

Development of Lightweight Oil Pans Made of a Heat-Resistant Magnesium Alloy

Seiichi KOIKE*

Tsuyoshi BABA**

Kazuhiro WASHIZU*

Kazuo KIKAWA*

Shigekazu TANAKA*

ABSTRACT

A new heat-resistant magnesium alloy (hereafter referred to as “ACM522”) for die-casting based on the Mg-Al-Ca-RE system has been developed. In the 150°C temperature range, ACM522 yields high creep characteristics which are superior to the conventional AE42 heat-resistant magnesium alloy for die casting. Further it exhibits an excellent resistance to both heat and corrosion which is equivalent to ADC12 general-purpose aluminum alloy. Use of magnesium for oil pans has raised a number of problems such as axial force drop in the bolted areas and, until now, oil pans made of magnesium had not been applied to mass-produced automobiles. The authors applied the ACM522 for oil pans and achieved a 35% weight reduction compared to conventional oil pans made of aluminum.

1. Introduction

Reducing weight to improve the fuel economy of transportation vehicles is important for the effective utilization of limited energy resources and global environmental issues. In the fall of 1999, Honda released its “Insight” hybrid car that achieves the lowest fuel consumption in the world, at 35 km/liter, for a mass-produced, gasoline-engined vehicle. The engine was developed exclusively for use in a hybrid system, and the application of weight-reduction technology throughout the vehicle, including the increased use of lightweight materials, has resulted in the lightest one-liter engine in the world. An external view of this engine is shown in Fig.1. Reducing the weight of the oil pan, one of the engine’s heaviest components, was essential to achieving this light weight. The use of magnesium for the oil pan would usually have resulted in a significant decrease with time in the clamping

force at the bolted joint when using the general-purpose AZ91D and AM60B alloys, so a new, heat-resistant magnesium alloy was needed. This newly developed alloy has as its basic components Mg-Al-Ca-RE and demonstrates outstanding heat resistance and corrosion resistance. In addition, this alloy also possesses suitable molten fluidity and low hot cracking for die-cast production. Oil pans made of this alloy were 35% lighter than conventional aluminum oil pans. This paper describes the material properties of this newly developed ACM522 heat-resistant magnesium alloy and presents an overview of oil pans made from this material.

2. Background

Magnesium alloy is the lightest metallic material for practical use, having a density of 1.78 g/cm³. Its use for automobile parts, portable telephone equipment and home appliances is increasing at a rapid pace due not only to its light weight, but also to its strength-to-weight ratio, specific rigidity, electromagnetic shielding and ease of recycling. However, when applying to automobile engine and transmission parts, it is necessary to use a heat-resistant magnesium alloy that can be easily cast at a low cost. The function of the oil pan is to hold the engine lubricating oil by sealing the bottom of the engine. The design that is typically employed is to bolt the oil pan to the underside of the cylinder block. Since the temperature in that area during engine operation can reach up to 150°C, oil pans have conventionally been made of sheet steel or a die-cast aluminum alloy. When attempting to make an oil pan out of a typical magnesium alloy such as AZ91D, which has balanced mechanical properties, castability and corrosion resistance, there is a substantial decrease with time in the clamping force of the bolted joint, thus creating the need to



Fig.1 Honda integrated motor assist engine system

* Tohigi R&D Center

** Wako Research Center

develop a new heat-resistant magnesium alloy for die-casting that does not suffer from this defect.

Several types of magnesium alloy have been developed in the past for heat-resisting applications. The AS41 and AS21 alloys offer good creep resistance by crystallizing the intermetallic Mg_2Si compound at the crystal grain boundary. In particular, although the castability of AS21, which has a low aluminum content, is inferior to that of AS41, it has outstanding creep resistance. In addition, although AE42 has creep resistance equal to or better than AS21, it has problems in terms of casting due to its high material cost and susceptibility to hot cracking.⁽¹⁾ In addition, an Mg-Zn-Al-Ca-based heat-resistant alloy has recently been developed in which Zn is the main added element to supplement Al and Ca.⁽²⁾ This alloy has been reported to have better creep resistance, corrosion resistance and die-castability than AE42.

We established the following alloy development objectives for a new heat-resistant magnesium alloy capable of being applied to oil pans.

- (1) Creep resistance and corrosion resistance comparable to die-cast ADC12 aluminum alloy.
- (2) Hot cracking properties equivalent to AZ91 and AE42 to enable mass production of oil pans.

