# FATIGUE STRENGTH CHARACTERISTICS OF QUASI-CRYSTAL ALUMINUM ALLOY WITH AND WITHOUT SiC-PARTICLE DISPERSION

**Shuhei ADACHI*, Tsuyoshi KUBOTA*, Tohru KOHNO**, Masato OTSUKI**, Masahisa MIYAHARA**, Jun-ichi NAGAHORA***, Kazuhiko KITA***, Takayuki MATSUDA****, Masahiro OGUCHI****, Shin TAKEDA*****, Toshiharu HOSHI******, Yuma HORIO******, Akihisa INOUE*********

*Yamaha Motor Co.,Ltd.R&D Center 2500 Shingai,Iwata 438-8501,Japan **Mitsubishi Materials Co. Central Research Institute, Omiya, Japan ***YKK Co. Sendai Institute of Material Science and Technology, Kurokawa, Japan ****Teikoku Piston Ring Co.,Ltd. Nagano Plant, Okaya, Japan *****Aisin Seiki Co.,Ltd. Cooprate R&D Center, Kariya, Japan ******Yamaha Co. Technical Development Laboratory, Iwata-gun, Japan ******* Institute for Materials Research, Tohoku University, Sendai,Japan

**ABSTRACT** The static and fatigue strength characteristics were evaluated for the extruded material made of quasi-crystal aluminum alloy with SiC-particle dispersion, which was developed to achieve both high specific strength and wear resistance, and these results were compared to those of the conventional material. The quasi-crystal alloy that does not contain dispersed particles showed a high fatigue-strength value of 240MPa and 210MPa at 20℃ and 150℃, respectively. Also, the fatigue strength of the quasi-crystal with particle dispersion at the same temperature was around 1.5 times higher than that of the conventional material, revealing an excellent fatigue-strength characteristic in the temperature range of up to 150℃.

**Keywords** : *quasicrystal, aluminum alloy, fatigue strength, SiC-particle dispersion, composite*

## 1. INTRODUCTION

In many cases, structural materials used for automotive components and sports gear require high specific strength, specific stiffness, wear resistance and low cost. The quasi-crystal aluminum alloy developed recently by Inoue, et al.([1]-[3]), promises to achieve many applications, having the level of strength comparable to the conventional steel-based materials, as well as a high modulus of elasticity. Utilizing the excellent characteristics of the alloy, the authors have developed and improved the alloy composition and manufacturing process, so that it can achieve the level of price competitiveness required of a commercial material.

In this paper, we will demonstrate the results of fatigue-strength characteristic testing with principle focus on the newly developed quasi-crystal aluminum alloy with particle dispersion, and shall examine the prospect of commercialization by comparing the material with the quasi-crystal alloy without particle dispersion and the conventional material.

## 2. EXPERIMENTAL PROCEDURE

Table 1 shows the chemical composition of the three material types used in the experiments. As for Alloy 1, or quasi-crystal aluminum alloy, the amount of alloy element is kept to a minimum so as to increase it cost-performance as a commercial material. Alloy 2 is made by using Alloy 1 as base and mixing in or dispersing silicon carbide pàrticles during the adjustment of powder materials. The average particle diameter of silicon carbide is 5 $\mu$ m, and its volume fraction at mixing is 5 percent. As a comparison material, we used Al-Si-based wrought alloy extruded bar (Alloy 3),

Table 1 Chemical composition of the materials (mass %)

| | Cr | Co | Mm | Zr | Si | Fe | Cu | Mn | Mg | Zn | Ti | Al | Note |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| alloy 1 | 4.35 | 2.96 | 4.68 | 3.06 | - | - | - | - | - | - | - | bal. | |
| alloy 2 | (4.35) | (2.96) | (4.68) | (3.06) | - | - | - | - | - | - | - | bal. | vf 5% SiC |
| alloy 3 | - | - | - | - | 11.8 | 0.24 | 4.22 | 0.23 | 0.63 | 0.02 | 0.02 | bal. | |

which is being used for automotive components and home appliances. This alloy can be cold forged, and the material exhibits relatively high strength and good wear resistance if the appropriate heat treatment is performed in accordance with the purpose of use.[4]

