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Low cycle thermal fatigue of aluminum alloy cylinder head in consideration of changing metrology microstructure

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Abstract

To meet several marketing demands, development of new aluminum alloys which can be used for future high-efficiency diesel engines has been widely pursued. Especially, cylinder heads (hereafter referred to as "head(s)") are used at high combustion pressure and very high temperature, which makes it difficult to achieve a structure with light weight and high rigidity. In this study, aluminum alloy A356 (Al-Si-Mg series) which is a major head material, were conducted the thermal fatigue tests. Thus, the authors focused on the changing of material characteristics (hardness and stress-strain curves as for macroscopic characteristic and microstructure as for microscopic characteristic) during the test. This paper deals with the effects of artificial aging on two aluminum alloys A356, which have been often used for engine cylinder heads. The aluminum alloys were artificially aged under several different conditions after T6 heat treatment. The alloys were tested for fatigue characteristics as thermo-mechanical fatigue failure. The microstructure was observed by TEM to see the effects on microstructure in terms of fatigue failure. In addition, we examined the microstructure of an actual head after a durability test, and tried to find out whether material test conditions above mentioned were reasonable. Finally, the relationship between the microstructure changes and the low cycle thermal fatigue is discussed.

Keywords: Aluminum Alloy, Cylinder Head, Elasto-Plastic deformation, Microstrucuture, Cyclic loading

1. Introduction

Development of highly efficient engines is critical to protect global environment, and this is much more serious for the development of diesel engines as they have been used on most trucks - the most popular means of transporting goods. Under such circumstances, aluminum alloys have been often studied and developed to achieve a highly-efficient next generation engine. As aluminum alloy cylinder heads are subjected to very high temperatures, many problems confront us, and solving these problems is considered critical in designing a cylinder head.

Cylinder heads are required to meet two essential material requirements. One is resistance to deformation, or strength, under combustion pressure and assembly loads. This is required to prevent gas leakage. The other

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requirement is toughness at high temperatures. This is required to prevent cracking in the area of a cylinder head between inlet and exhaust valves, which is exposed to flames.

The index for the former requirement is 0.2% proof stress or tensile strength, and that for the latter is elongation. Stress or strength is traded off against toughness, so we need to balance the two properties as a cylinder head material. Strength has been improved by adding metals to typical aluminum alloys [1, 2, 3, 4]. For example, Fujikawa [1] et al found that precipitation is promoted by adding Sc not only to Al-Sc alloys but also to other aluminum alloys, and both thermal resistance and toughness are improved. Hori [2] studied the effects of adding alloys to aluminum alloys on Young modulus, and his study turned out that Li is the most effective for improving Young modulus. Besides these studies, potential of composite of SiC whisker and aluminum alloys has been studied [5].

Manufacturing methods have been also developed to change the properties of a material to be suitable for purposes, and this is considered better than the development of a new alloy in terms of cost saving because it is easy to change material properties locally. Tohriyama [6] et al studied the effects on material properties of cooling speed during the time of cast aluminum alloy being solidified, and found that the material strength is improved by increasing the cooling speed. There are a few reports [7, 8, 9, 10, 11, 12, 13] on the study of heat treatment methods. Masawak i[7] studied the behavior of atomic vacancy for the aged aluminum alloy during fatigue deformation. Vankateswara [8] et al aged aluminum alloy 8090 at different temperatures for a long time, studied the changes in mechanical properties, and observed the microstructure to relate aging with the changes in microstructure. In all these studies, attention was focused on either strength or fatigue life, and few studies have been made with attention focused on both.

In theory, heat treatment conditions should be optimized for each material, considering the conditions of the material being actually used. Very few studies have been made on optimizing heat treatment conditions to improve both strength and toughness of a cylinder head considering the thermal and mechanical conditions of a running engine. The final objective of our study is to optimize not only the aluminum alloy formulation but also the heat treatment conditions.

