

Stir-casting Process and Mechanical Properties of Forged Mg-Zn-Y Alloys for Piston

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ABSTRACT

Research has been conducted on a high-strength, heat-resistant extruded and forged magnesium alloy able to be formed into large-diameter ingots, with a view towards application in pistons for internal combustion engines, parts in which weight savings are sought. The addition of Zr to an $\text{Mg}_{96}\text{Zn}_2\text{Y}_2$ (at.%) alloy with a long-period stacking ordered structure phase refined the crystal grains. In addition, the use of a new casting method in which the ingot case is rotated and the molten metal is agitated helped to prevent segregation and the coarsening of the crystal grains, in order to make it possible to form large ingots (diameter: 335 mm; height: 850 mm) for extrusion displaying fine and uniform microstructures. Following formation of extruded pieces of 100 mm in diameter at an extrusion ratio of 10, dummy piston shapes were forged, and the mechanical properties of the material were measured before and after forging. From room temperature to 573 K, the developed alloy displayed tensile and fatigue strength in excess of commercial aluminum alloys. The alloy displayed a 0.2% yield strength of 209 MPa at 523 K following forging, approximately twice that of the high-strength aluminum alloy A4032-T6 that is used as a piston material. The addition of a high specific gravity element had minimal effect on the alloy's density, and reduced its weight to approximately 70% that of aluminum alloys. Given the above, the developed Mg-Zn-Y forged alloy can be considered to be an extremely promising material in terms of realizing fuel efficiency and performance increases through the achievement of weight reductions in automobile, motorcycle and power product pistons.

1. Introduction

Magnesium alloys are the lightest metal materials in practical use, and are expected to contribute to addressing environmental issues, for example through the realization of increased fuel efficiency in automobiles, motorcycles, and power products. It is known that the strength of Mg-Zn-Y alloys, which have a long-period stacking ordered structure (LPSO) phase, increases significantly even at high temperatures when they are subjected to extrusion processing and their microstructure is refined^{(1), (2)}. However, these materials have not been reported as possessing good mechanical properties for the large-diameter extruded materials used in pistons, nor has a casting process for the large ingots used to manufacture pistons been reported. This is because in large ingots the low speed of solidification and uneven temperature distribution can produce coarsening of the crystal grains and solidification segregation, with the result that a homogeneous material cannot be obtained. As a result, it has not been possible to obtain adequate mechanical properties (tensile characteristics and fatigue strength) in tests conducted on small test pieces. The research discussed in this paper therefore sought to develop

a heat-resistant magnesium alloy for casting possessing higher strength than conventional heat-resistant aluminum alloys, and developed an alloy composition for large ingots, a casting method, and extrusion and forging conditions.

2. Research Method applied to Forged Alloy

Subjecting Mg-Zn-Y alloys to plastic working processes such as extrusion gives the materials strength characteristics exceeding those of heat-resistant aluminum. In addition to compound strengthening when the material is cast, this effect is due to work hardening during extrusion, texturing and refinement of the crystal grains, and kink band strengthening^{(3), (4)}. However, when ingots of this material are increased in size to help enable its practical use, the coarsening and non-uniform dispersion of the as-cast microstructure (the LPSO phase) and other compound phases mean that using conventional methods, the target strength and ductility cannot be realized. The present research was therefore advanced with a focus on three processes – casting, extrusion, and forging.

At the commencement of the project, casting experiments were conducted with a focus on the refinement

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of the crystal grains and the realization of a uniform microstructure, two of the factors in strengthening the material discussed above. Compared to metals such as iron or aluminum, the contribution of refinement of the crystal grains to increased strength is high in the case of magnesium⁽⁵⁾. In the research under discussion, the crystal grains were refined through the addition of Zr, which has a high melting point and could be expected to form the point of origin for the formation of crystal nuclei⁽⁶⁾. In addition, nucleus formation was promoted by rotating the ingot case and agitating the melt inside the case. In the standard casting process, the ingot solidifies from the wall of the mold inwards, with the center of the ingot the last section to solidify. This results in the segregation of concentrated eutectic components in the center of the ingot. Rotation and agitation controls solidification commencing from the mold wall until the center of the ingot is at solidification temperature. Because this would mean that solidification would commence close to solidification temperature and be completed in a short period of time, it was expected that this method would significantly reduce solidification segmentation.

Next, ingots for extrusion were produced with varying compositions and under varying conditions. The basic characteristics of the developed alloy were studied and compared with existing magnesium alloys and aluminum alloys.

Finally, the material was forged into dummy piston shapes and evaluated. It was verified that forging temperature influenced the occurrence of forging defects and tensile characteristics. The material displayed a higher level of performance than heat-resistant aluminum alloy in unit endurance tests.

