Homogenization of Microstructure and Improvement of Elevated Temperature Tensile Properties in a Ni-Base Superalloy by Rheocasting*

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An investigation is made on the homogenization of microstructures and the improvement of elevated temperature tensile properties in the Ni-base superalloy containing 6.74%Co, 11.15%Cr, 3.12%Mo, 3.25%W, 3.98%Al, 2.74%Ti, 3.93%Nb and Bal.Ni by rheocasting with the rotation of a stirrer at a speed in the range of 20 to 70 rev/s. The results are as follows:

(1) When the superalloy is agitated at 70 s^{-1} from the start of solidification to above the volume fraction of solid of 0.42, the columnar dendrites are broken up and equiaxed grain structures are formed. However, when the rotation of a stirrer immersed in the alloy at a speed of 10 or 70 s^{-1} is interrupted at the fraction of solid of 0.19, equiaxed dendrites will grow from the primary solid particles in the subsequent process of solidification.

(2) When the fraction of solid at the end of stirring is increased from 0.42 to 0.95, the average primary solid particle size is slightly decreased.

(3) The primary solid particle sizes in the alloy agitated from the start of solidification to the fraction of solid of 0.95 at the stirrer speeds of 20, 30, 40, 50, 60, 65 and 70 s^{-1} are 87 ± 21 , 80 ± 16 , 75 ± 18 , 73 ± 15 , 76 ± 14 , 72 ± 13 and $66 \pm 14\text{ }\mu\text{m}$.

(4) The elongation values are 91% for the strain rate of $1.67 \times 10^{-4}\text{ s}^{-1}$ at 1373 K and 70% for the strain rate of $0.83 \times 10^{-4}\text{ s}^{-1}$ at 1323 K in the alloy agitated at 70 s^{-1} from the start of solidification to the fraction of solid of 0.42 and subsequently solidified without stirring.

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I. Introduction

The semi-solid processing technique including the microstructural control by the mechanical stirring applied to the solidifying zone of alloys has attracted special interest with the recent trend of reducing the materials manufacturing cost. This new casting process of homogenizing the microstructures at the whole parts of an ingot only by the fragmentation of dendritic crystals with rotation of a stirrer has been known mainly as the rheocasting process⁽¹⁾⁽²⁾. However, the rotational speed of the stirrer in the previous investigations has been restricted to below 17 s^{-1} (1000 rpm) in order to prevent the entrapment of air into the solidifying alloy⁽³⁾. As the dendritic crystals cannot be completely destroyed by such slow rotations of a stirrer, the primary solid particles observed after solidification will generally show not the spherical morphology but the irregular or rosette-type one⁽³⁾.

The authors have already accomplished the refinement and the homogenization of microstructures in several aluminum and copper alloys⁽⁴⁾⁻⁽¹³⁾ and have also produced some rheocast aluminum and copper alloys with high ductility at elevated temperatures⁽⁵⁾⁻⁽¹⁰⁾ by increasing the stirrer speed up to four times as fast as the maximum speed in the conventional rheocasting processes.

In the present study the refinement and homogenization of microstructures in the René 95 type superalloy named as TMP-3 can be accomplished by the continuous rotation of a stirrer at a speed of 20 to 70 s^{-1} during solidification and the superalloy rheocast at 70 s^{-1} can show high ductility at high temperatures in comparison with the conventionally cast ones.

II. Experimental Procedure

The specimen used for the present work is a Ni-base superalloy TMP-3 designed by National Research Institute for Metals. The chemical composition of the superalloy is shown in Table 1. The outline of an ex-

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Table 1 Chemical composition of Ni-based superalloy TMP-3 (mass%).

Co	Cr	Mo	W	Al	Ti	Nb	Ni
6.74	11.15	3.12	3.25	3.98	2.74	3.93	Bal.