In this paper, the authors studied the effects of artificial aging (tempering) after T6 heat treatment a typical aluminum alloys Al-Si-Mg alloy (A356) on fatigue failure. A method to evaluate low cycle thermal fatigue failure, and microstructure changes during the thermal fatigue failure was studied using the aluminum alloy for cylinder heads. First, low cycle thermal fatigue tests were performed under engine running conditions to clarify the elastic, plastic, viscoplastic deformation, and thermal fatigue failure. An efficient method to evaluate the low cycle thermal fatigue failure was developed to estimate the fatigue failure due to different temperature ranges, symmetric and asymmetric strain ranges, and cycle periods. Microstructural changes after low cycle thermal fatigue tests were observed by TEM, especially focusing on precipitates and density of dislocations. The relationship between precipitates versus aging time, symmetric strain ranges during the low cycle thermal fatigue tests are discussed.

2. Test pieces and equipment

Test pieces were made from A356 aluminum alloys, which have been generally used for automobile engine parts. These test pieces were cut away from the bottom deck of an engine cylinder head by means of gravity die casting. Dendrite Arm Spacing (DAS) is about 20~30μm and maximum porosity area is smaller than 0.25mm^2. Table 1 shows the chemical composition of the material. The test pieces are shaped in a solid cylindrical rod in a diameter of 7mm and gauge length 21mm, which are given surface treatment.

An electro-hydraulic servo fatigue tester, MTS's MTS810, was used to evaluate thermal mechanical fatigue (TMF). Strain was measured by a extensometer, MTS's model 632, 50C-05. Test pieces were heated by an induction heater, Shimada Rika's SST-20L, and cooled down by blowing air onto the test pieces.

2.1. Tem and sampling

Microstructure was observed by using TEM, Hitachi's H-800 at an electron acceleration voltage of 200 kV. Specimens were sampled in a shape of 2 mm diameter and 0.2 mm thickness from the longitudinal centre of the test piece, soaked in a 30% methanol nitrate solution, and polished by the twin-jet electrolytic method to films at 15 V, 200 mA, -30ºC. Minimum thickness around the centre of the film was approximately 0.5m.

Table 1 Chemical composition

	Cu	Si	Mg	Zn	Fe	Mn	Ni	Ti	Al
A356	0.2	7	0.3	0.3	0.5	0.3	–	0.2	others

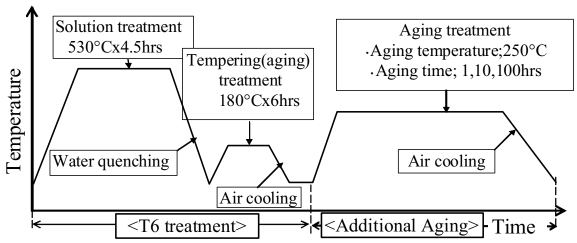


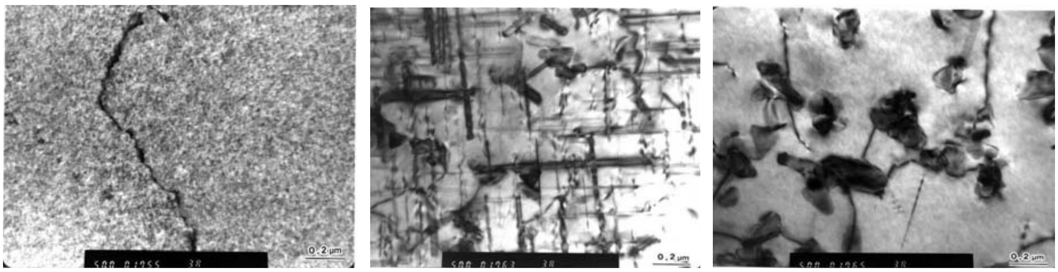
Fig. 1 Heat treatment conditions

3. Test method

3.1. Heat treatment conditions

As show in Fig.1, all T6 heat-treated test pieces were artificially aged. After T6 heat treatment with solution annealing at 530ºC for 4.5hrs quenching in water and aging 200ºC for 1hr, test pieces were treated additional aging at 250ºC for 0,1,10 and 100hrs respectively. Figures 2(a) through (c) show the TEM photos of initial microstructure before the thermal mechanical fatigue(TMF) test. Microstructure was observed in <110> direction with g vector in {111} direction.