3. Test Method

An $\text{Mg}_{96}\text{Zn}_2\text{Y}_2$ alloy and an $\text{Mg}_{95.8}\text{Zn}_2\text{Y}_2\text{Zr}_{0.2}$ alloy were employed as test materials for the study. Table 1 shows representative values for the materials determined through analysis of their chemical composition. For melting and casting, a turntable was positioned in a vacuum melting furnace, as shown in Fig. 1. The alloys were melted in an iron crucible in an Ar gas environment using high-frequency melting equipment. 200 kg of each of the alloys were poured into ingot cases of 1,200 mm in height, with internal diameters of 335 mm. The ingot cases were rotated to produce agitation as the melt was poured. Conditions that would effectively agitate the melt without causing excessive disturbance were determined from water models. The ingot cases were rotated at 30 rpm, reversing every 35 sec, until the melt solidified. For the purpose of comparison, ingots were also cast without agitation. The ingots were peeled to 305 mm in diameter, and extruded at diameters of 100 mm at a temperature of 623 K. Finally, the extruded alloys were sliced and forged into dummy piston shapes after pressing in a 1,000-ton hydraulic press at material temperatures of 598-

Table 1 Chemical composition of Mg-alloys used in this study (at. %)

	Zn	Y	Zr	Mg
$\text{Mg}_{96}\text{Zn}_2\text{Y}_2$	1.96	2.10	-	Bal.
$\text{Mg}_{95.8}\text{Zn}_2\text{Y}_2\text{Zr}_{0.2}$	1.93	1.85	0.27	Bal.

783 K for 30 min. In order to evaluate the ingots, vertical cross-sections were taken, and inductively coupled plasma emission spectrometry (ICPES) and optical microscopy (OM) were employed to analyse chemical composition and observe as-cast microstructures. Phases formed following casting and extrusion were identified using x-ray diffraction (XRD) and energy-dispersive x-ray spectrometry (EDS), and microstructures were observed using scanning electron microscopy (SEM).

Mechanical properties were evaluated in tensile tests, tension and compression fatigue tests, and creep tests. Tensile tests employed micro test pieces of 3 mm in diameter in parallel sections, and with 15 mm between reference points. A strain rate of 5×10^{-4} /s and temperatures of 298-573 K were used in tensile tests. Fatigue tests were conducted using micro test pieces of 3 mm in diameter in parallel sections, and with 8 mm between reference points. The stress ratio was $R=-1$, at sine wave frequencies of 20-40 Hz, with a maximum number of repetitions of 10^7 and a test temperature of 473 K. Creep tests used micro test pieces of 3.65 mm in diameter in parallel sections, with 28 mm between reference points, and were conducted at a temperature of 573 K and a pressure of 50 MPa. The laser flash method specified by JIS R 1611 was used to measure thermal conductivity, and the thermomechanical analysis method specified by JIS R 1618 was used to measure the coefficient of thermal expansion. The ultrasonic method specified by JIS Z 2280 was used to measure Young's modulus, and Archimedes' principle, as specified by JIS Z

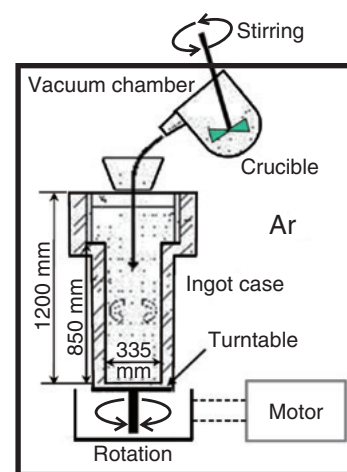


Fig. 1 Method of ingot casting in vacuum melting furnace using turntable

8807, was used to measure density. Values for the alloys were compared with values for existing materials.

4. Test Results and Discussion

4.1. Analysis of Stir-cast Ingots

4.1.1. Distribution of chemical composition

The results of analysis of the chemical composition of the ingots following casting showed that in the ingots cast using a conventional method, with no agitation, Zn and Y had become concentrated at 270 mm from the bottom of the ingot and above, and exceeded 2.25 at.%, higher than the 2.00 at.% allowable limit. The Zr added in order to refine the crystal grains was concentrated at a height of 140 mm, and exceeded 0.60 at.%. Zn and Y are constituent elements of the crystalline phase, and it was considered that they were concentrated in the sections of the ingot that were the last to crystallize. Because Zr has a high melting point, a low solid solubility limit, and a high specific gravity at 6.52, it is considered that gravity segregation affected the unmelted Zr. By contrast, the stir-cast alloys were within the 10% acceptable limit for target chemical composition, including distribution in the radial direction.

4.1.2. As-cast microstructure

Figure 2 shows changes in the as-cast microstructures of the $\text{Mg}_{96}\text{Zn}_2\text{Y}_2$ and $\text{Mg}_{95.8}\text{Zn}_2\text{Y}_2\text{Zr}_{0.2}$ alloy ingots in the height direction of the central axis, and includes differences between stir-cast and conventionally cast ingots. The conventionally cast $\text{Mg}_{96}\text{Zn}_2\text{Y}_2$ alloy ingot [Fig. 2(a)] displays increased crystal grain diameter (2 mm and above) in the region above a height of 530 mm. By contrast, in the stir-cast $\text{Mg}_{96}\text{Zn}_2\text{Y}_2$ alloy ingot [Fig. 2(b)], the crystal grain diameter is uniform in all regions in the direction of height. This indicates that the crystal grains coarsened in the areas of the ingot produced by conventional casting that were the last to solidify, because the ingot solidified slowly from the bottom and walls of the ingot case towards the top or the center, while in the stir-cast ingot, solidification did not commence until the center of the ingot reached solidification temperature, and actual solidification time was short, controlling coarsening and segregation. Similarly, in the conventionally cast $\text{Mg}_{95.8}\text{Zn}_2\text{Y}_2\text{Zr}_{0.2}$ alloy ingot [Fig. 2(c)], crystal grains are fine at a height of 10 mm above the bottom of the ingot case but become progressively coarser towards the top. By contrast, in the stir-cast $\text{Mg}_{95.8}\text{Zn}_2\text{Y}_2\text{Zr}_{0.2}$ alloy ingot [Fig. 2(d)], crystal grains are fine at approximately 0.1 mm in all regions in the direction of height and a homogeneous as-cast microstructure has been achieved. Because the crystal grains in the case of the stir-cast ingots were noticeably finer than was the case for other as-cast microstructures, it was judged that stir-casting contributed significantly to promoting the formation of crystal nuclei.