Fig. 1 Experimental apparatus for vacuum rheocasting. 1: Tungsten mesh heater, 2: Reflector, 3: Thermocouple for temperature control, 4: Automatic shutter, 5: Water-cooling outer tube, 6: Cooling water, 7: Video camera, 8: Sight port, 9: Rotor axis, 10: Stirrer, 11: Electrode, 12: Graphite crucible, 13: Alumina crucible, 14: Thermocouple for temperature measurement, 15: Chamber and 16: Crucible support.

perimental apparatus used in this work is shown in Fig. 1. A chamber provided with the panel of a door for permitting insertion of crucibles into the chamber and inspection of the chamber is a vacuum container.

The interior of the chamber is partitioned into the upper cooling and the lower heating room by a shutter, which is made of tungsten and designed to be opened and closed by an air cylinder. Inside the lower heating room is disposed a tungsten mesh heater in which two concentric crucibles are on a support bar so as to be movable up and down automatically. The upper cooling room has a water-cooling outer tube and a graphite stirrer is suspended downwardly into the water-cooling outer tube. The stirrer has a generally square cross-section and is tapered from a thickness of 0.030 m at the upper end to 0.025 m at the lower end, with the four corners cut as illustrated in Fig. 2. This stirrer is so constructed that it may be rotated at the high speed of up to 84 s^{-1} by a motor provided at the upper end. The motor is provided on the rotary shaft with a torque and a rotation detector connected with a digital unit for displaying and recording both the torque of the stirrer and the rotational speed to be detected simultaneously. The temperature measurement is made by a recorder connected with a Pt94%Rh6%–Pt70%Rh30% thermocouple 0.0005 m in diameter, the tip of which is set at the center of the outer bottom surface of the inner crucible as shown in Fig. 1. The outer one of two concentric crucibles is made of

Fig. 2 Transverse sections (mm) of mold and stirrer used for the present work.

graphite. The inner alumina crucible is 0.078 m in outer diameter and tapered from a thickness of 0.060 m in inner diameter at the upper end to 0.055 m at the lower end, and 0.130 m in depth.

The experimental procedure is as follows. First of all, the nickel-base superalloy TMP-3 blocks are placed in the inner crucible. Then the chamber is evacuated with a vacuum pump and the shutter over the furnace is closed to heighten the efficiency of heating. When the degree of vacuum in the chamber attains $1 \times 10^{-3} \text{ Pa}$, the raw material in the crucible is heated to produce a molten superalloy weighing 1.1 kg. After the superalloy in the crucible has been thoroughly melted at 100 K above the equilibrium liquidus temperature of it, the shutter over the furnace is opened and the support bar supporting the crucible by the bottom thereon is raised by an elevating mechanism until the crucible is located inside the water-cooling outer tube. As a result, the stirrer is gradually inserted into the melt in the crucible until the leading end of the stirrer reaches a distance of 0.01 m from the bottom wall of the crucible. At this time, the length of the stirrer immersed in the melt is about 0.1 m. Then, flow of cold water through the water-cooling outer tube is started to effect cooling of the melt at a rate of 1.6 K/s , while the stirrer is kept rotated at a low speed of 18 s^{-1} . The rotational rate of the stirrer is raised in 10 s to a high speed in seven stages of 20, 30, 40, 50, 60, 65 and 70 s^{-1} after the superalloy has substantially reached the temperature for starting solidification in the recorded cooling curve and torque value. In this case, the stirrer speed is increased at a fixed rate so as to prevent the semi-solid alloy from being scattered because of a sharp increase in stirrer speed. The rotational stirring at the fixed speed indicated above is continued until the volume fraction of solid of 0.19, 0.42, 0.68 and 0.95 (see Appendix) after the start of solidification is confirmed by the cooling curve of the recorder and the elapsed time recorded by the digital torque printer. Then the support bar supporting the crucible is lowered by the falling mechanism until the leading end of the stirrer reaches a distance of 0.20 m from the bottom wall of the crucible in order to prevent the stirrer from adhering to the rheocast ingot. As a result, columnar dendrites inherently formed by the superalloy are

Fig. 3 Size (mm) and shape of test piece used for the present work.

finely divided into many primary phases.

Furthermore, optical microscope observations are made on the top, middle and bottom sections cut transversely from the superalloy ingot rheocast and stationary cast without stirring inside the water-cooling outer tube. The size of the primary solid crystals is determined by an automatic image analysis system under the condition of residual error of $\sigma=5\%$. The rheocast microstructures are compared with the stationary cast ones in the superalloy with the same chemical composition.