This newly developed alloy is based on an Mg-5Al composition in consideration of die-castability, and contains Ca and Ce-based misch metal for improving the heat resistance. Moreover, a small amount of manganese has been added to improve the corrosion resistance, resulting in the final Mg-5Al-2Ca-2M.M-0.3Mn alloy (ACM522).

3. Experimental Method

3.1. Test Pieces

A master alloy prepared in advance was melted in a melting furnace in a protective atmosphere of SF_6 , CO_2 and air. After melting, the temperature was maintained at about 700°C, and the tensile test pieces and creep test pieces were cast with a 350-ton cold chamber die-casting machine. The resulting test pieces were used while still in the cast state after removing the burrs generated at the parting line of the die. On the other hand, the fatigue test pieces were taken from an oil pan cast with a 1000-ton cold chamber die-casting machine and, the chilled layer on the surface was removed by machining before being used for fatigue testing.

The shapes of the tensile test, creep test and fatigue test pieces are shown in Fig.2. In addition, a sample cut from the tensile test piece was analyzed by ICP for its chemical composition. The results of that analysis are shown in Table 1.

3.2. Mechanical Properties

The tensile test was performed with an Instron type universal tester at a strain rate of 0.5 mm/min. Testing was performed at room temperature, and at 100, 150, 180 and 250°C. The test was started at each temperature after holding at that temperature for 10 minutes. Elongation was measured with an extensometer, while the 0.2% proof stress and maximum tensile strength were determined by preparing stress-strain curves.

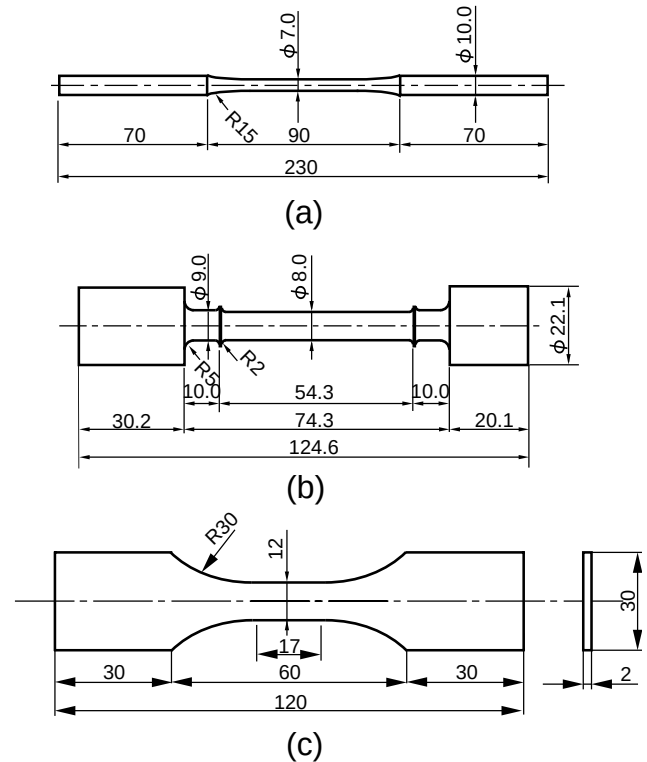


Fig.2 Die casting test specimens:
(a) tensile specimen
(b) creep specimen
(c) fatigue specimen

Table 1 Chemical composition of ACM522 alloy

Al wt%	Rare earth wt%	Ca wt%	Mn wt%	Fe ppm	Cu ppm	Ni ppm
5.3	2.6	2.0	0.17	19	18	< 1

The creep test was performed in compliance with JIS Z 2271. A single lever, 3-ton creep tester having a lever ratio of 10:1 was used for the test. Testing was performed at temperatures of 150, 180 and 200°C. The temperature was held to within $\pm 1.5^\circ C$ by PID control. Creep elongation was determined by pinching a protruding portion of the test piece with an extensometer jig, reading the amount of displacement outside the furnace and recording the mean value of two linear gauges on the left and right sides. A load equivalent to the prescribed tensile stress (50-100 MPa) was applied after allowing the test piece to reach the set temperature and then holding at that temperature for 20 hours.

The fatigue characteristics were evaluated by a pulsating tensile fatigue test at a stress ratio of 0.2 and frequency of 25 Hz. Testing was performed at room temperature, and at 120° and 150°C.

