affected by crystal grains, and smaller crystal grains hinder the propagation of micro-cracks and extend the fatigue life.[11]

Thus, a study has been conducted to improve the fatigue strength of KS2000 by crystal grain refinement. Crystal grain refinement is effectively accomplished by adding transition elements to suppress the coarsening of crystal grains, or by increasing the dislocation density through plastic deformation. The addition of transition elements to the present alloy, however, makes the alloy more quench sensitive, making it difficult to achieve the required strength in large products, and increases the number of constituents, which may lead to decreased fatigue strength. Therefore, the study focused on the refinement of crystal grain by optimizing the forging conditions for applying plastic deformation.

The change in grain size during plastic deformation correlates with the dislocation density inside the material, and dislocation density depends on the amount of strain, strain rate and forging temperature. Hence a small hot-compression tester was used to study the relationship between the forging condition and grain size to understand how these factors affect grain size. Fig. 9 shows how the forging temperature and equivalent plastic strain influence grain size after T61 artificial aging. These photographs show that the greater the equivalent plastic strain and the lower the forging temperature,

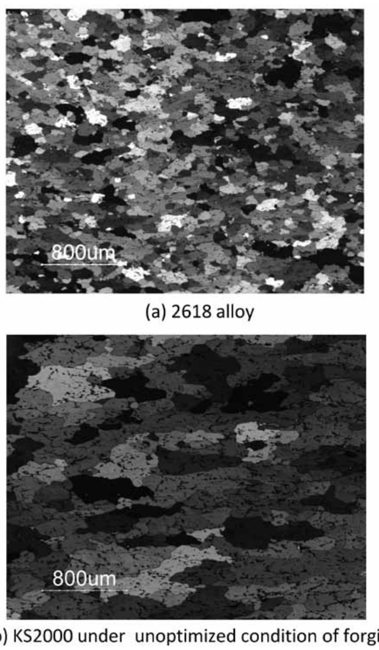

Fig. 8 Optical micrographs of crystal grain

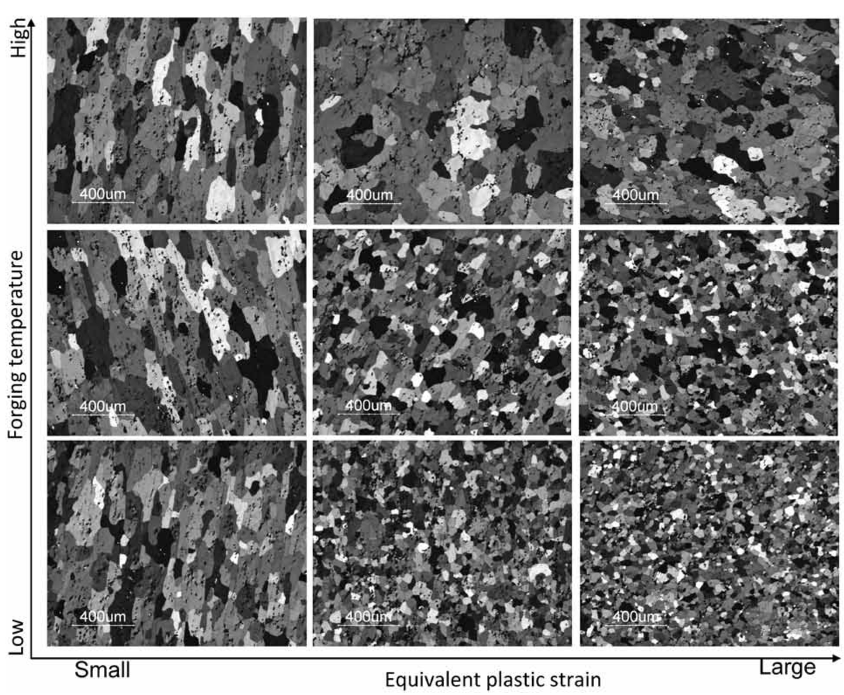

Fig. 9 Influence of crystal grain-size after T61 artificial aging in forging conditions

the finer the grain size becomes. On the basis of the test results shown in Fig. 9, further adjustment has been made in the mass manufacturing process, which has led to the establishment of optimum forging conditions for controlling the grain size of KS2000.

Fig. 10 shows a fatigue fracture surface of KS2000 after the optimization of homogenization and forging conditions. **Fig. 11** shows the scanning electron micrographs of a fracture surface of samples before and after the optimization of forging conditions. The sample after the optimization of forging conditions exhibits a finer grain size, as fine as that of 2618 alloy shown in Fig. 7 (a), along with finer cleavage cracks, compared with the sample before the optimization.

Table 3 summarizes the fatigue strength of 2618 alloy, as well as KS2000 before and after the optimization. As described above, a process that makes the fatigue strength of KS2000 comparable to that of 2618 alloy has been developed by:

i) the refinement of constituents through the optimization of homogenization conditions, and
ii) the refinement of grain size through the optimization of forging conditions.

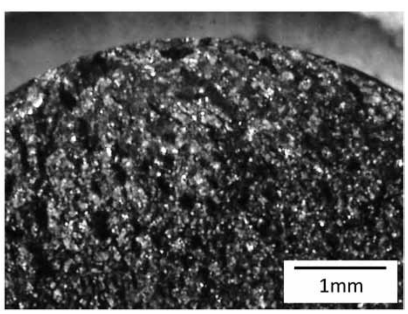

Fig.10 Fractograph in rotary bending fatigue test under optimized condition of forging

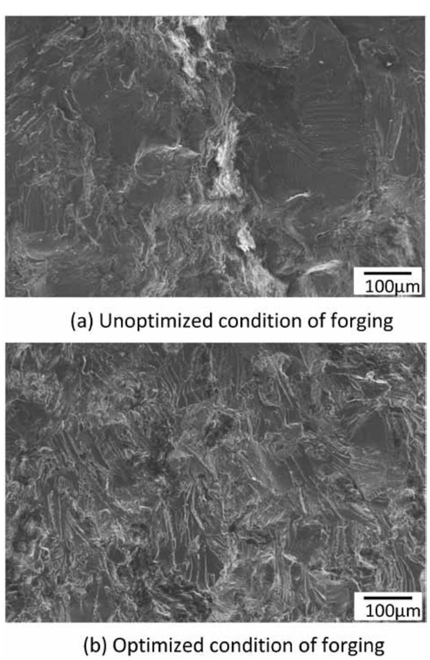

Fig.11 Scanning electron micrographs around starting point of fatigue fracture of rotary bending fatigue tests

Table 3 Fatigue strength of each alloy

Alloys		2618-T61	KS2000-T61	
			Unoptimized condition of forging	Optimized condition of forging
Fatigue strength (MPa)	RT, 10^7cycles	160	150	165
	180℃, 10^7cycles	120	110	120

Conclusions

A process has been established to fully realize the properties of the newly developed KS2000, as a result of the composition adjustment for high-temperature properties and the optimization of homogenization and forging conditions for fatigue strength. The requirement for high-temperature properties is expected to become more stringent for aluminum alloys used in products such as rotating bodies. We will strive to develop materials meeting the customers' needs, approaching them from the aspects of both composition and process.

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