Tensile test pieces are also machined from the rheocast and stationary cast superalloy ingots as illustrated in Fig. 3. The tensile test is carried out in reducing atmosphere under the condition that the test temperature is 1323 or 1373 K and the strain rate is 0.83×10^{-4} or $1.67 \times 10^{-4} \text{ s}^{-1}$.

The value of torque induced by the viscosity of solidifying superalloy is the difference between the apparent torque during the solidification and the standard torque during rotation of a stirrer in an empty crucible under the same condition.

III. Experimental Results and Discussion

1. Apparent viscous flow during solidification with stirring

The changes in torque during the solidification of the superalloy are summarized in Fig. 4. The temperatures for starting and ending solidification of the superalloy were 1604 and 1520 K. The temperature at the stop of stirring during solidification of the superalloy was 1527 K, which corresponded with the volume fraction of solid of 0.95 (see Appendix).

At the rotation speed of 20 s^{-1} the torque decreased rapidly from $0.31 \text{ N}\cdot\text{m}$ at the start of solidification to $0.06 \text{ N}\cdot\text{m}$ in the lapse of 54 s, and increased gradually with some fluctuations to $0.11 \text{ N}\cdot\text{m}$ when the stirring was ceased at a fraction of solid of 0.95.

At the rotation speed of 40 s^{-1} the torque decreased from $0.13 \text{ N}\cdot\text{m}$ at the start of solidification to $0.10 \text{ N}\cdot\text{m}$ and subsequently increased up to $0.14 \text{ N}\cdot\text{m}$ in the lapse of 72 s, remained to be about $0.11 \text{ N}\cdot\text{m}$ in the lapse of 100 s, and rapidly increased immediately before the stop of stirring.

At the rotation speed of 50 s^{-1} the torque decreased

Fig. 4 Variation in torque during rotation of stirrer at the speeds of 20 to 70 s^{-1} from the start of solidification in Ni-base superalloy TMP-3.

from 0.22 to $0.16 \text{ N}\cdot\text{m}$ and began to increase in the initial stage of solidification, and remained to be about $0.25 \text{ N}\cdot\text{m}$ from the lapse of 60 s to the end of stirring.

At the rotation speed of 60 s^{-1} , the torque increased from $0.15 \text{ N}\cdot\text{m}$ at the beginning of solidification to $0.34 \text{ N}\cdot\text{m}$ in the lapse of 90 s, and subsequently began to decrease gradually to $0.29 \text{ N}\cdot\text{m}$ at the stop of stirring.

At the rotation speed of 65 s^{-1} the torque increased from $0.18 \text{ N}\cdot\text{m}$ at the start of solidification to $0.38 \text{ N}\cdot\text{m}$ in the lapse of 54 s, and subsequently decreased gradually to $0.32 \text{ N}\cdot\text{m}$ at the stop of stirring.

At the rotation speed of 70 s^{-1} the torque remained to be about $0.24 \text{ N}\cdot\text{m}$ from the start of solidification to the lapse of 36 s, and subsequently began to increase steeply to $0.42 \text{ N}\cdot\text{m}$ in the lapse of 66 s, and showed a slightly decreasing tendency in the latter stage of solidification.

It was generally observed that the levels of torque in the superalloy increased with the increase in stirrer speed from 20 to 70 s^{-1} except several fluctuations in the initial stage of solidification. This experimental result showed the same increase in torque with increasing stirrer speed as in the solidification of Cu-7 mass% Si and Cu-8 mass% Al alloys⁽¹⁰⁾.