3.3. Corrosion Resistance Test

Corrosion resistance was evaluated by a salt water spray

test. The test piece was obtained by cutting out a plate measuring $25 \times 20 \times 3$ mm from the flat surface of a die-cast magnesium alloy oil pan. The cut surfaces of the test piece were ground with #1500 waterproof abrasive paper. The test method was in accordance with JIS Z 2371, whereby the test conditions include a salt water concentration of 5% NaCl a pH of 6.7-6.8, under the atmospheric conditions of 35°C and 99% humidity. After 400 hours of spraying, the test piece was boiled and washed in a 10% aqueous chromic acid solution before being washed with distilled water. The test piece allowed it to completely dry and then it was weighed.

3.4. Physical Properties

Density was determined according to the Archimedes method. Thermal constants such as the specific heat and thermal conductivity were determined by the laser flash method. Electrical conductivity was measured by the four terminal measurement method, and thermal expansion was measured with a push rod type vertical thermal expansion meter. The vertical elastic modulus and damping capacity were determined according to the resonance method.

3.5. Hot Cracking Test

The ring test method developed by Singer and Jennings was used for measuring hot cracking. This test is suited for evaluating hot cracking in the semi-solid phase. The shape of the ring-die plate is shown in Fig.3, and cast iron was used for the material. The bottom of the casting die was coated with BN as an adiabatic mold release agent, and the casting die was held at the prescribed temperature to cast a 700°C melt. Cracking was evaluated as the total length of cracks that formed in the cast ring test piece.

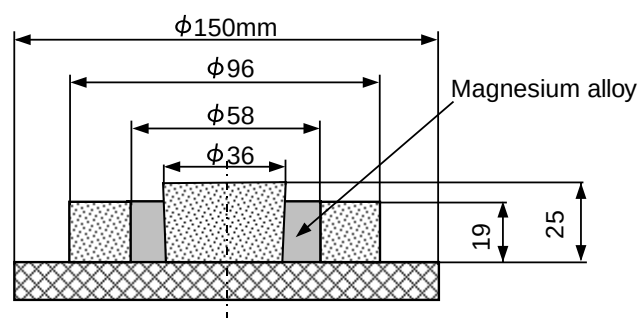


Fig.3 Ring-die plate for hot-cracking test

3.6. Bolt Load Retention Test

The test piece used in the bolt load retention test was sampled from a die-cast biscuit portion. An axial tension bolt incorporating a strain gauge in an M6 bolt (internal thread length of 2.5 D) was used. The test piece was placed in a constant temperature oven at 150°C , and the change in axial tension was measured by the method indicated in the schematic drawing in Fig.4. A similar bolt load retention test was performed on AZ91D alloy for comparative purposes.

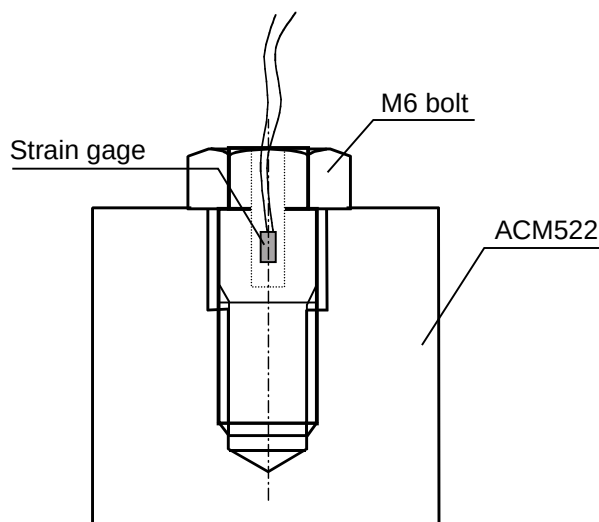


Fig.4 Bolt load retention test assembly

4. Results and Discussion

4.1. Mechanical Properties

The temperature dependence of the strength properties of ACM522 are shown in Figs.5, 6 and 7. AZ91D, AE42 and ADC12 are also given for comparison. As shown in Fig.5, the tensile strength of ACM522 is inferior to that of AZ91D. Although the tensile strength at room temperature is inferior to that of AE42, ACM522 demonstrates superior tensile strength at temperatures of 100°C . and above. In addition, as shown in Fig.6, although the 0.2% proof stress of ACM522 is equal to that of AZ91D at room temperature, it is better than AZ91D at temperatures of 100°C . and above. ACM522 demonstrates better properties than AE42 over the entire temperature range from room temperature to 250°C . As shown in Fig.7, AE42 demonstrates the highest value for elongation. The elongation of ACM522 is about 3% at