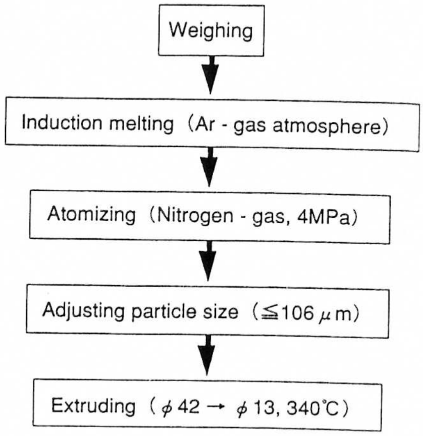
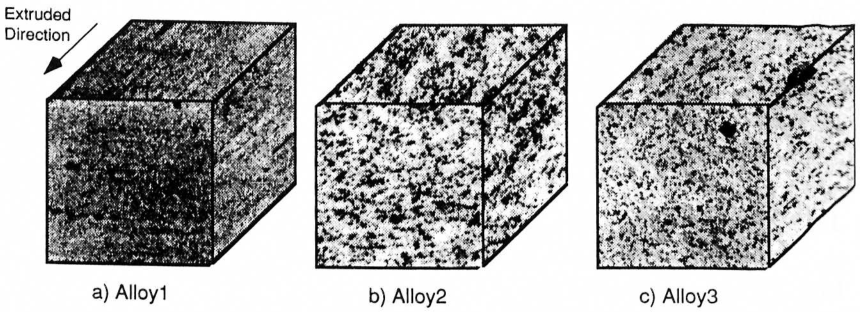


Fig. 1 Manufacturing process of the quasi-crystal alloy extruded barstock

The materials used in the experiments are all extruded barstock. Alloy 1 and Alloy 2 are made from rapidly solidified powders produced via the nitrogen-gas atomizing technique. After the particle size and composition are adjusted, the powders are charged and sealed in a container, then extruded at 340℃ to consolidate. The diameter of the powder particle is 106 μm or less, and the extrusion ratio is 10. Figure 1 shows a schematic diagram of the manufacturing process for making the quasi-crystal material. Alloy 3 is a round bar of 20 mm in diameter, formed from round barstock of 60 mm in diameter through hot extrusion at 450 ℃ (extrusion ratio: 9).



a) Alloy1 b) Alloy2 c) Alloy3

Fig. 2 Microstructures of tested materials

Figure 2 shows optical micrographs describing the microstructure of each extruded material. In Alloy 2, the added SiC particles are dispersed almost uniformly. In Alloy 3, fine eutectic silicon particles and Si-Mn-Fe intermetallic compound particles are uniformly dispersed.

Figure 3 shows transmission electron micrographs and electron-beam diffraction patterns. The major phase consists of a spherical quasi-crystal phase structure of around 100 nm in diameter, surrounded by an fcc-Al phase.

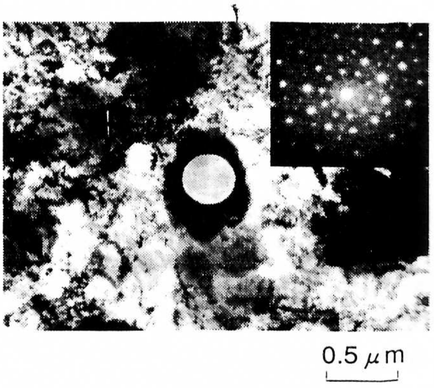


Fig. 3 TEM-image and diffraction pattern of the quasi-crystal material

Tensile testing was conducted at room temperature using specimens cut out in such a way that the tensile direction would become parallel with the direction of extrusion. The specimens were round bars consisting of a holding section provided at both ends and a measurement section of 3 mm by 21 mm in parallel portion diameter and length, respectively. The test was conducted using an Instron-type testing machine, with the initial strain rate set at $10^{-3}$/sec.

As for Alloys 1 and 2, the fatigue-test specimen stock was prepared by cutting an extruded round bar of around 13 mm in diameter to about 100 mm in length. As for Alloy 3, the extruded round bar described above was cut to a specified length, then given a solution and aging treatment (T6 treatment). After the treatment, the bar was shaped through machining into the specimen shape of Ra 1.6, in parallel-portion surface roughness.

In the case of all alloys, the fatigue-test specimen stock was directly machined into the specimen shape if it was used for fatigue testing at room temperature, while the specimen used for the testing at 150℃ was prepared by letting the stock stand for 100 hours at the test temperature, furnace-cooling it, then machining it before testing.