However, this seemed to be the phenomenon opposite to the earlier work⁽⁶⁾ in which the torque in Al-10 mass% Cu alloy has increased with increasing stirrer speed. The reason for this contradiction might be considered as follows: in the case of Al-10%Cu alloy the refinement and homogenization of primary solid particles were strongly controlled by the stirrer speed during the solidification, so that the torque decreased with the increase in stirrer speed because of liquefying of the light semi-solid alloy with spheroidization of primary solid particles. However, in this study the primary solid particle size could not decrease steeply with increasing stirrer

Fig. 5 Microstructures in the middle section of TMP-3 superalloy ingot which was (a) stationary cast or (b) agitated at the rotation speed of 10 s^{-1} from the start of solidification to the volume fraction of solid of 0.19.

speed from 20 to 70 s^{-1} as later shown in Fig. 9. Then the torque might be increased with the increase in stirrer speed because the stronger shearing force with increased stirrer speed should overcome the weaker liquefying action of the heavy semi-solid superalloy.

2. Rheocast microstructures in Ni-base superalloy

The rheocast microstructures of the superalloy ingots were compared with the stationary cast microstructures of them. An example of the results is shown in Fig. 5.

Figure 5(a) shows the stationary cast microstructure of the superalloy. Columnar dendrites were observed to be arranged in a regular manner with the secondary arm spacing of $26 \pm 2 \mu\text{m}$.

Figure 5(b) shows the microstructure of the superalloy agitated at 10 s^{-1} until the stop of stirring at 1594 K after the start of solidification and naturally solidified. The temperature at the stop of stirring corresponded with the fraction of solid of 0.19 (see Appendix). As the superalloy was agitated at 10 s^{-1} during solidification, the primary solid particles were formed by fragmentation

of columnar dendrites originated in the initial stage of solidification. When the stirring was ceased at a fraction of solid of 0.19 and the superalloy was solidified naturally, the primary solid particles existing at the stop of stirring returned to the formation of dendrite morphology with equiaxed dendrites growing in random directions on the cooling process after the stop of stirring. The equiaxed dendrites had the major axis of $86 \pm 20 \mu\text{m}$ and the minor axis of $20 \pm 7 \mu\text{m}$. Their shapes were rather fat as compared with the secondary arm spacing in the stationary cast one (see Fig. 5(a)).

Generally the almost same microstructures were observed at the whole parts of the rheocast superalloy ingot.

3. Effect of fraction of solid at the stop of stirring on microstructures

Vacuum-melted superalloys were agitated at a stirrer speed of 70 s^{-1} until the stop of stirring at 1594 , 1579 , 1557 and 1527 K after the start of solidification, and solidified naturally. The temperatures at the stop of stirring corresponded with the fraction of solid of 0.19, 0.42, 0.68 and 0.95 (see Appendix). These rheocast microstructures are shown in Fig. 6.

Figure 6(a) shows the microstructure of the superalloy agitated at 70 s^{-1} until the fraction of solid of 0.19. As the stirring was ceased in the initial stage of solidification, the primary solid particles formed by destruction of columnar dendrites originated inherently (see Fig. 5(a)) were observed to return to the formation of dendrite morphology with equiaxed dendrites having random growth directions. The sizes of the equiaxed dendrites were $112 \pm 34 \mu\text{m}$ in major axis and $50 \pm 13 \mu\text{m}$ in minor axis. These values were large as compared with $86 \pm 20 \mu\text{m}$ in the major axis and $20 \pm 7 \mu\text{m}$ in the minor axis of equiaxed dendrite sizes of the superalloy agitated at a slow speed of 10 s^{-1} until the same fraction of solid of 0.19 as shown in Fig. 5(b). As the solute concentration distribution in the remaining liquid between primary crystals would be equalized with the increase in stirrer speed even for such short period of stirring as the initial stage of solidification, it should be easier for the primary crystals to coarsen on the subsequent solidification process.

Figure 6(b) shows the microstructure of the superalloy agitated at 70 s^{-1} until the fraction of solid of 0.42. When the stirring was ceased in the middle stage of solidification, it was observed that such columnar dendrites as shown in Fig. 5(a) were almost destroyed and the majority of them became spheroidal primary solid particles. The size of primary solid particles was $72 \pm 17 \mu\text{m}$.

Figure 6(c) shows the microstructure of the superalloy agitated at 70 s^{-1} until the fraction of solid of 0.68. When the stirring was continued until the fraction of solid of 0.68, the coarsening of primary solid particles would be restricted to some extent by the neighboring particles. The size of primary solid particles was $68 \pm 15 \mu\text{m}$.