The results discussed above demonstrated that the new stir-casting method had realized initial goals set for

controlling the coarsening of the crystal grains and the segregation of the chemical composition of the alloy when the ingots were increased in size. Together with the addition of Zr, the new casting method refined the alloy crystal grains and realized a homogeneous microstructure.

4.2. Analysis of Extruded Material

4.2.1. Microstructure

Figures 3 and 4 show XRD patterns and photographs of the microstructures of the $\text{Mg}_{95.8}\text{Zn}_2\text{Y}_2\text{Zr}_{0.2}$ alloy ingot before and after extrusion. This alloy is made up of α -Mg, Mg_{12}ZnY (LPSO) and $\text{Mg}_3\text{Zn}_3\text{Y}_2$ phases, and there is no change in the constituent phases following extrusion. However, there are differences in the form of each phase. Before extrusion, the LPSO phase is insular, as shown in Fig. 4(a). Following extrusion, the LPSO phase becomes extended in the direction of extrusion [Fig. 4(c)]. In the case of the $\text{Mg}_3\text{Zn}_3\text{Y}_2$ phase, before extrusion the phase displays a coarse reticulated structure [Fig. 4(b)], while following extrusion it transforms into a sub-micron fine crystal grain structure, as shown in Fig. 4(d).

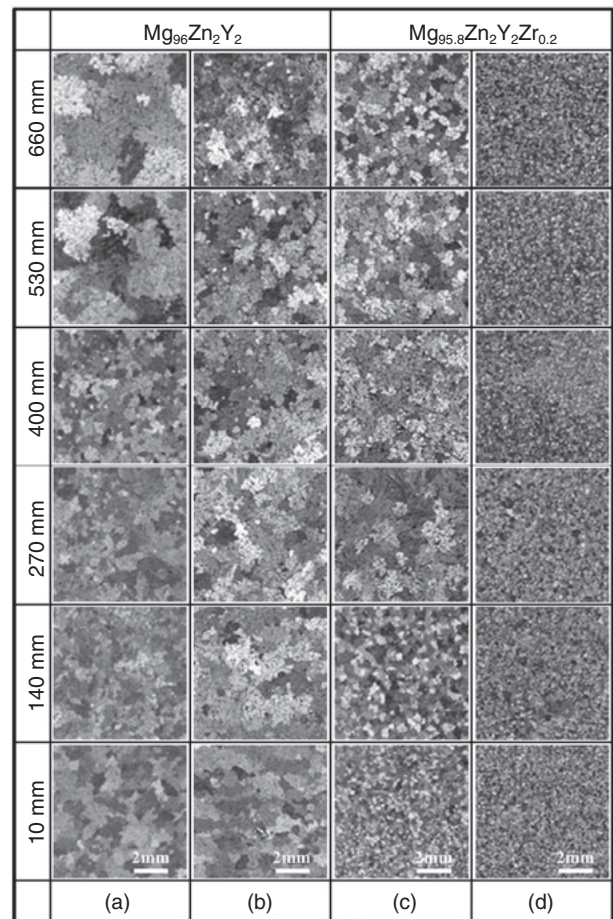


Fig. 2 Optical microscope images at various distances from base of ingot: (a) Conventional casting; (b) Stir-casting; (c) Conventional casting with Zr; and (d) Stir-casting with Zr

4.2.2. Mechanical properties

Figure 5 shows the test temperature dependence of 0.2% yield strength ($\sigma_{0.2}$) in the $\text{Mg}_{96}\text{Zn}_2\text{Y}_2$ and $\text{Mg}_{95.8}\text{Zn}_2\text{Y}_2\text{Zr}_{0.2}$ alloys from room temperature to 573 K, including lab data for small test pieces of 9 mm in diameter. 0.2% yield strength for the commercially available heat-resistant magnesium alloys WE54-T6 and RZ5-T5 and the aluminum alloy A4032-T6 is also shown for the sake of