In Fig.2(a), the microstructure of T6 in a state of theta'(semi stable) phase, and a number of tiny precipitates are



(a) T6 + 250ºC x 0-hour aging (b) T6 + 250ºC x 10-hour aging (c) T6 + 250ºC x 100-hour aging

Fig. 2 Initial microstructure of A356 aged at 250ºC for 0,10,100 hours before fatigue test

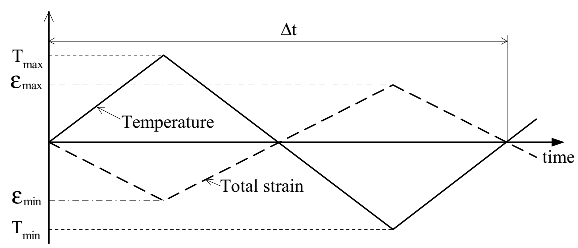


Fig. 3 Strain and Temperature versus time

found in the microstructure. In Fig.2(c), meanwhile, the number of precipitates is greatly reduced, and the precipitates are enlarged in the microstructure aged for 100 hours. As seen from the oval shape of the precipitates, the microstructure is considered to be overaged. The EDX analysis of the precipitates turned out that the composition of the precipitates is similar to that of Mg_2Si. As seen in this photo, the precipitates are widely spaced, and this enhances the mobility of dislocation, which results in the reduction in resistance to external force.

3.2. Test conditions

Table 2 shows the TMF [14] test conditions for A356. Temperature ranges from 100 to 250ºC. One cycle is 10 minutes. Total strain amplitude was set in a range between ±0.5% to ±0.8%. Fig.3 shows periodic application of thermal and mechanical load in synchronized 'inverted-phase' triangular waves with an intention of simulating the severest engine conditions; 'inverted phase' means the highest temperature at the maximum compression and the lowest at the maximum tension. First, the test piece was compressed. Amplitude of total strain (thermal and mechanical strains) Δε=(εmax-εmin)/2, temperature range ΔT=Tmax-Tmin, a cycle time Δt. Fatigue life was determined to the number of cycles when loop-end tensile stress suddenly decreases because the stress greatly differs by the influence of aging.

4. Test results and observations(Effects of aging time on fatigue life)

4.1. Relation between aging time and fatigue life

Table 2 Results of TMF test

Test No.	Strain range Δε (%)	Temperature range ΔT (° C)	Periodic time (min)	Aging Time (hr)	Aging Temp (℃)	Number of cycle to fatigue failure Nf	Time to fatigue failure Tf
1	±0.7	250～100	10	0	250	97	58200
2	±0.5	250～100	10	0	250	530	318000
3	±0.5	250～100	10	1	250	702	421200
4	±0.6	250～100	10	1	250	480	288000
5	±0.8	250～100	10	10	250	205	123000
6	±0.5	250～100	10	10	250	870	522000
7	±0.65	250～100	10	10	250	472	283200
8	±0.5	250～100	10	100	250	1700	1020000

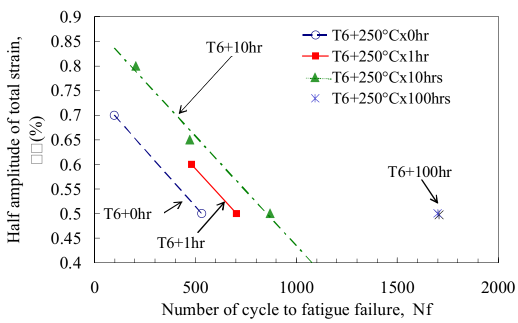


Fig.4 Total strain amplitude vs fatigue life with respect to aging times(ΔT;100-250ºC,Δt;10min)

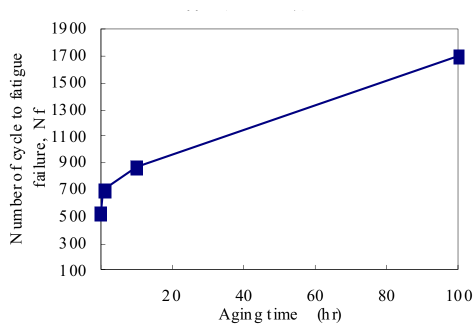


Fig.5 Fatigue life versus aging time (Δε;±0.5%,ΔT;100-250ºC,Δt;10min)