Figure 6(d) shows the microstructure of the superalloy agitated at 70 s^{-1} until the fraction of solid of 0.95. Even

Fig. 6 Microstructures in the middle section of TMP-3 superalloy ingot which was agitated at the rotation speed of 70 s^{-1} from the start of solidification to the volume fraction of solid of (a) 0.19, (b) 0.42, (c) 0.68 or (d) 0.95.

if the stirring was continued until the final stage of solidification, the size of primary solid particles was $66 \pm 14 \mu\text{m}$ and was almost the same size of primary solid particles of $68 \pm 15 \mu\text{m}$ for the stop of stirring at the fraction of solid of 0.68. However, it was observed that the spheroidization in the configuration of primary solid particles proceeded clearly with the increase in fraction of

solid at the stop of stirring.

Next, the effect of the stirrer speed and the fraction of solid at the stop of stirring on the primary solid particle size in the rheocast alloys was examined as summarized in Fig. 7.

The primary solid particle sizes of the superalloy agitated at rotation speeds of 50 and 70 s^{-1} until the fraction of solid of 0.42, 0.68 or 0.95 (see Appendix) and then solidified naturally were 77 and $72 \mu\text{m}$, 73 and $68 \mu\text{m}$ or 73 and $66 \mu\text{m}$, respectively. The primary solid particle size of the superalloy rheocast at 50 s^{-1} was somewhat larger than that rheocast at 70 s^{-1} . This experimental fact suggested that the effect of stirring on the microstructure of the superalloy increased with increasing stirrer speed. The primary solid particle size could be scarcely decreased when the stirring was continued until exceeding the fraction of solid of 0.68.

Fig. 7 Relation between the size of primary solid particles and the volume fraction of solid at the end of stirring from the start of solidification in Ni-base superalloy TMP-3.

4. Effect of rotational speed of stirrer on microstructures

The effect of stirrer speed on the microstructure of the rheocast superalloy was examined as represented in Fig. 8.

Fig. 8 Microstructures in the middle section of TMP-3 superalloy ingot which was agitated at the rotation speed of (a) 30 s^{-1} or (b) 50 s^{-1} from the start of solidification to the volume fraction of solid of 0.95.

Figure 8(a) shows the microstructure of superalloy agitated at 30 s^{-1} until the fraction of solid of 0.95. The almost destroyed dendrite morphology was observed with partly the equiaxed dendrites. The primary solid particles had a comparatively large size of $80 \pm 16 \mu\text{m}$.

Figure 8(b) shows the microstructure of superalloy agitated at 50 s^{-1} until the fraction of solid of 0.95. The oval primary particles were seen on the greater part of the microstructure with partly the incompletely destroyed dendrites. The primary particle size was $73 \pm 15 \mu\text{m}$ and was small as compared with that of the superalloy rheocast at 30 s^{-1} as shown in Fig. 8(a).

In the microstructure of the superalloy agitated until the fraction of solid of 0.95 as shown in Fig. 6(d), it was observed that the homogeneous refinement and the spheroidization of primary solid particles were accelerated with increasing stirrer speed as compared with the microstructures in Fig. 8(a) and (b).

Next, the relation between the primary solid particle size and the stirrer speed in the superalloy agitated until the fraction of solid of 0.95 and then solidified naturally is shown in Fig. 9.

Fig. 9 Relation between the size of primary solid particles and the rotation speed of stirrer in Ni-base superalloy TMP-3.

The primary solid particle sizes of the superalloy rheocast at $20, 30, 40, 50, 60, 65$ and 70 s^{-1} were $87 \pm 21, 80 \pm 16, 75 \pm 18, 73 \pm 15, 76 \pm 14, 72 \pm 13$ and $66 \pm 14 \mu\text{m}$, respectively. Thus the primary solid particle size showed a tendency of gradual decrease with the increase in stirrer speed. It was well-known that the size of primary solid particles is generally controlled by both the cooling rate and the stirrer speed during solidification⁽⁴⁾. In the present experiment the primary particle size should be strongly controlled by the cooling rate rather than the stirrer speed when exceeding 20 s^{-1} .