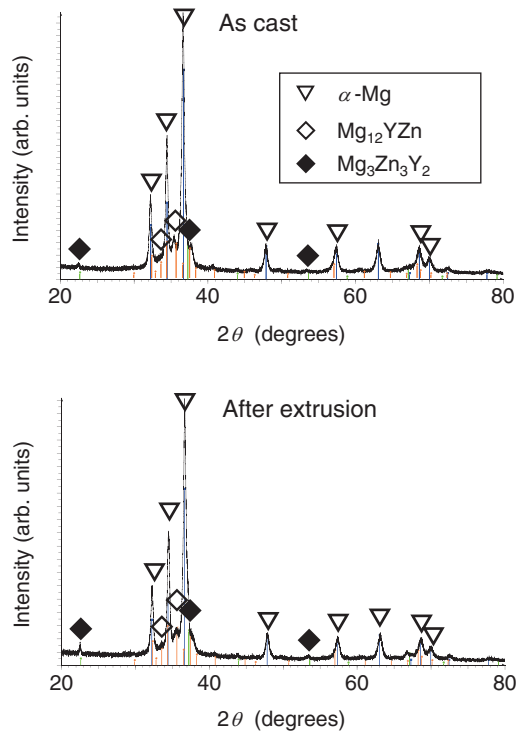


Fig. 3 XRD patterns of $\text{Mg}_{95.8}\text{Zn}_2\text{Y}_2\text{Zr}_{0.2}$ alloy before and after extrusion

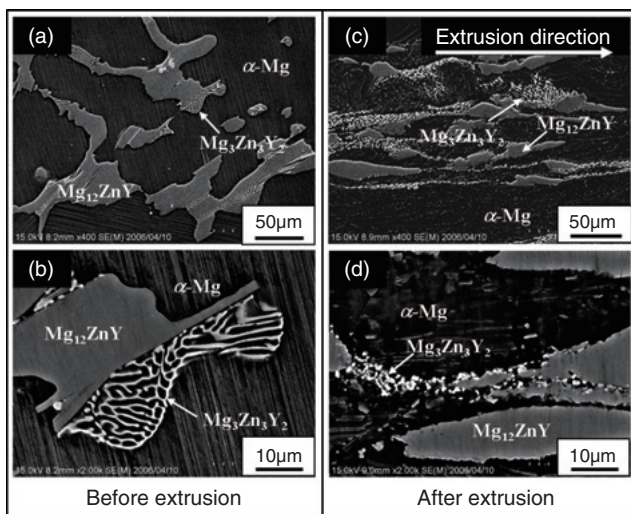


Fig. 4 Microstructures before ((a) and (b)) and after ((c) and (d)) extrusion; (a) and (c) shown at low magnification and (b) and (d) at high magnification

comparison. The developed alloys not only display greater yield strength than the commercially available heat-resistant magnesium alloys, but their yield strength also exceeds that of A4032-T6. It is noteworthy that at 523 K, the 0.2% yield strength of the developed alloys is approximately twice that of A4032-T6 at 208 MPa or higher, and almost three times higher at 573 K. In addition, by contrast with A4032-T6, which displays a significant decline in strength at 473 K and above, no sudden decline in the strength of the Mg-Zn-Y alloys was observed up to 523 K. The Mg-Zn-Y alloys display increasing strength in proportion to the refinement of their crystal grains, but this strength increase reverses at 573 K. Figure 6 shows differences in surfaces of the $\text{Mg}_{95.8}\text{Zn}_2\text{Y}_2\text{Zr}_{0.2}$ alloys fractured at 298 K and 573 K in order to elucidate this phenomenon of reversal of strength increase. Figure 6(a) shows a ductile fracture producing fine dimples, while Fig. 6(b) shows a grain boundary fracture producing large voids corresponding to the diameters of crystal grains, as indicated by the arrows in the figure⁽⁷⁾. Based on the fact that dimples can be observed in fracture surfaces up to 473 K, it was conjectured that between 523 and 573 K, there is a change in the fracture morphology, and alloys with large-diameter crystal grains

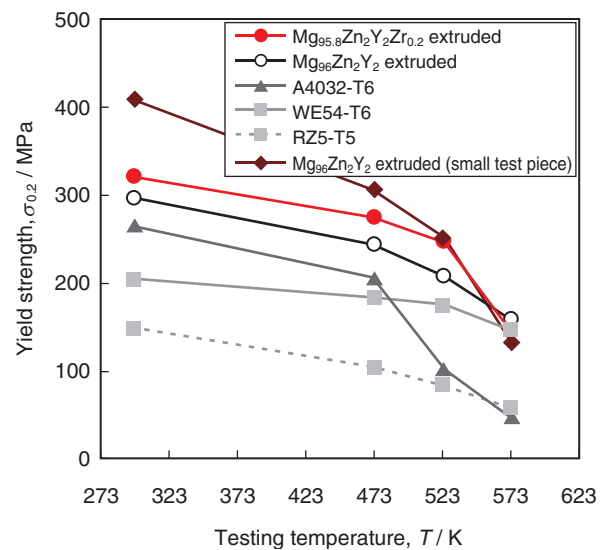


Fig. 5 Yield strength of Mg-Zn-Y alloys compared to A4032, WE54 and RZ5 alloys

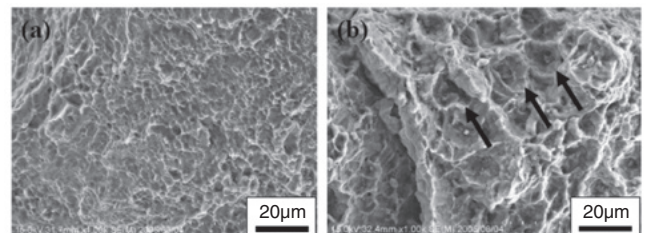


Fig. 6 Fractured surfaces of specimen $\text{Mg}_{95.8}\text{Zn}_2\text{Y}_2\text{Zr}_{0.2}$ alloys at (a) 298 K and (b) 573 K after extrusion

displaying resistance to grain boundary fracture increase in strength.