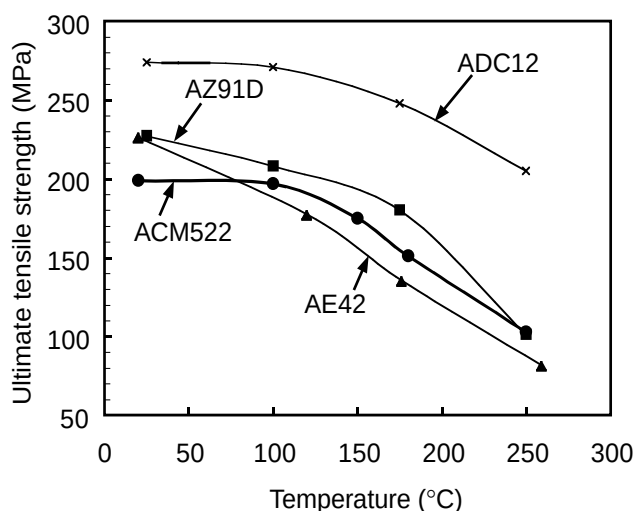


Fig.5 Ultimate tensile strength of ACM522 alloy compared with conventional die casting alloys

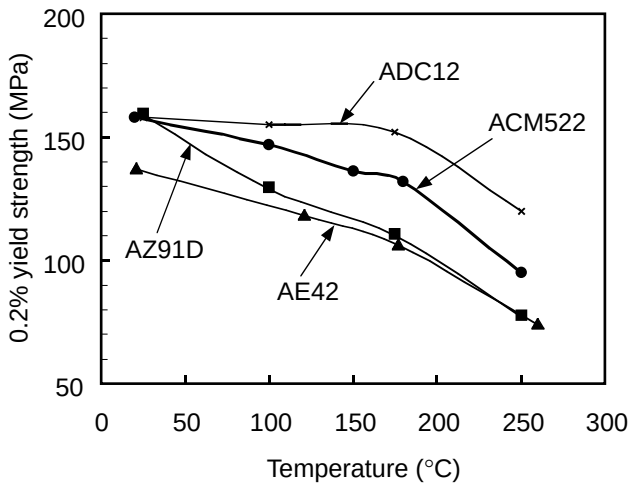


Fig.6 0.2% yield strength of ACM522 alloy compared with conventional die casting alloys