5. Solute redistribution of rheocast Ni-base superalloy

An investigation was made on the redistribution of solutes in the rheocast and the stationary cast superalloy. An example of the results is represented in Fig. 10.

Figure 10(a) and (b) show the secondary electron image and the redistribution of main eight elements at the same position in the middle part of the superalloy ingots agitated at 70 s^{-1} until the fraction of solid of 0.68 after the start of solidification and stationary cast inside the water-cooling outer tube. In both the rheocast and the stationary cast microstructures $\text{Mo(W)} + \text{Ni}_3(\text{Al, Ti, Nb})$ eutectics were observed with scattered granular $\text{Ni}_3(\text{Ti, Nb})$. When the mechanical stirring was applied to the solidification of the superalloy, the enrichment of solutes into the matrix of primary crystals was promoted by the mixing diffusion of remaining liquid with violent fluid flow of the semi-solid superalloy. It was thus observed that $\text{Mo(W)} + \text{Ni}_3(\text{Al, Ti, Nb})$ eutectics accumulated with refinement and spheroidization (compare Fig. 10(a) with Fig. 10(b)). On the other hand the $\text{Ni}_3(\text{Ti, Nb})$ particulates were multiplied in the rheocast superalloy (see white arrows in Fig. 10).

6. Mechanical properties in rheocast Ni-base superalloy

An example of elevated temperature tensile test data on the rheocast and stationary cast superalloy test pieces (see Fig. 3) in the reducing atmosphere is represented in Table 2.

Fig. 10 Secondary electron images and distribution of main eight elements in TMP-3 superalloy ingot which was (a) agitated at the rotation speed of 70 s^{-1} from the start of solidification to the volume fraction of solid of 0.68 and (b) stationary cast. Arrow marks show $\text{Ni}_3(\text{Ti, Nb})$ particles.

The elongation of a superalloy agitated at 70 s^{-1} from the start of solidification to the fraction of solid of 0.42 and solidified naturally showed a very large value of 91% as compared with the value of 11% in the stationary cast one for a strain rate of $1.67 \times 10^{-4} \text{ s}^{-1}$ at 1373 K. It also represented a value of 70% for a strain rate of $0.83 \times 10^{-4} \text{ s}^{-1}$ at 1323 K. It was considered that the origination of high ductility in the rheocast superalloy was mainly due to the formation of equiaxed grain structure and the removal of microporosities by the destruction of dendrite morphology with the stirring.

IV. Conclusion

An investigation was made on the homogenization of microstructures and the improvement of ductility only by the rotation of a stirrer at a speed of 20 to 70 s^{-1} applied to the solidification of René 95 type Ni-base superalloy containing 6.74%Co, 11.15%Cr, 3.12%Mo, 3.25%W, 3.98%Al, 2.74%Ti, 3.93%Nb and Bal.Ni. The results are summarized as follows.

(1) Generally the torque induced by the viscosity of the superalloy remains almost unchanged until the final stage of solidification except some fluctuations in the initial stage of it. The torque level increases with increasing stirrer speed.

(2) When the rotational stirring of the superalloy at a speed of 70 s^{-1} is continued until exceeding the fraction of solid of 0.42 after the start of solidification and then the superalloy is naturally solidified, the equiaxed grain structure is formed by the fragmentation of columnar dendrites. However, the equiaxed dendrite morphology is formed in the superalloy when the rotation of a stirrer at speeds of 10 and 70 s^{-1} is ceased at a fraction of solid of 0.19. Even if the fraction of solid at the stop of stirring is protracted from 0.68 to 0.95, the primary solid particle size can be scarcely decreased. The primary solid particles of the superalloy rheocast at 70 s^{-1} become refined as compared with those rheocast at 50 s^{-1} .

(3) The primary solid particle sizes of the superalloy agitated until the fraction of solid of 0.95 at the stirrer speeds of 20, 30, 40, 50, 60, 65 and 70 s^{-1} are 87 ± 21 , 80 ± 16 , 75 ± 18 , 73 ± 15 , 76 ± 14 , 72 ± 13 and $66 \pm 14 \mu\text{m}$, respectively.