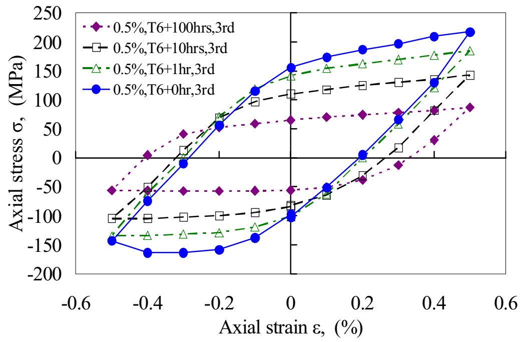


Fig.6 Comparison of stress-strain relation at 3rd cycle with respect to aging time (Δε;±0.5%,ΔT;100-250ºC, Δt;10min)

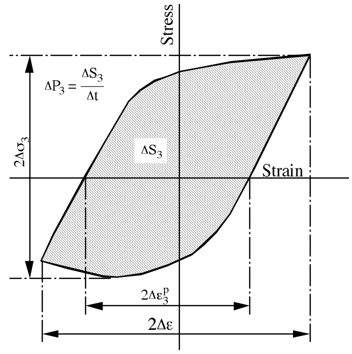


Fig.7 Plastic strain amplitude, stress amplitude and plastic work density per unit time

The results of the TMF test made under the conditions shown in Table 2. The Nf and tf in Table 2 show the number of cycles to fatigue failure. There are large differences in the Nf fatigue lives due to the strain range and aging time. The fatigue life becomes longer as the strain range becomes smaller, and it is longer as the aging time is longer. Fig. 4 shows relation between total strain amplitude and fatigue life for aging time. As aging time is longer, tempering becomes more significantly effective and the life becomes longer. This tendency can be understood by comparing Test No.1(Δε=±0.7%) with No.5(Δε=±0.8%). Naturally, the more strain amplitude is, the less fatigue life is. However, the fatigue life of No.5 is longer than that of No.1 because the aging time of No.5 from No1 is longer. These results indicate that, even with a large total strain amplitude, fatigue life is long if the material is aged for a long time. This suggests the possibility of thermal fatigue life being greatly improved by setting the aging time properly.

Results of the same test condition except aging time are compared to understand the relation of aging time to fatigue life plainly. Fig. 5 shows relation between aging time and fatigue life at a strain amplitude of Δε=±0.5%, a temperature range of ΔT=100 to 250ºC, a cycle time of Δt=10 minutes. With reference to the life without aging after T6 treatment, fatigue life is lengthened 1.6 times by the 10-hour aging, and 3.2 times by the 100-hour aging. Increasing the aging time from 10 hours to 100 hours is obviously less effective for lengthening fatigue life than aging for 10 hours.

4.2. Fatigue life evaluation method for different aging time

As explained in the previous section, fatigue life is affected by aging time. In Fig. 6, the strain-stress relations at

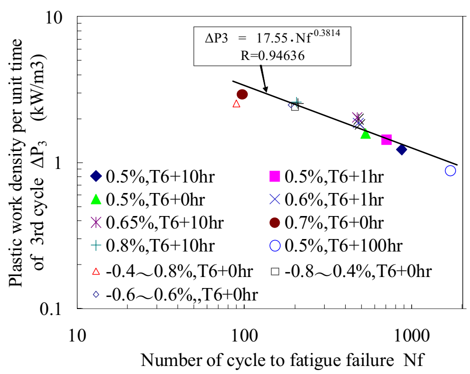


Fig.8 Plastic work density per unit time versus fatigue life

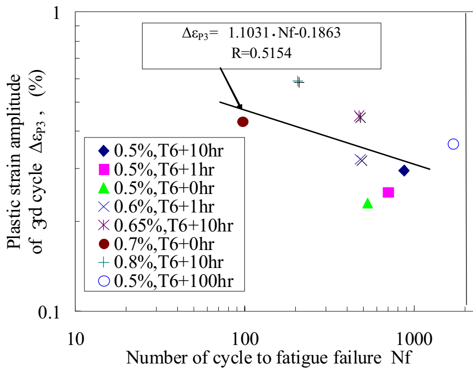


Fig.9 Plastic strain amplitude versus fatigue life

third-cycle are compared under the same conditions except aging time. Fig. 6 indicates that the relations greatly differ by the aging time. As Fig. 6 indicates that strength decreases as the material is aged longer, stress is little changed by deformation, and stress at a loop end is small. On the other hand, plastic strain amplitude becomes larger as the material is aged longer. As these results, it was clarified that aging time produces a great effect on the strain-stress loops in the TMF test.