Next, the fatigue strength characteristic of the $\text{Mg}_{95.8}\text{Zn}_2\text{Y}_2\text{Zr}_{0.2}$ alloy at 473 K was compared with A4032-T6. The results are shown in Fig. 7. The arrows in the figure show test pieces remaining unfractured even after 10^7 repetitions. In other words, by contrast with aluminum alloys that do not display clear fatigue limits like A4032-T6, the $\text{Mg}_{95.8}\text{Zn}_2\text{Y}_2\text{Zr}_{0.2}$ alloy shows a fatigue limit at 100 MPa, as indicated by the bent line⁽⁸⁾. In addition to exceeding the 85 MPa limit for A4032-T6 at 10^7 repetitions, it was conjectured that an even more significant difference would be obtained at 10^8 repetitions, a figure that is essential in modern parts design.

Modern high-power engines use oil jets and other cooling mechanisms to reduce the temperature of the apices of the pistons, but these cooling methods have limits. In cases in which it is necessary to realize temperature resistance at the 573 K level, it is necessary to increase both fatigue strength and creep strength in reducing the weight of the pistons⁽⁹⁾. Figure 8 shows the creep properties of A4032-T6 and the $\text{Mg}_{95.8}\text{Zn}_2\text{Y}_2\text{Zr}_{0.2}$ alloy at 573 K under a 50 MPa load. The $\text{Mg}_{95.8}\text{Zn}_2\text{Y}_2\text{Zr}_{0.2}$ alloy displays greater creep strength than A4032-T6. It has been reported that the creep strength of the alloy is increased at high temperatures because compound phases such as the LPSO phase (a crystallized grain boundary phase) control grain boundary slip, and stacking faults strengthen the α -Mg matrix⁽¹⁰⁾.

As this demonstrates, even when fashioned into large extruded materials of a size suited to practical use, the high-temperature properties of the $\text{Mg}_{95.8}\text{Zn}_2\text{Y}_2\text{Zr}_{0.2}$ alloy surpass those of high-strength forged aluminum alloys, as exemplified by A4032.

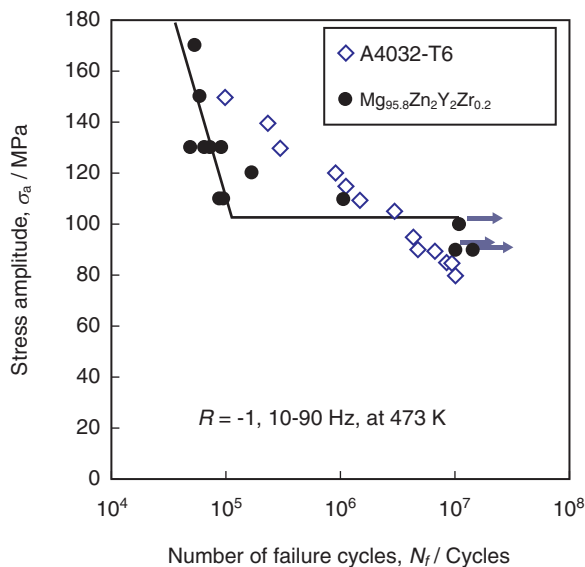


Fig. 7 S-N curves of A4032-T6 and stir-casting $\text{Mg}_{95.8}\text{Zn}_2\text{Y}_2\text{Zr}_{0.2}$ alloys after extrusion

4.3. Analysis of Forged Material

4.3.1. Forging temperature and forging defects

Figure 9 shows photographs of sections cut from the $\text{Mg}_{95.8}\text{Zn}_2\text{Y}_2\text{Zr}_{0.2}$ alloy and subjected to dye penetrant tests following forging into dummy piston shapes (Fig. 9(b) shows a crack occurring at 773 K). Table 2 shows the relationship between forging temperature and forging defects. At 613 K and below, cracking occurs and there are unfilled sections. From 623 to 748 K, there are regions with no forging defects. Cracking occurs again at the higher

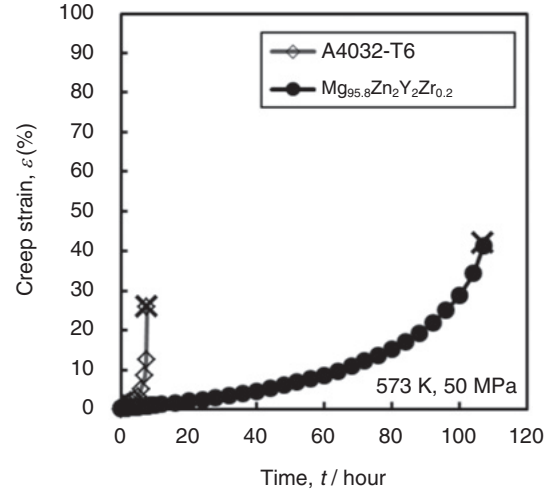


Fig. 8 Creep properties of A4032-T6 and stir-casting $\text{Mg}_{95.8}\text{Zn}_2\text{Y}_2\text{Zr}_{0.2}$ alloys after extrusion