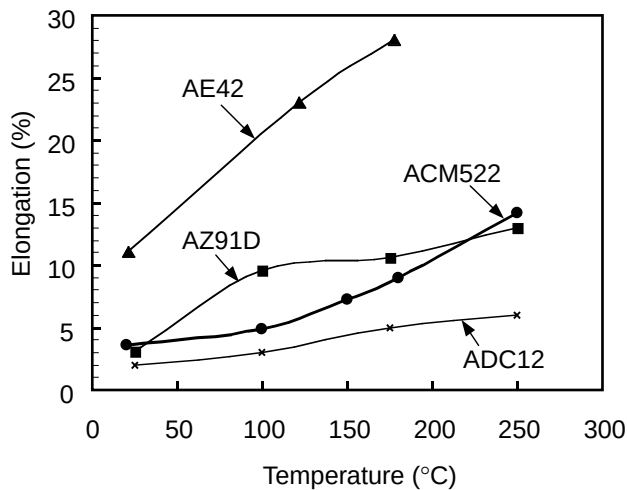


Fig.7 Elongation of ACM522 alloy compared with conventional die casting alloys

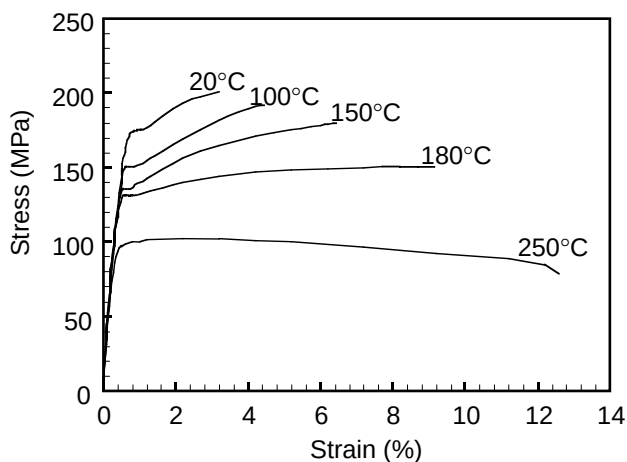


Fig.8 Stress-strain curves of ACM522 alloy

room temperature, which is equal to that of AZ91D, and this elongation increases as the temperature rises. In a comparison with general-purpose die-cast ADC12 aluminum alloy, the tensile strength of ACM522 is inferior over the entire temperature range, while its 0.2% proof stress is equal to that of ADC12 at room temperature, and the decrease in strength at high temperatures is greater for ACM522. The elongation of ACM522 is higher from room temperature to 250°C. Typical stress-strain curves at each temperature are shown in Fig.8. Since the amount of work hardening is low and ACM522 demonstrates a stress-strain curve shape similar to that of AE42, the strengthening mechanism of ACM522 is not in the form of solid solution strengthening or precipitation strengthening, but is believed instead to be the result of a grain boundary compound phase that inhibits slippage of the crystal grains.

The stress at which the creep elongation at 100 hours of ACM522 reaches 0.1% at each test temperature is shown in Fig.9 as compared with various other die-cast alloys. The stress that yields 0.1% creep elongation was calculated by a logarithmic approximation of the creep elongation (X) and stress (Y), rearranging to the formula $Y = a \times \log(X) + b$ and determining the stress at 0.1%. The creep strength of ACM522 is roughly comparable to that of ADC12 over a temperature range of 150-200°C, and the ACM522 alloy demonstrates outstanding creep strength properties that surpass those of AE42.

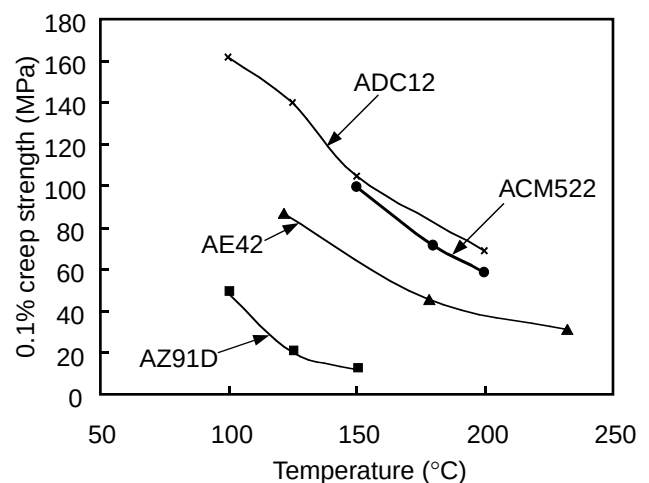


Fig.9 0.1% creep strength of ACM522 alloy compared with conventional die casting alloys

Fig.10 shows the S-N curves at room temperature, 120°C and 150°C for ACM522. The fatigue strength decreases as the temperature rises, the fatigue strength after 10^7 repetitions being 130 MPa at room temperature, 100 MPa at 120°C and 80 MPa at 150°C.

The microstructure of ACM522 was observed in order to examine the mechanism by which it is strengthened. Fig.11 is a photograph of the SEM image microstructure of die-cast ACM522. The phase consisting of black granules dispersed within the pro-eutectic α phase is the Al-Ce compound phase. The lightly colored compounds are