Based on the relation between strain and stress, possibilities of estimating fatigue life were studied. Fig. 7 shows a schematic figure of plastic strain amplitude, stress amplitude and plastic strain work density per unit time [14] where $\Delta\varepsilon$ is total strain amplitude, $\Delta\varepsilon p_3$ the third-cycle plastic strain amplitude, ΔS_3 the third-cycle plastic strain energy density. Plastic strain work density per unit time ΔP_3 is expressed by using a cycle time Δt by the following equation (1):

$$\Delta P_3 = \frac{\Delta S_3}{\Delta t} \tag{1}$$

In the previous study [14], the authors reported the usefulness of plastic strain work density per unit time as an index in estimating low-cycle fatigue life for A319-T6 alloy under various test conditions of temperature amplitudes and strain amplitudes. In this study, the usefulness of the index is studied on A356 aged after T6 treatment with the aging time varied. Reasons for focusing on the third cycle are that life is estimated in a short time after starting the test, and that a great deal of calculation time can be saved in estimating life based on the results of structural analysis and TMF tests.

By using the least square method on all the test results, the following equation (2) was formulated, and the solid line in Fig.8 was obtained:

$$\Delta P_3 = 24.752 \cdot N_f^{-0.4345} \tag{2}$$

Correlation coefficient in this case is 0.946, and this supports the usefulness of plastic strain work density per unit time not only for strain amplitude, temperature amplitude, a cycle time as explained in the last report, but also for aging time.

Fig.9 shows relation between the conventional plastic strain amplitude and fatigue life. The amount of scatter in values is obviously large, and no correlation is observed. Moreover, in the case of 0.55% total strain amplitude, plastic strain amplitude becomes larger as the material is aged longer, yet fatigue life becomes longer. This tendency is obviously contradicted. As in the case of Fig.9, the following equation (3) is formulated by using the least square method:

$$\Delta \varepsilon_3^p = 1.1031 \cdot N_f^{-0.1863} \tag{3}$$

Correlation coefficient in this case is 0.515, which is much lower than the coefficient expressed by equation (2) in the case of using the plastic strain work density per unit time. So it is difficult to estimate lives for different aging times by using plastic strain amplitude.

4.3. Effects of aging time on inelastic deformation

Since the stress-strain relations at 3rd cycle shown in Fig.6 were obtained soon after the fatigue test was started, the changes of that after 4th cycle are not clarified. Sometimes gas leaks from an aluminum alloy cylinder head in an engine durability test as deformation proceeds faster than anticipated. Therefore, the loop-end stress should be continuously monitored during such a strain-controlled TMF test as our test, so that the loop-end stress does not become smaller than a criterion.

Fig.10 shows how loop-end stress amplitude changes as the fatigue test proceeds under the conditions shown in Fig. 10. The loop-end stress amplitude is defined as $2\Delta\sigma$ in Fig.10. Fig.10 indicates that the loop-end stress amplitude more gradually changes as the material is aged longer, or in other words loop-end stress amplitude more sharply changes as the aging time is shorter. Especially, in the case of 100-hour aging, the stress amplitude little changed, and the life is long. At a number of cycles more than 200, the loop-end stress amplitude for the aging times up to 10 hours little differs by the aging time. Although 100-hour aging is considered stable, strength is not

