A Technology for Manufacturing Magnesium Alloy Components with Excellent Heat Resistance

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Magnesium alloy forgings have been attracting attention for use in next-generation components with light weight and high heat resistance. A two-step process consisting of casting small diameter rods and forging them offers a viable solution for reducing the cost of forged Mg alloy products. To establish the process, we have developed technologies for continuously casting small diameter rods and for forging Mg alloys with low deformability.

Introduction

As a measure against global warming, various industries are promoting the reduction of the weight of transportation equipment to improve the fuel economy. In such an effort, Kobe Steel is carrying out the development of heat-resistant wrought Mg alloys that are applicable even for engine parts, and the development of their manufacturing technologies.

In general, Mg alloys are light in weight, but their melting and casting require a means to prevent the combustion of the molten metal. In addition, the alloys, with their close packed hexagonal crystal structures, are more difficult to deform plastically, compared with Al alloys having cubic crystal structures. Because of this, the conventional production process (Casting of large-diameter bar → Extrusion → Forging) requires many forming steps, which increases the production cost. In order to expand the applications of Mg alloys, their production cost must be decreased.

With this background, we have developed a new technology for producing forging stocks with fine crystal grains that are effective in improving plastic formability, by continuous casting with excellent productivity (i.e., Casting of small-diameter bar → Forging).

This paper introduces the forging characteristics of the cast alloy and the technology for continuously casting the small-diameter bars.

1. The characteristics of Mg alloys having long-period stacking ordered structure

Lately, a Mg alloy with an adequate addition of rare earth elements and Zn has been discovered to have an atomic arrangement called the long-period stacking ordered structure and has become the subject of studies[1]. This long-period stacking ordered Mg alloy consists of two phases, one being a phase with a long period stacking ordered structure that accompanies the concentration modulation precipitated by heat treatment at an elevated temperature, and the other being the α-Mg phase. The phase with the long period stacking ordered structure is thermally stable and exhibits excellent mechanical properties as a result of kink deformation caused by plastic forming. Kobe Steel participated in the "Collaboration For Regional Entities for the Advancement of Technological Excellence (Basic Technology Research and Development of Next-generation Heat-resistant Magnesium Alloys)", led by the Japan Science and Technology Agency (JST) from 2006 to 2011, and aims at making a long-period stacking ordered Mg alloy, Mg-2Gd-1Zn [at%] (Mg-11.5Gd-2.4Zn [wt%]), into a product[2].

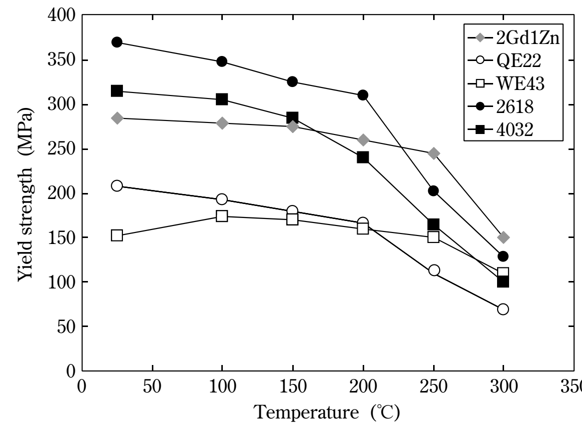

Fig. 1 Yield strengths of various Mg and Al alloys

Fig. 1 shows the data comparing the proof strengths of the conventional heat-resistant Mg alloys, QE22 and WE54, and heat-resistant aluminum alloys, 2618 and 4032, with the newly developed alloy. The newly developed alloy has greater strength than those of the conventional heat-resistant Mg alloys in the range from the ambient temperature to 300℃ and, above 250℃, becomes superior to the heat-resistant Al alloys, whose strength starts to decrease at that temperature. The newly developed alloy is expected to be used for parts that require heat resistance and light weight.

2. The effect of grain size on the formability and strength of the newly developed alloy

The newly developed alloy, Mg-2Gd-1Zn-0.2Zr [at%], was melted and cast to study the effect of grain size, an influential factor in formability. Forging stocks with different grain sizes were prepared by changing the cooling rate and addition of Zr, a grain refining agent. The forging stocks were heated at 520℃ for 2h, quenched in 80℃ water, and subsequently held at 400℃ for 1h (a process hereinafter referred to as "pre-forging heat treatment"). The materials were used to study the effect of forging conditions on formability and strength.