(4) It is observed that $\text{Mo(W)} + \text{Ni}_3(\text{Al, Ti, Nb})$ eutectics are accumulated with refinement and spheroidization and $\text{Ni}_3(\text{Ti, Nb})$ particulates are multiplied in the microstructure of the superalloy agitated at 70 s^{-1} until the fraction of solid of 0.68 as compared with those in the stationary cast one.

(5) The value of elongation in the superalloy agitated from the start of solidification to the fraction of solid of 0.42 and then solidified naturally is 91% for a strain rate of $1.67 \times 10^{-4} \text{ s}^{-1}$ at 1373 K. Also it is 70% for a strain rate of $0.83 \times 10^{-4} \text{ s}^{-1}$ at 1323 K. These values show high ductility of the rheocast superalloy as compared with those of the stationary cast superalloy.

Table 2 Elevated temperature tensile test data of the Ni-based superalloy TMP-3 ingots which were stationary cast and agitated at the rotation speed of 70 s^{-1} from the start of solidification to the fraction of solid of 0.42.

Casting condition	Testing condition	Temperature (K)	1373	1323
	Strain rate (10^{-4} s^{-1})		1.67	0.83
Stationary cast	Elongation (%)		11	
	Rupture Strength (MPa)		137	
Rheocast at 70 s^{-1}	Elongation (%)		91	70
	Rupture Strength (MPa)		110	74

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Appendix

How to determine the volume fraction of solid during the solidification with rotational stirring

The solute concentration in liquid, C_L , within a small volume element of half the secondary dendrite arm spacing during conventional solidification is expressed by applying the solidification to the equilibrium phase diagram⁽¹⁴⁾,

$$C_L = C_0 [1 - (1 - 2\alpha k_0) f_s]^{(k_0 - 1)/(1 - 2\alpha k_0)} \quad (1)$$

where C_0 is the initial solute concentration in liquid, k_0 is the equilibrium distribution coefficient, and f_s is the fraction of solid within the volume element. The solidification parameter, α , is expressed as follows:

$$\alpha = D_s \theta_f / l^2 \quad \text{for } 0 < \alpha \leq 0.5 \quad (2)$$

where D_s is the diffusivity of solute in solid, θ_f is the local solidification time and l is half the secondary dendrite arm spacing.

Substituting eq. (1) into the equation for conservation of solute in the volume element⁽⁴⁾⁽¹⁵⁾, the local average solute concentration in solid within the volume element is expressed by the following equation⁽⁴⁾:

$$\bar{C}_s = C_0 [1 - (1 - f_s) \times \{1 - (1 - 2\alpha k_0) f_s\}^{(k_0 - 1)/(1 - 2\alpha k_0)}] / f_s. \quad (3)$$

However, the primary solid particles are formed and suspended in the remaining liquid by the fragmentation of dendritic crystals caused by rotational stirring. When the remaining liquid is perfectly mixed by the violent stirring in the present investigation, i.e. $\alpha = 0.5$, the solute concentration in liquid and the average solute concentration in solid within the volume element is rewritten as

follows⁽⁴⁾:

$$C_L = C_0 / \{1 - (1 - k_0) f_s\} \quad (4)$$

$$\bar{C}_s = C_0 [1 - (1 - f_s) / \{1 - (1 - k_0) f_s\}] / f_s. \quad (5)$$

Assuming that the solute concentration in liquid, C_L , eq. (4) increases along the liquidus line of the equilibrium phase diagram with the advance of solidification, the average solute concentration in solid, $\bar{C}_s$, of eq. (5) also should increase consistently with the solidus line. On the basis of this assumption the volume fraction of solid is represented by using eq. (4) and the equilibrium phase diagram as follows:

$$f_s = (T_M - T_s)(T_L - T) / (T_L - T_s)(T_M - T) \quad (6)$$

where T_M is the melting point of the base metal, T_L is the liquidus temperature of the superalloy, T_s is the solidus temperature of the superalloy and T is a given temperature in the freezing range of the superalloy.