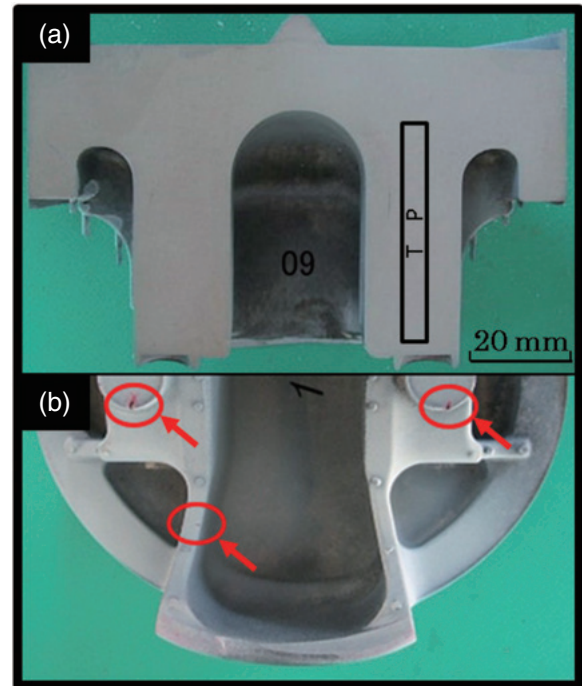


Fig. 9 Forged pistons after penetrant inspection: (a) Location for cutting of tensile specimen; (b) Cracked piston after forging at 773 K

Table 2 Relationship between forging temperature and forging defects

Forging temperature (K)	Forging defect	
	Crack	Unfilled
598	existence	existence
613	existence	existence
623	none	none
648	none	none
673	none	none
698	none	none
723	none	none
748	none	none
773	existence	none

temperature of 773 K. Defects in the low-temperature range are believed to be due to the fact that there is insufficient plastic flow at these temperatures. Because the cracks occurring in the high-temperature range follow the grain boundaries, it was conjectured that the components with low melting points that had crystallized at the grain boundaries had melted again due to the forging temperature.

4.3.2. Tensile properties

Figure 9(a) shows an image of a cross-section of the developed alloy following forging into a dummy piston shape and the position at which a tensile test piece was taken (the boss section). Figures 10(a) and (b) respectively show the tensile properties of the material at 298 K and 523 K (σ_B : Tensile strength; $\sigma_{0.2}$: 0.2% yield strength; δ : Elongation). At 209 MPa, the yield strength of the alloy at 523 K is almost twice that of the extruded A4032-T6 shown in Fig. 5. Forging has reduced the yield strength of the $Mg_{95.8}Zn_2Y_2Zr_{0.2}$ alloy by almost 20% against the alloy following extrusion, as shown in Fig. 5. The horizontal axes of the graphs show the holding temperature of the material prior to forging. As the holding temperature increases, strength declines further. The cause of this phenomenon will be discussed through a consideration of the alloy microstructure.

4.3.3. Microstructure

Figure 11 shows the microstructure of the boss sections of $Mg_{95.8}Zn_2Y_2Zr_{0.2}$ alloy dummy pistons of different pre-forging holding temperatures following forging. The forging direction was vertical, and the microstructures are elongated in the same direction. In the 648 K sample shown in Fig. 11(a), only a vertical microstructure possessing anisotropy can be observed. A fine, recrystallized microstructure has begun to form in the 698 K sample shown in Fig. 11(b), as shown by the arrows in the figure. In the 748 K sample, the α -Mg matrix is entirely filled by recrystallized grains, and the recrystallized grains have become coarser. It was conjectured that because basal slip is generated at a lower level of stress than other slip systems in the hexagonal

crystals characterizing the developed alloy, a decline in the basal texture in the tensile direction due to recrystallization would produce a decline in 0.2% yield strength. Figure 12 shows the results of a study of the relationship between forging temperature and the degree of texture. The degree of texture of vertical cross-sections in the direction of forging was analyzed using XRD, and the value obtained by dividing the peak strength of the prismatic planes of the hexagonal crystals by the peak strength of the basal planes was multiplied by 100. The degree of orientation of the basal plane declines with increase in the holding temperature prior to forging, corresponding to the tendency of 0.2% yield strength to decline, as shown in Fig. 10(a).

These results indicated that forging at the low temperature of 623 K, at which forging defects and recrystallization did not occur, made it possible to realize a yield strength approximately twice that of A4032 forged aluminum alloy (209 MPa at 523 K).