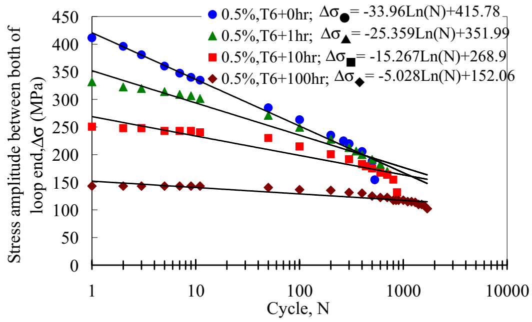


Fig.10 Loop-end stress amplitude versus cycle (Δε;±0.5%,ΔT;100-250ºC, Δt;10min)

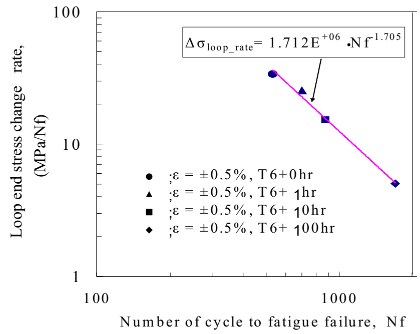


Fig.11 Rate of loop-end stress amplitude between vs fatigue life (Δε;±0.5%,ΔT;100-250ºC, Δt;10min)

sufficient enough to prevent deformation. On the other hand, 10-hour aging not only lengthens fatigue life 1.6 times as long as that without aging, but also the loop-end stress amplitude for the 10-hour aged alloy becomes nearly equal at more than 200 cycles. In summary, 10-hour aging is considered best as the aged alloy meets both fatigue life and strength requirements.

Changes of the loop-end stress amplitudes in Fig.10 are processed by the least square method, and approximates in linear equations (4) – (7) as follows, as shown in the semi-log format.

$$\Delta\sigma_{\bullet} = -33.96 \cdot Ln(N) + 415.78 \quad (4)$$

$$\Delta\sigma_{\blacktriangle} = -25.359 \cdot Ln(N) + 351.99 \quad (5)$$

$$\Delta\sigma_{\blacksquare} = -15.267 \cdot Ln(N) + 268.9 \quad (6)$$

$$\Delta\sigma_{\blacklozenge} = -5.028 \cdot Ln(N) + 152.06 \quad (7)$$

The gradient indicates the rate of loop-end stress amplitude reduction, and can be considered as an index for stress relaxation. Fig. 11 shows relation between fatigue life and loop-end stress amplitude reduction rate. This Fig. indicates significant correlation between the two, and that life is shorter as the gradient is steeper. If the aged alloy cylinder head is used on an engine, the cylinder head is considered more advantageous in strength and more rigidity to combustion pressure and bolt tighten force as aging time is shorter, but the strength will sharply drop under repeated loading, and the cylinder head may crack sooner than anticipated. This should be addressed in engineering.

4.4. Effects of aging time on microstructure at fatigue life

As mentioned above, it is clarified that aging time affects fatigue failure of A356. Then, the microscopic structures after the fatigue test with extremely different life are compared.

.Fig.12 shows the TEM photos of the aged alloys tested under the same loading conditions; Fig.12(a) without aging after T6 treatment, (b) aged for 10 hours after T6 treatment and (c) aged for 100 hours after T6 treatment. Crystal orientation and magnification are the same as those for Fig.2. As shown in Fig. 9, fatigue life for the 100-hour aged alloy is about three times as long as that for the alloy without aging. This is probably reasoned as follows: In Fig.12(a), a lot of dislocations are seen around the needle and ellipsoidal precipitates. The dislocation runs from one precipitate to another. Probably the precipitates prevent dislocation from moving, which results in resistance to deformation. Precipitates are fewer and dislocation is not so dense in Fig.12(c) than in Fig.12(a), which means little damage to the material, and probably resulted in the long life. These pictures were compared with Fig.2(a) and (c) before the fatigue test. Microstructure in Fig.2(a) was greatly changed to that in Fig.12(a). Precipitates became large

(a) T6 + 250ºC x 0-hour aging, Nf=530 (b) T6 + 250ºC x 10-hour aging, Nf=870 (c) T6+aging time 100hrs, Nf=1700

Fig.12 Microstructure of TEM after fatigue test, (Δε;±0.5%,ΔT;100-250ºC, Δt;10min)