Using the specimens described above, rotating-beam fatigue testing was conducted and S-N curves were plotted. The tests were conducted at air atmosphere using two test-temperature levels: one at room temperature (20℃) and the other at 150℃. The stress amplitude frequency was 60 Hz. As for the fractured specimens, their fractured surfaces were observed using an optical microscope (OM) and a scanning electron microscope (SEM). For some specimens, surface analysis of elemental distribution was conducted, using a wave-diffraction-type electron probe microanalyser (WDX-EPMA).

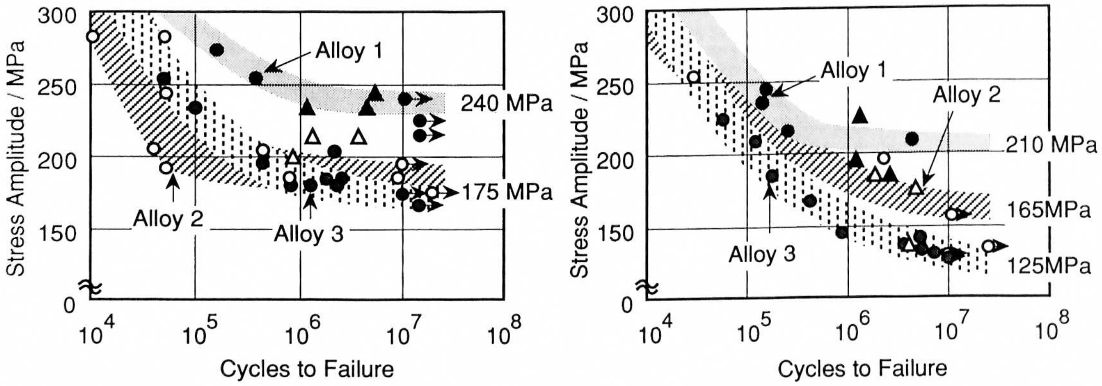
## 3. EXPERIMENTAL RESULTS

Table 2 Tensile testing results

| | $\sigma_B$ (MPa) | $\sigma_{0.2}$ (MPa) | E (GPa) | $\varepsilon$ (%) | Note |
|---|---|---|---|---|---|
| alloy 1 | 577 | 521 | 90 | 9 | |
| alloy 2 | 576 | 519 | 96 | 5 | |
| alloy 3 | 451 | 382 | 78 | 2 | Ref. (4) |

Table 2 shows the tensile testing results of respective alloys at room temperature. The values are all in the direction parallel with the direction of extrusion. The tensile strength and 0.2 percent yield strength of Alloys 1 and 2, which are both quasi-crystal alloy, are almost the same, being higher than those of the conventional Al-Si alloy (Alloy 3) by 25 percent or more. Alloy 2, to which SiC particles have been added, has an approximately 7 percent higher Young's modulus than Alloy 1, which does not contain SiC particles. This value is 20 percent higher than that of the conventional material (Alloy 3). With regard to elongation, the quasi-crystal material showed a significantly improved characteristic as compared to the conventional material.

Figure 4 shows S-N curves at respective test temperatures. At room temperature, the quasi-crystal alloy (1) exhibited a significantly high fatigue-strength value of 240 MPa measured at the number of cycles to failure of $10^7$ times (hereinafter referred to as "fatigue strength"). However, the fatigue strength of the material with SiC particles added (Alloy 2) was only 175 MPa. While the static tensile strength of the two materials was virtually the same, the fatigue strength was dramatically lower with the material to which SiC particles were added. In the case of Alloy 2, little superiority in fatigue strength was found relative to the conventional material (Alloy 3).



a) Room temperature b) 150℃

Fig. 4 Fatigue testing results - S-N curves ( ○ : Normal fracture △: Fretting fracture )

On the other hand, fatigue testing at 150℃ yielded results similar to those of the testing conducted at room temperature. That is, the nondispersion-type quasi-crystal material showed the highest fatigue strength. However, the difference between the nondispersion-type quasi-crystal alloy (Alloy 1) and the dispersion-type quasi-crystal alloy (Alloy 2) became smaller, and the fatigue strength of Alloy 2 was clearly higher than that of the conventional material (Alloy 3). Figure 5 shows a comparison by ratio of the fatigue strength at 150 ℃ to the fatigue strength at room temperature. As for quasi-crystal alloy, it is found that the drop in fatigue strength at high temperature is smaller than the drop observed in the conventional material. In particular, the drop in fatigue strength at elevated temperature is significantly smaller for the material with SiC particles added (Alloy 2).