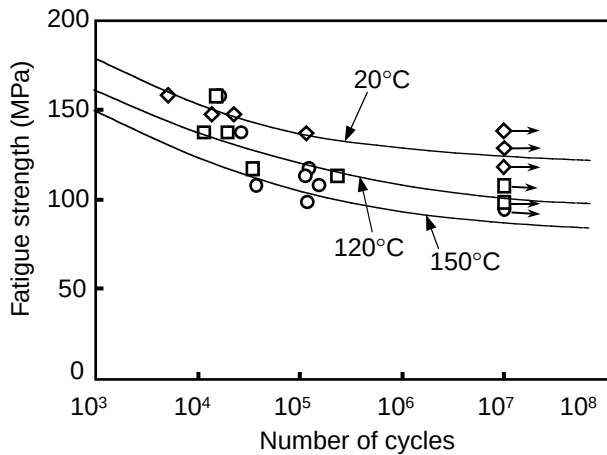


Fig.10 Fatigue strength of ACM522 alloy

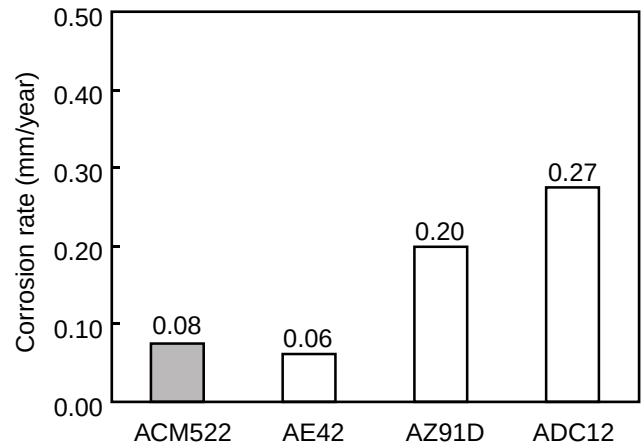


Fig.12 Corrosion rate of each alloy of the salt water spray test in 400 hours for some die casting alloys

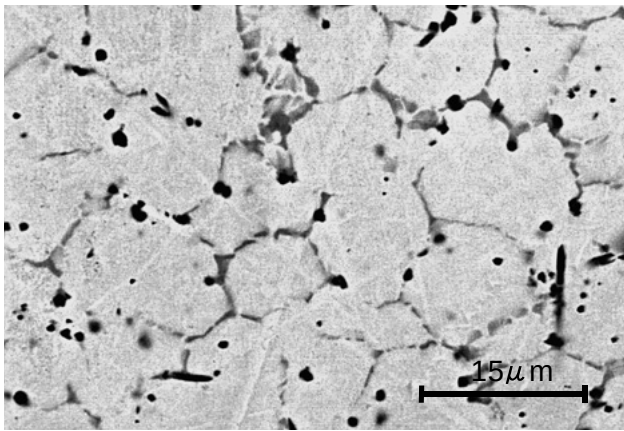


Fig.11 SEM image microstructure of ACM522 alloy

thought to be Al-Ca and Mg-Ca. As a result of this relatively fine intermetallic compound phase being finely dispersed along the grain boundaries of the α phase, the grain boundaries are strengthened. This is considered to have produced the superior creep properties.

4.2. Corrosion Resistance

Fig.12 shows the corrosion rate of ACM522 after 400 hours of the salt water spray test as compared to the AZ91D, AE42 and ADC12 alloys. ACM522 exhibits corrosion resistance that is similar to that of AE42, which is considered to be favorable, and is superior to that of AZ91D and ADC12. The corrosion resistance of magnesium alloys has been reported to be greatly affected by the presence of impurities.⁽³⁾ Typical examples of impurities include Fe, Cu and Ni. It is known that magnesium alloys are able to demonstrate outstanding corrosion resistance if a critical impurity level exists at which the corrosion resistance decreases, and if these impurities are controlled to be below that critical level. This is the reason why the corrosion resistance of ACM522 is superior to that of ADC12. In addition, the form of corrosion of ACM522 involved preferential dissolution of the α phase, indicating corrosion behavior similar to that of AZ91D and AE42.

4.3. Physical Properties

A list of physical properties is shown in Table 2. The physical properties of AZ91D, AE42 and ADC12 are also shown for comparison. Although the thermal conductivity and electrical conductivity of ACM522 are lower than the values for ADC12, they are somewhat higher than those for AE42. ACM522 also exhibits the lowest value for thermal expansion among all the other magnesium alloys. This is advantageous with respect to temperature change in a bolted joint. The damping capacity is equal to that of the other magnesium alloys and die-cast aluminum materials.

Table 2 Physical properties of some die cast alloys

Properties	ACM522	AE42	AZ91D	ADC12
Density (g/cm ³)	1.79	1.81	1.81	2.70
Specific-heat (J/kg·°C)	0.91	0.96	0.96	0.96
Thermal conductivity (W/mK)	86.9	78.6	53.8	100
Electrical conductivity (%ICAS)	22.5	20.3	12.7	27.0
Thermal expansion ($\times 10^{-6}$ /°C)	25.6	27.7	28.5	24.0
Modulus (GPa)	45	45	45	69
Damping capacity (%)	0.325	NA	0.289	0.305

4.4. Hot Cracking

The ring cracking test was performed on AZ91, AM60, AE42 and ADC12. Cracking in AZ91 and AE42 occurred over a maximum of 20 mm, while ring cracking did not occur in ADC12.