2.1 The effects of the cooling rate and grain refining agent on the grain size

Forging stocks of different grain sizes were prepared at four levels; i.e., two levels of cooling rate (sand mold and copper mold) and two levels (the addition and non-addition) of a grain refining agent (hereinafter referred to as "Zr"). The sand mold and copper mold each had an inner diameter of 65mm and a height of 200mm. **Fig. 2** shows the cooling curves during casting using the sand mold and copper mold. A sheathed thermocouple with a diameter of ϕ1mm was used for the temperature measurement and the cooling rate was defined by the solidification rate of the liquid phase. The cooling rates were 0.017℃/s for the sand mold and 0.34℃/s for the copper mold. **Fig. 3** shows how the cooling rate and the addition / non-addition of Zr affects the grain size. **Fig. 4** shows the microstructures (grain size) of the materials cast at the different cooling rates with/without Zr. As the effect of the increased cooling rate, the grain size decreased from 2,800μm to 840μm for the material without Zr, and from 130μm to 57μm for the material with Zr added. The size of the coarse primary crystals (Mg3Gd phase), observed at the triple points of the grain boundaries, was largely affected by the cooling rate and decreased from approximately 25μm to approximately 7μm with the increase of the cooling rate from 0.017℃/s to 0.34℃/s.

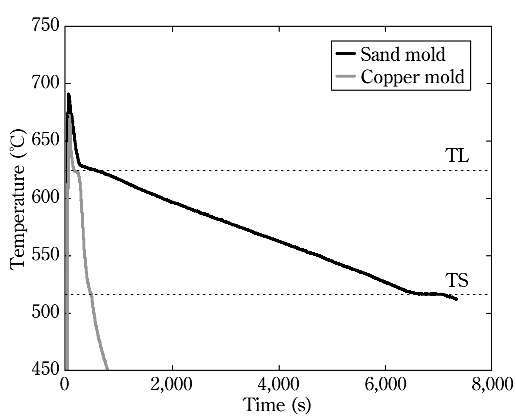

Fig. 2 Cooling curves of sand mold and copper mold

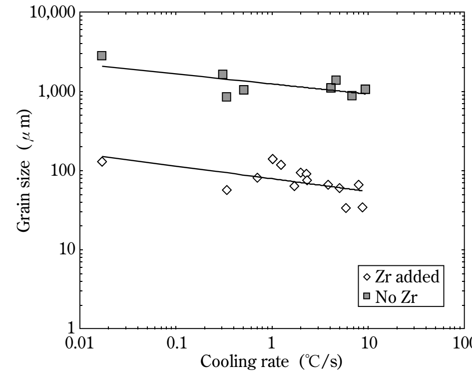

Fig. 3 Effect of cooling rate and Zr on grain size

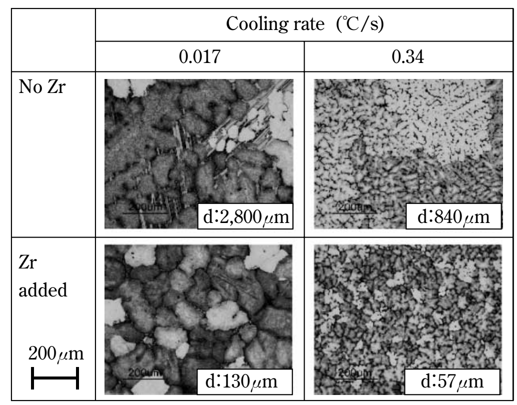

Fig. 4 Microstructures for each cooling rate and Zr addition (as-cast)

2.2 The effect of the cooling rate and grain refining agent on formability

Forging tests were conducted on solid cylindrical samples having a diameter of ϕ60mm. Each sample was upset-forged by a hydraulic press in its axial direction with three levels of reduction ratios, 50%, 65%, and 80%, at a forging temperature of 380℃. The formability was evaluated by the appearance of each sample after the forging on three levels. **Table 1** summarizes the results of the formability evaluation, in which "×" designates the fact that at least one crack was observed on the top/bottom surface(s); "△", that at least one crack was observed on the lateral face; and "○", that no crack was observed. The formability was found to be improved by increasing the cooling rate from 0.017℃/s to 0.34℃/s. The addition of Zr also turned out to improve the formability.