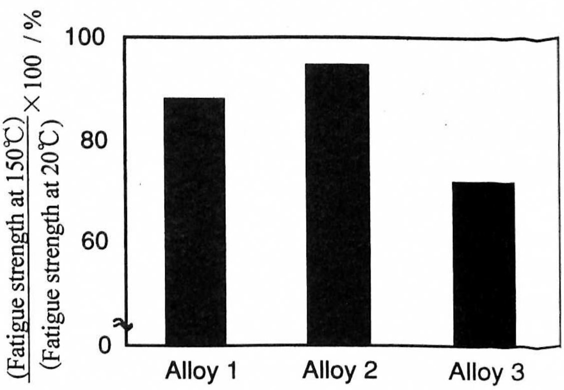


Fig. 5 Ratio of the fatigue strength at 150℃ to the fatigue strength at 20℃

During fatigue testing, fretting occurred in the holding section of the quasi-crystal material specimens, causing some specimens to fracture from the point of crack initiation. The results of these specimens were also recorded by calculating their stress amplitude using the cross-sectional area of the fractured section, then plotting the calculated values on the same S-N curve using a different symbol.

## 4. DISCUSSION

The Young's modulus for Alloy, to which SiC particles are added, is around 107 percent of that for Alloy 1, to which no SiC particle is added. When the Young's modulus for the particle-dispersion-type material is calculated based on the law of mixture, assuming that the Young's modulus for the SiC particle is 450 GPa [5], the composite material containing SiC particles by 5 percent in volume fraction should have a Young's modulus of 108 GPa. The measured value is in good agreement with this calculated value. With regard to tensile strength, no improvement in SiC particle dispersion is found. In the 7075 alloy, it is reported that tensile strength increases as volume fraction increases, reaching the maximum value at the volume fraction of 20 percent. [6]

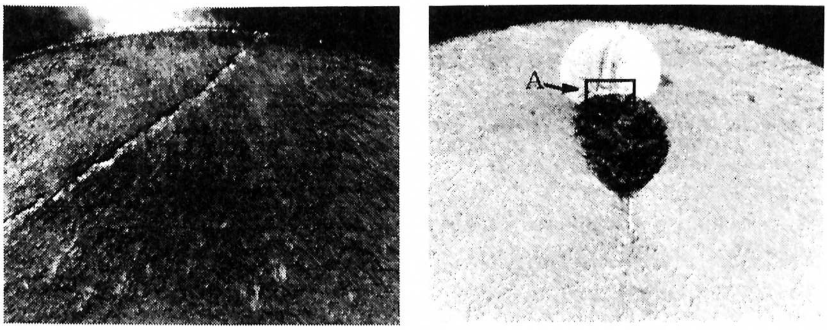
While the SiC-particle dispersion quasi-crystal material (Alloy 2) shows the same level of static tensile strength as that of the nondispersion material (Alloy 1), the fatigue strength measured by testing at room temperature was only 70 percent of the nondispersion material's value. With regard to the effect of particle dispersion on fatigue strength, no such significant drop in fatigue strength has been reported with the conventional material. When the fractured surfaces of the fatigue-test specimens of Alloy 2 were examined, it was found that most of the specimens tested at the stress amplitude of 200 MPa or less had subsurface crack-initiation points. These results are shown in Figure 6. In addition, a detailed EPMA study has found that all of the crack-initiation points on the fractured surface had segregations of SiC particles, as shown in Figure 7. The size of such SiC particle segregation on the fractured surface was around 320 to 840 μm in diameter. These observation results suggest that in Alloy 2 the segregation of SiC particles acted as an aggregate flaw, promoting the initiation of fatigue cracks. When the segregation of SiC particles is considered a penny-shaped crack, and the fracture stress amplitude of the specimen is considered the threshold stress amplitude $\Delta\sigma$ for crack propagation, the following equation holds water as the simplest linear-fracture dynamics model [7]:

$$\Delta \mathrm{Kth} = 2\Delta\sigma\sqrt{a/\pi}$$

where,

$\Delta$ Kth: the range of the threshold stress intensity factor, assuming a short crack

a : radius of the penny-shaped crack flaw


$\sigma$ a= 273MPa, Nf= 1.6×$10^5$ — a) Alloy 1 (nondispersion material)