The relationship between ring cracking and the composition of ACM522 was investigated by varying the amount of Al, Ca and RE, its main components. Fig.13 indicates the relationship between hot cracking and the amounts of added Al and Ca when the amount of added RE was held constant at 2%.

When the amount of Al was 2-3%, large cracks formed even if a trace amount of Ca was present. As the amount of

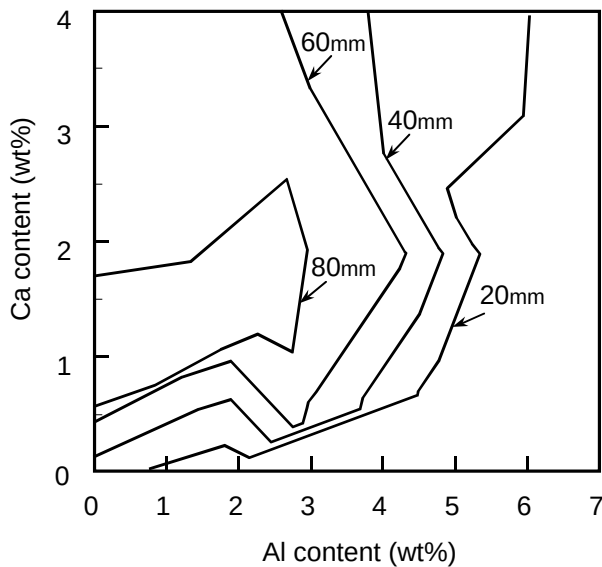


Fig.13 The effect of Al and Ca content on the total hot-crack length for the ACM522 alloy with rare earth = 2wt%

Al was increased, the length of the cracks decreased; when the amount of Al reached about 5% and the amount of Ca was set to approximately 2% or less, hot cracking was at about the same level as that in AZ91 and AE42.

4.5. Bolt Load Retention Test

Fig.14 shows the change in axial tension of a bolted joint at 150°C. The axial tension increases slightly immediately after placing in the high-temperature furnace due to the difference in thermal expansion between ACM522 and the steel bolt. In the case of AZ91D, the axial tension subsequently decreased rapidly with time, and essentially dropped to zero after 1000 hours. In contrast, there was hardly any decrease in the axial tension in the case of ACM522, even after 1000 hours. This is the result of the outstanding creep strength of ACM522 inhibiting set-in fatigue of the bolt seat and internal threads.

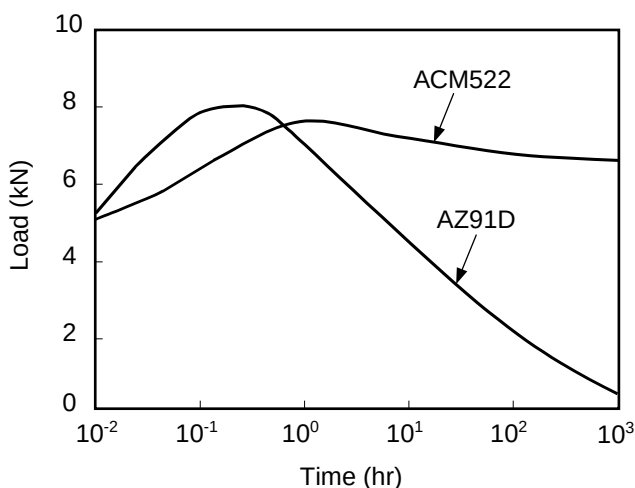


Fig.14 Bolt load retention test at 150°C

5. Overview of Magnesium Alloy Oil Pans

A photograph of the exterior of an oil pan made of ACM522 is shown in Fig.15. This oil pan weighs only 2.5 kg, despite allowing for the direct attachment of an air compressor and oil filter to the side of the oil pan, and weighs 35% less than an aluminum oil pan. An oil pan with a complex shape was created by integrated die-casting to take advantage of the high degree of freedom in shape offered by die-casting. A design was employed to minimize variation in the wall thickness in order to prevent hot cracking during die-cast forming, and the wall thickness of typical sections was set at 2.5-3.0 mm. In addition, ribs were positioned as necessary to ensure adequate rigidity.