Microscopic observation was performed to clarify the effects of the cooling rate and Zr addition on the microstructure. **Fig. 5** shows the microstructures of the samples after the pre-forging heat treatment. Although the primary crystals at the grain boundaries have been dissolved into the solid solution by the pre-forging heat treatment, they have been refined by the increased cooling rate; the same phenomenon was observed in the as-cast material. On the basis of the fact that the fracture surface of the heat-treated material after forging exhibits grain boundary cracks (**Fig. 6**), the primary crystals remaining on the grain boundaries are considered to be the factor influencing formability. In other words, the refinement of the grain size and primary crystals on the grain boundaries, the refinement caused by the increased cooling rate, is considered to prevent the cracks from originating at the primary crystals in the pre-forge heat treated sample, leading to improved formability. It is also considered that, even though the effect of the Zr addition on the size of the primary crystals on the grain boundaries is smaller than that of the cooling rate, its grain refining effect has increased the ductility, further improving the formability.

Table 1 Influence of cooling rate and Zr on formability

Cooling rate (℃/s)	Grain refiner	Reduction ratio 50%	Reduction ratio 65%	Reduction ratio 80%
0.017	No Zr	Good	Poor	Poor
	Zr added	Excellent	Excellent	Poor
0 34	No Zr	Excellent	Poor	Poor
	Zr added	Excellent	Excellent	Good

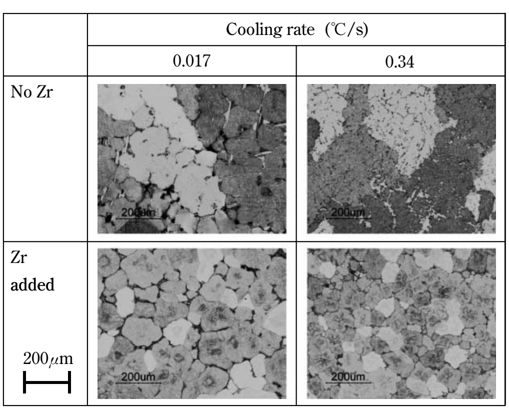

Fig. 5 Microstructures for each cooling rate and Zr addition (heat treated)

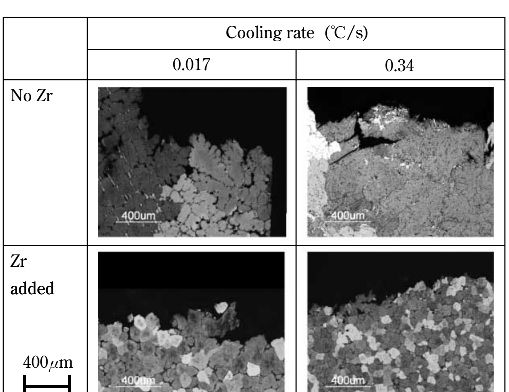

Fig. 6 Fracture surfaces for each cooling rate and Zr addition (heat treated)

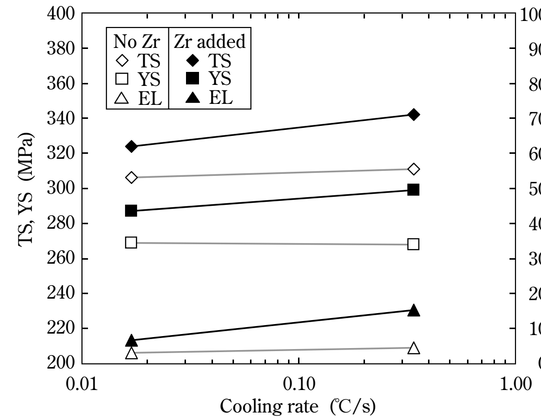

Fig. 7 Effect of cooling rate and Zr on mechanical property (forged)

2.3 The effect of the cooling rate and grain refining agent on strength

Fig. 7 show the results of tensile tests conducted on the samples, with and without Zr, solidified at different cooling rates and forged at a reduction ratio of 80%. An increased cooling rate caused the samples without Zr to exhibit a slight increase in tensile strength and elongation, while it caused the samples with Zr to significantly improve in proof strength, as well as in tensile strength and elongation. For example, in the case of the material with Zr, an increase in the cooling rate from 0.017℃/s to 0.34℃/s caused the proof strength to increase slightly from 287MPa to 299MPa, while causing the elongation to increase significantly from 6.6% to 15.4%. This effect exerted on the elongation by the cooling rate and Zr addition agrees with their effect on formability as described in Section 2.2.