$\sigma$ a= 185MPa, Nf= 8×$10^5$ — b) Alloy 2 (SiC-particle dispersion material)

Fig.6 A comparison of fatigue fractgraph

When a value between 160 and 420 $\mu$m is applied to this relationship as the SiC particle segregation radius "a" obtained from the observation of fatigue-fractured surfaces, and 190 MPa as the value of $\Delta\sigma$, then $\Delta$ Kth for a short crack on this quasi-crystal alloy matrix material is estimated to be in the range of 2.7 to 4.4MPa · $m^{1/2}$. It is considered that if the uniformity of SiC-particle dispersion is increased so as to prevent the formation of such segregation, the fatigue strength of Alloy 2 can be increased further.

It is considered that the ratio of fatigue strength at 150℃ to that in room temperature is higher for the quasi-crystal alloy than the conventional material, because the characteristics of the nano-size quasi-crystal phase, as shown above, remain effective in the elevated temperature region [8]:

1) Existence of a strong bonding force between Al and solute atoms

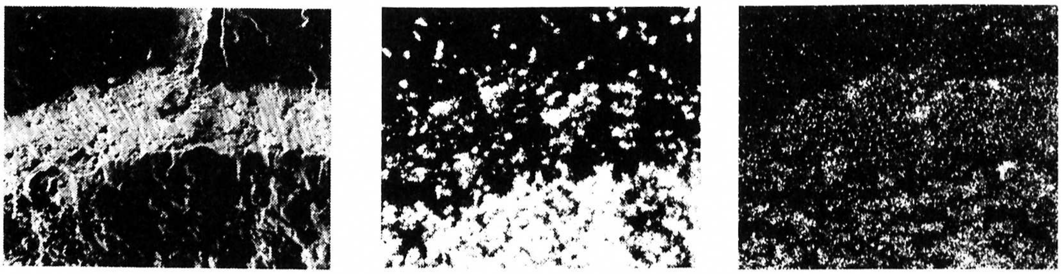

a) SEM image of "A" part in Fig. 6 b) EPMA surface analysis : Si c) EPMA surface analysis : C

Fig. 7 Segregation of SiC particles found on the fatigue-fractured surface of Alloy 2

2) Nonexistence of a slip plane in a long-range scale
3) Existence of a microvoid that causes local movement of the structural atoms
4) The short-range random arrangement of atoms that causes structural relaxation
5) Existence of Al-Al atomic pairs due to high Al content

In addition, the examination of the fractured surfaces of specimens that underwent fatigue fracturing at 150℃ has found that fractures initiated from the surface on all specimens. It is possible that surface oxidation was promoted during testing at high temperature, causing the specimens to become more susceptible to fatigue cracking.

## 5. CONCLUSIONS

The static and fatigue strength characteristics were evaluated for the extruded material made of quasi-crystal aluminum alloy with SiC-particle dispersion, which was developed to achieve both high specific strength and wear resistance, and the results were compared to those of the conventional material. As a result, the following were confirmed:

1. The static tensile strength at room temperature of the quasi-crystal aluminum alloy containing dispersed silicon carbide by 5 percent in volume fraction was around 30 percent higher than the Al-Si type conventional material containing dispersed eutectic silicon particles, while the Young's modulus was higher by 20 percent. The quasi-crystal material not containing silicon-carbide particles showed an even higher elongation level at a similar strength.

2. The fatigue strength in room temperature of the quasi-crystal alloy not containing dispersion particles was high, at around 46 percent of the yield strength, while the value was only around 34 percent for the alloy containing dispersion particles. The reason for this is assumed to be that the segregation of SiC particles acted as flaws and promoted the initiation of fatigue cracks. It is believed possible to further improve the level of fatigue strength by increasing the uniformity of particle dispersion.

3. The quasi-crystal alloy not containing dispersion particles showed a high fatigue-strength value of 210 MPa at 150℃. In addition, the fatigue strength of the particle-dispersion quasi-crystal was around 1.5 times higher than that of the conventional material at the same temperature, revealing an excellent fatigue-strength characteristic in the temperature range of up to 150℃.

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