Fig.15 Appearance of magnesium oil pan using ACM522 alloy

Since the oil pan is located at the lowest point of the engine, it is subjected to a more severe corrosive environment than other engine parts due to being splashed with water and mud on the road during vehicle travel. In addition, when magnesium alloy is placed in a corrosive environment while in electrical contact with a dissimilar metal such as carbon steel, the magnesium serves as an anode and is selectively corroded. Consequently, it is necessary to take measures to prevent galvanic corrosion by reducing the potential difference through placing a metal such as aluminum having an electrical potential close to that of magnesium between the magnesium and dissimilar metal or by inserting an electrical insulating material between the two. In the development of this new magnesium alloy oil pan, measures to prevent corrosion were employed basically by inserting anodic oxidation-treated aluminum washers under each steel bolt. Anticorrosion measures were also provided for the drain plug and other bolts that are frequently removed during maintenance by providing separate alumite-treated plates.

Although there was initial concern over greater noise and vibration levels that would result from decreased rigidity around the bottom of the engine, this could be compensated for by making small changes to the shape of the oil pan. The results of these changes are shown in Fig.16. As a result of a one-third octave analysis of the vibration noise above and below the engine side mounting bracket,

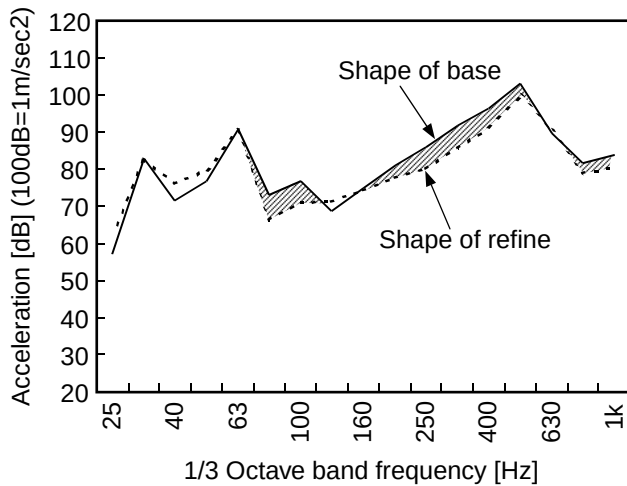


Fig.16 The effect of frequency of side mounting bracket (2000rpm, 250mmHg)

attenuation was obtained in the range of 70-500 Hz by increasing the flange thickness and by reviewing the shape of the curved surfaces and so forth. This was particularly effective in reducing the noise level in the 200-400 Hz band that presents a problem in the form of crankshaft pounding noise and engine acceleration noise.

6. Conclusion

This report has presented an evaluation of the material properties of the newly developed heat-resistant magnesium alloy, and an overview of a lightweight magnesium oil pan made of this alloy.

- (1) The newly developed alloy is based on an Mg-5Al composition for die-castability, and contains Ca and Ce-based misch metal for improved heat resistance. Moreover, a small amount of Mn is added to provide good corrosion resistance, resulting in the final Mg-5Al-2Ca-2M.M-0.3Mn material (ACM522).
- (2) ACM522 demonstrates creep properties and corrosion resistance comparable to those of ADC12, a general-purpose die-cast aluminum alloy.
- (3) A magnesium oil pan made of ACM522 alloy was 35% lighter than a conventional aluminum oil pan.

This lightweight magnesium oil pan is employed in the engine installed in the "Insight" hybrid car that has achieved the lowest level of fuel consumption in the world, at 35 km/liter, for a mass-produced, gasoline-engined vehicle. It went into mass production in November 1999.

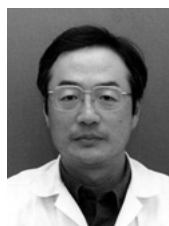
It is expected that the application of this magnesium alloy will be expanded in the future to include engine and transmission parts requiring a high level of heat resistance.

References

- (1) Mercer II, E. W.: Magnesium Die Cast Alloys for Elevated Temperature Applications, SAE Paper 900788

- (2) Luo, A. and Shinoda, T.: A New Magnesium Alloy For Automotive Powertrain Applications, SAE Paper 980086
- (3) Hills, J., E and Reichek, K.N : Controlling the Salt Water Corrosion Performance of Magnesium AZ91 Alloy, SAE Paper 860228

■ author ■



Seiichi KOIKE



Kazuhiro WASHIZU



Shigekazu TANAKA



Tsuyoshi BABA



Kazuo KIKAWA