3. The effect of the forging condition on the formability and strength of the newly developed alloy

Because most Mg alloys have close-packed hexagonal crystal structures with only one sliding plane, (0001), at ambient temperature, they are less formable than aluminum alloys and copper alloys having cubic crystal structures[3].

Hence, a study was conducted on the effect of the forging condition on the formability and strength of the newly developed alloy. A billet of the newly developed alloy was prepared by copper mold casting. The billet was heated at 520℃ for 2h, quenched in water at 80℃ and subsequently heat treated at 400℃ for 1h before forging.

3.1 The effect of the pressing speed on formability and strength

In order to confirm the effect of the pressing speed, forging tests were conducted using a mechanical press and hydraulic press at a forging temperature of 350℃ for three levels of reduction ratio, 30%, 50% and 80%. The pressing speed was 250mm/s for the mechanical pressing and 5mm/s for the hydraulic pressing. **Table 2** summarizes the result of the formability evaluation performed in the same manner as described in Section 2.2. With a pressing speed of 250mm/s, cracking occurred at a reduction ratio as small as 30%, while, at a pressing speed of 5mm/s, the forging continued without cracking, up to a reduction ratio as high as 50%. **Fig. 8** shows the results of the tensile test conducted on the samples pressed at different speeds with a reduction ratio of 30%. It should be noted that the elongation value of the sample pressed at 250mm/s was excluded because the sample failed outside the gauge length. The sample pressed at 250mm/s has a strength lower than that of the sample pressed at 5mm/s.

Table 2 Effect of press speed on formability

	Reduction ratio		
Press speed (mm/s)	30%	50%	80%
250	Good	Poor	–
5	Excellent	Excellent	Poor

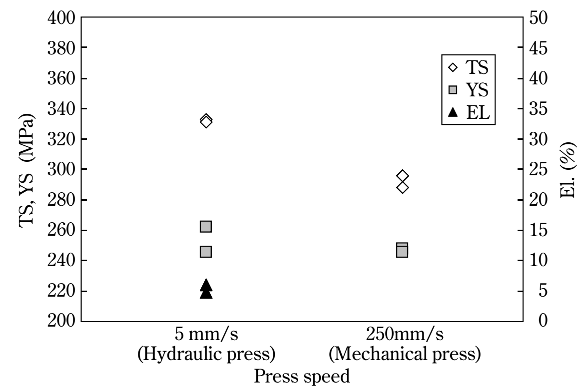

Fig. 8 Effect of press speed on mechanical property

3.2 The effect of the forging temperature on formability and strength

Fig. 9 shows the photographs of samples hydraulically pressed at 300℃, 350℃ and 400℃ under a constant reduction ratio of 80%. Cracking occurred throughout the surface of the sample forged at 300℃, while the sample forged at 400℃ exhibited cracking on only its lateral face, indicating improved formability with increasing forging temperature. **Fig.10** shows the mechanical properties of the samples hydraulically forged at 350℃ and 400℃ with a reduction ratio of 80%. The effect of the forging temperature on the elongation is small, and the lower the forging temperature, the higher the tensile strength and proof strength. The proof strength of the sample forged at 400℃ is approximately 240MPa, while that of the sample forged at 350℃ increases to approximately 290MPa.