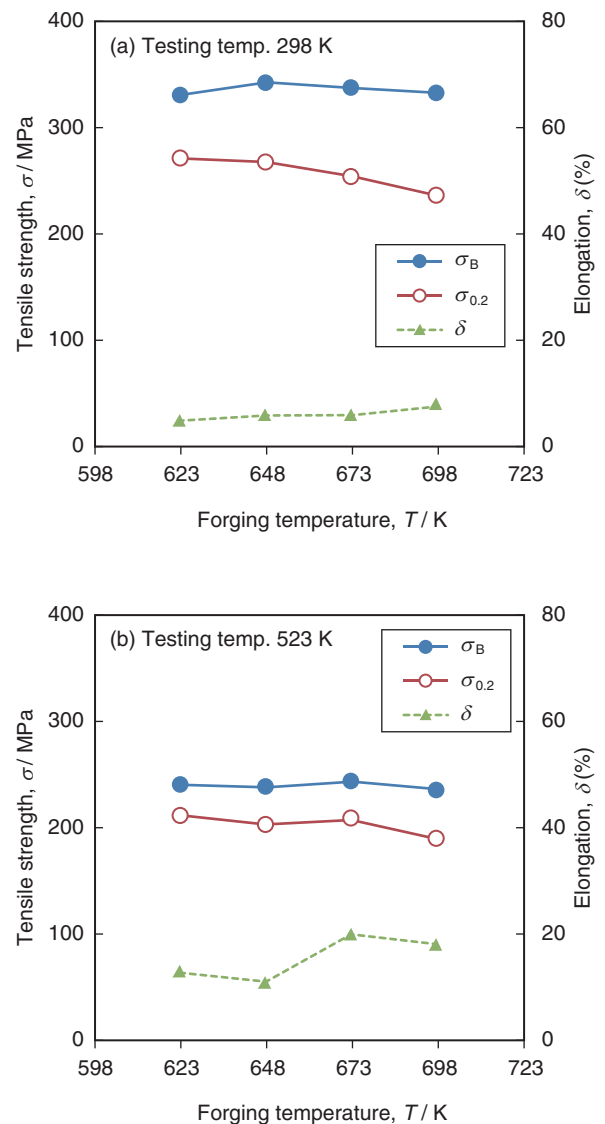


Fig. 10 Tensile properties after forging: (a) 298 K and (b) 523 K

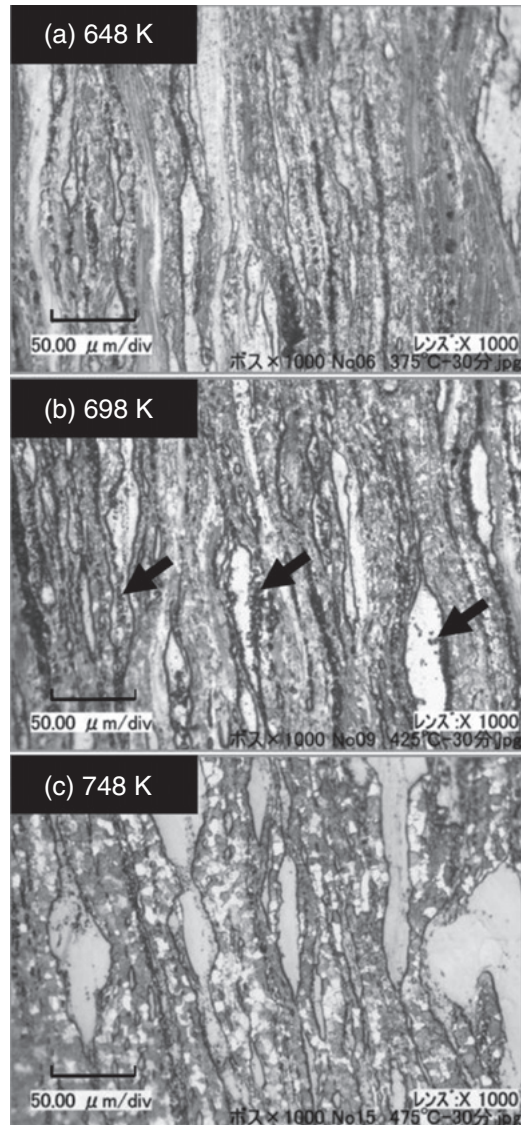


Fig. 11 Microstructure of forged $\text{Mg}_{95.8}\text{Zn}_2\text{Y}_2\text{Zr}_{0.2}$ alloys: (a) 648 K, (b) 698 K and (c) 748 K

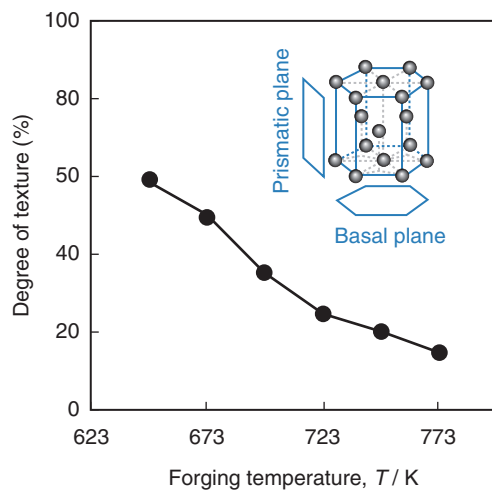


Fig. 12 Relationship of degree of texture and testing temperature after forging

4.3.4. Physical properties and other characteristics

Thermal dimensional stability, an essential property for the $\text{Mg}_{95.8}\text{Zn}_2\text{Y}_2\text{Zr}_{0.2}$ alloy as a high-temperature material, was studied. Figure 13 shows a comparison of the rate of dimensional change in the alloy after 100 hr at 503 K with A4032-T6. Compared to A4032-T6 at $33 - 34 \times 10^{-3}\%$, the alloy displays an extremely low rate of dimensional change at $5 - 13 \times 10^{-3}\%$. By contrast with the precipitation-hardened microstructure of A4032-T6, the alloy's constituent phases (Mg_{12}ZnY (LPSO) and $\text{Mg}_3\text{Zn}_3\text{Y}_2$) are stable, and do not display volumetric expansion as a result of aging.