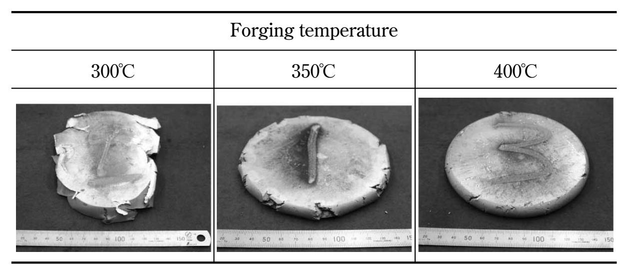

Fig. 9 Effect of forging temperature on formability

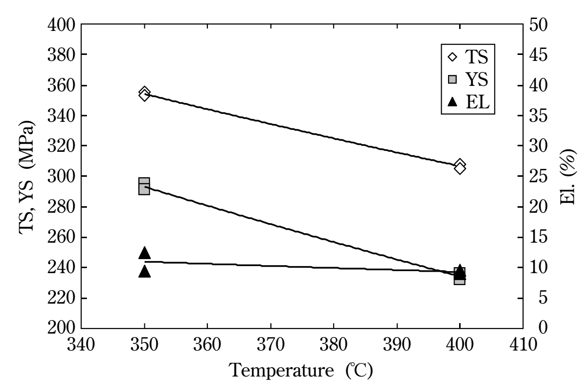

Fig.10 Effect of forging temperature on mechanical properties

3.3 The effect of the reduction ratio on formability and strength

Fig.11 shows the samples hydraulically pressed at a constant forging temperature of 350℃ with varying reduction ratio of 30%, 50% and 80%. The sample was forgeable without cracking, up to the reduction ratio of 50%, however, it exhibited cracking at the reduction ratio of 80%. **Fig.12** shows the results of the tensile tests conducted on the

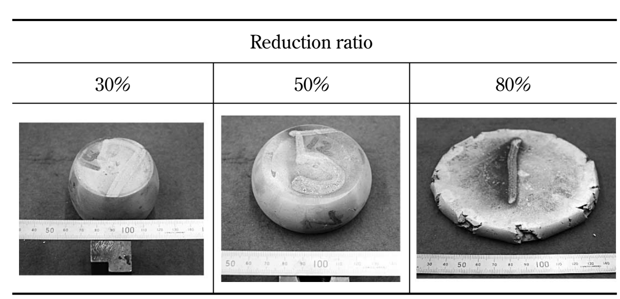

Fig.11 Effect of reduction ratio on formability

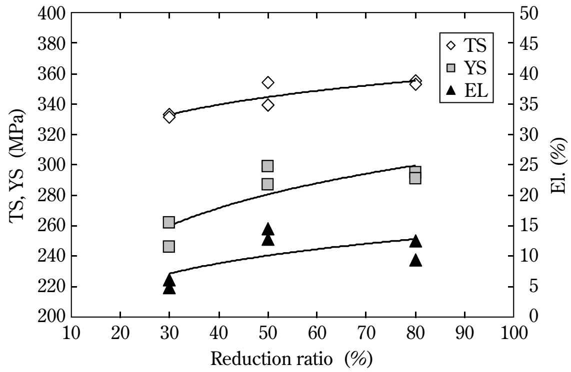

Fig.12 Effect of reduction ratio on mechanical properties

samples forged at different reduction ratios. The reduction ratio tends to have a proportional relationship with the mechanical properties, with the proof strength being approximately 260MPa for the reduction ratio of 30% and increasing up to approximately 290MPa for the reduction ratios of 50% and 80%.

4. Continuous casting technology

Continuous casting is roughly classified into the vertical type and the horizontal type. The vertical type is a method in which the casting is done in the direction of gravity. As a result, this method is less likely to cause macro segregation, yields superior internal quality, and can be used to cast billets with large diameters. On the other hand, the horizontal type allows cutting of the billet during casting, enabling fully continuous operation, improving the yield and productivity. Above all, this method is less costly because it requires less expensive equipment without the need for a pit. The horizontal type was adapted to develop the technology for producing small forged parts because, in terms of cost, this method is more advantageous for the mass production of billets with small diameters. **Fig.13** schematically shows the horizontal type continuous casting machine used for the prototype production.

The following compares the continuous casting technology for the newly developed Mg alloy and the continuous casting technology for Al alloys that

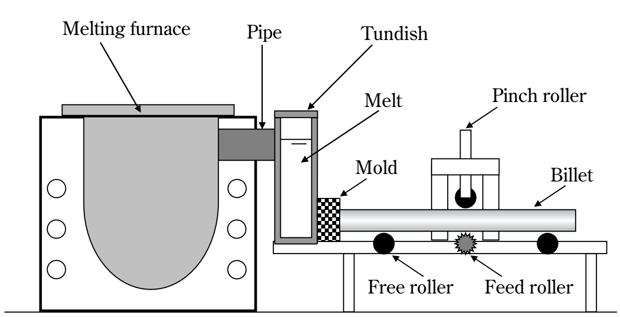

Fig.13 Horizontal continuous casting machine

has been developed and used for production by Kobe Steel.

4.1 Melting yield

Unlike Al alloys, molten Mg alloys are extremely reactive and easily react with oxygen in the air and burn. In order to prevent the metal loss caused by the burning and by the carrying of the metal by covering flux, the molten metal is protected by inert gas from the holding furnace to the tundish. Ensuring the airtightness of the furnace and tundish, as well as ensuring an adequate inert gas replacement, has achieved a melting yield no lower than 95%.

4.2 The casting speed and surface quality

The casting speed directly affects productivity, and the higher the speed, the better. The process of continuous casting, however, requires a balance between the casting speed and the solidification rate of the molten metal cooled by the mold, which limits the casting speed. A casting speed that is low enough in comparison with the solidification rate enables casting. However, an excessive cooling capacity of the mold increases the surface rippling of the billet; this problem is intrinsic to horizontal type continuous casting, which increases the stock removal by peeling.

Table 3 compares the physical properties of Mg and Al. Magnesium has a specific heat greater than that of Al and also has a density that is far smaller than that of Al, which makes the volumetric specific heat of Mg somewhat smaller. In order to ensure a reasonable casting speed and smooth cast surface, the mold must be designed to have a cooling capacity that matches the properties of Mg alloy and must be built with a carefully selected material. **Fig.14** shows

Table 3 Physical properties of Mg and Al

Material	Density (kg/m^3)	Specific heat (J/kg/K)	Volumetric specific heat ($J/m^3/K$)	Latent heat (kJ/kg)
Mg	1,738	1,050	$1,825\times10^3$	368
Al	2,700	920	$2,484\times10^3$	385

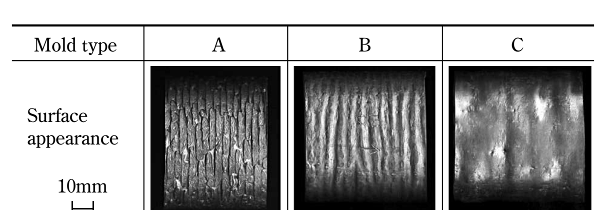

Fig.14 Influence of mold material on billet surface appearance

examples of the surface appearance of billets cast in three types of molds made of different materials. Mold A, which has a higher cooling capacity, results in a deeply rippled surface, while mold C, having a lower cooling capacity, results in a smoother surface.

4.3 The formability of the continuously cast billets

In order to confirm the formability of the continuously cast material, the newly developed alloy was cast into billets with diameters of ϕ65mm and ϕ168mm. The billets were pre-forging heat treated as described previously and forged at 380℃ with three reduction ratio levels, 50%, 65%, and 80%. A hydraulic press was used for the forging. **Table 4** summarizes the results of the formability evaluation conducted according to the method previously described. Compared with the larger diameter billet, ϕ168mm, the smaller diameter billet, ϕ65mm, has a better formability almost equal to that of the material cast in the copper mold with the addition of Zr, the material that exhibited the highest formability, as described in Section 2.2. **Fig.15** shows the microstructures of the cast billets having diameters of ϕ65mm and ϕ168mm. The grain size is rather small, as small as approximately 50μm, regardless of the billet diameter; however, the size of the primary crystals on the grain boundaries has been decreased from 11μm to 6μm by reducing the diameter from ϕ168mm to ϕ65mm. This is considered to have caused the improvement in formability by preventing cracks originating from the remaining primary crystal as an effect of the pre-forging heat treatment described in Section 2.2.

Table 4 Effect of each continuous casting diameter on formability

Casting diameter	Reduction ratio		
	50%	65%	80%
ϕ65mm	Excellent	Excellent	Good
ϕ168mm	Excellent	Good	Poor

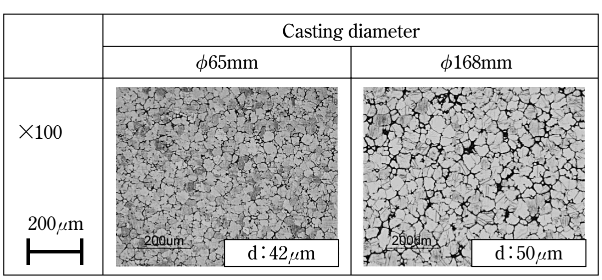

Fig.15 Microstructure for each continuous casting diameter (as-cast)

Conclusions

This paper describes a heat-resistant Mg alloy newly developed for transportation equipment. In particular, attention was focused on the alloy's characteristics, its forging technology, the continuous casting of small diameter billets for low cost production, and the formability of the billets. Kobe Steel recognizes the newly developed Mg alloy as a future weight reduction material ranking next to aluminum alloys and strives to resolve issues, including cost, to satisfy the users' needs and to expand the scope of its application.

References

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