Table 3 shows various characteristics of the $\text{Mg}_{95.8}\text{Zn}_2\text{Y}_2\text{Zr}_{0.2}$ alloy. Results for the commercial aluminum alloys A4032 and AC8A and the commercial magnesium alloys AZ91 and WE54 are also shown for the sake of comparison. Taking the use of the materials in high-temperature environments as pistons and other automotive parts into consideration, thermal conductivity is an issue from the perspective of cooling performance. The developed alloy displays significantly higher thermal conductivity than the commercial magnesium alloys, and realizes a comparatively good characteristic in this area. The material's coefficient of thermal expansion and Young's modulus are of a similar level to the commercial magnesium alloys, and lower than those of the commercial aluminum alloys. The developed alloy displays a low density like the commercial magnesium alloys, and is approximately 70% that of the aluminum alloys, meaning that it can be expected to contribute to the reduction of the weight of parts in automotive and other engines.

In addition, unit fatigue tests of pistons manufactured from forged Mg-Zn-Y alloys in oil at 523 K demonstrated that the pistons realized approximately 1.5X the strength of A4032 pistons (10^7 repetitions).

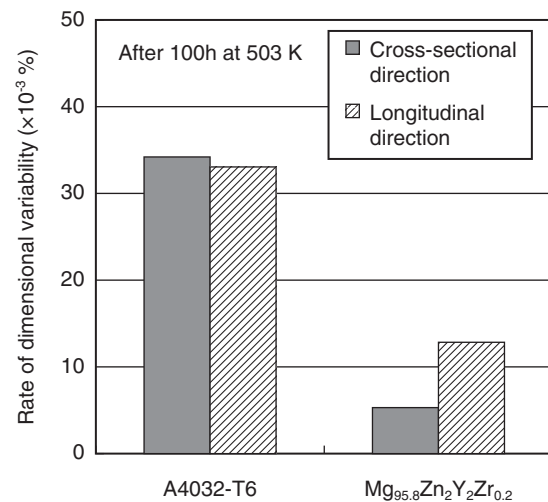


Fig. 13 High-temperature dimensional stability of A4032-T6 and stir-casting $\text{Mg}_{95.8}\text{Zn}_2\text{Y}_2\text{Zr}_{0.2}$ alloys after extrusion

Table 3 Characteristics of stir-casting $\text{Mg}_{95.8}\text{Zn}_2\text{Y}_2\text{Zr}_{0.2}$ alloy compared to commercial aluminum and magnesium alloys

Alloy	Thermal conductivity (W/(m·K))		Coefficient of thermal expansion at 298-573 K (1/K)	Young's modulus (GPa)	Density (kg/m ³)
	at 473 K	at 298 K			
$\text{Mg}_{95.8}\text{Zn}_2\text{Y}_2\text{Zr}_{0.2}$	89.8	72.4	25.4×10^{-6}	46.9	1920
A4032-T6	141	-	21.5×10^{-6}	73	2690
AC8A-T6 (JIS)	128	125	21.4×10^{-6}	78	2720
AZ91D	-	51	27.2×10^{-6}	45	1830
WE54-T6	-	52	24.6×10^{-6}	44	1850

5. Conclusion

In an effort to reduce the weight of structural automotive parts through the use of a high-strength heat-resistant magnesium forged alloy, the solidification microstructures of Mg-Zn-Y alloys were controlled, and the microstructures and properties of the alloys were examined. The research produced the following findings.

- (1) A new casting method in which the ingot case is rotated and the molten metal inside the case is agitated was developed. In addition to promoting the formation of crystal nuclei, this stir-casting method controls the solidification of the molten metal from the walls of the ingot case inwards until the solidification temperature was reached. This has helped to prevent the usual segregation and coarsening of the crystal grains, and made it possible to realize a fine and uniform microstructure in a large ingot for extrusion, measuring 335 mm in diameter and 850 mm in height.
- (2) A plastically worked (extruded) Mg-Zn-Y alloy formed from ingots displaying this fine and uniform microstructure realized tensile, fatigue and creep characteristics exceeding those of commercial heat-resistant magnesium alloys and aluminum alloys at a wide range of temperatures, from room temperature to 573 K. With regard to physical properties, the alloy displayed 70% lower specific gravity than aluminum alloys. Thermal conductivity can represent an issue, and the performance of the alloy significantly exceeded the commercial magnesium alloys in this respect, reaching levels close to those of commercial aluminum alloys.
- (3) Forging the alloy at the low temperature of 623 K, at which forging defects and recrystallization do not occur, made it possible to realize a yield strength at 209 MPa and a fatigue strength respectively approximately twice and 1.5 times those of A4032 forged aluminum alloy used in pistons in 523 K high-temperature conditions.

Mg-Zn-Y alloys possess good high-temperature characteristics, and can be considered promising forging materials in the attempt to reduce the weight of heat-resistant parts. They possess a 30% lower specific gravity than aluminum alloys, and thin-wall design exploiting their

high yield strength and fatigue strength can be expected to realize weight savings of over 30%.

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