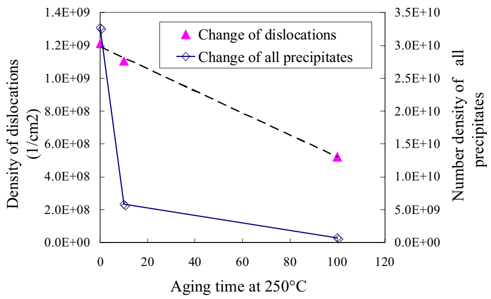


Fig.13 Both density dislocation and precipitates vs Aging time

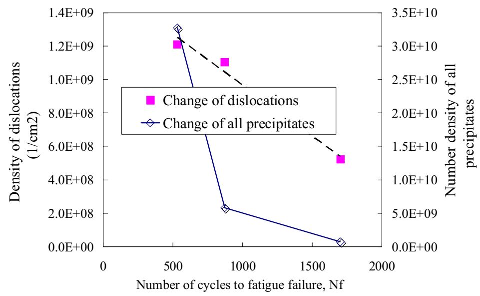


Fig.14 Both density dislocation and precipitates vs Number of cycles to fatigue failure

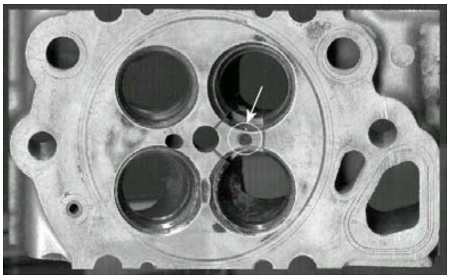
and dislocation diffused. However, there is little difference in microstructure between Fig.2(c) and Fig.12(c). Precipitates became generally small but the number of precipitates remained to be a few, and that of dislocations slightly increased. This means that the overaged alloy was already in a stable state before the fatigue test, as shown in Fig.2(c), so the number of precipitates was little changed under the thermal conditions during the fatigue test. Even if dislocations are increased by the mechanical loading, they are mobile easily because there are few precipitates as obstacles, and moved to grain boundary. So the dislocations do not remain in a grain.

Figure13 shows that the relationship between the values of change in the densities of both dislocation and precipitate and the time of the additional aging. The values of change were obtained from the comparison of the microstructure before the tests as shown in Fig.2 with that after the tests as shown in Fig. 12. It is found out that the longer aging time leads to the lower increment of the density of both dislocation and precipitate, and especially that there is the strong correlation between the dislocation density and aging time. This means that the effect of the mechanical and thermal loading is lower on the microstructures in the case of the longer aging time.

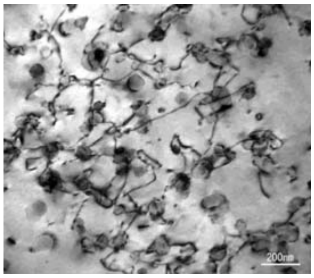
Figure 14 shows the relationship between the value of change in the densities of both dislocation and precipitate and number of cycle to fatigue failure. The aging condition, which gives lower values of change in the density of the both dislocation and precipitate, leads to larger number of cycle to fatigue failure. The reason is that the precipitate density and the dislocation density decrease due to the overaging. This phenomena also gives a conclusion that the choice the condition of heat treatment that leads to the smaller change in microstructure during the test is important to improve the proof against the fatigue failure.

4.5. Microstructure of a lower deck of cylinder head after engine durability test

As for a severest test, a cold-hot durability test is proceed to a newly diesel engine as usual. This test is a cold-hot durability test in which the engine is operated for several minutes under full load, then stopped, and the whole of



(a) A part of lower deck of cylinder head



(b) Microstructure photograph at the focus region of the lower deck after durability test (Arrow mark in Fig.15(a))

Fig.15 Photos of microstructure lower deck after engine durability test

engine is rapidly cooled by coolant. Therefore, temperature in a lower deck of a head rises rapidly and then drops sharply as the rapidly cooling takes effect, and this cycle is repeated.

Fig.15(a) shows the photograph of a part of the lower deck of a cylinder head taken from the direction of the combustion chamber. This cylinder head which had been T6-treated only is a part of a diesel engine with two valves each in the intake and exhaust systems. The weakest part of a cylinder is usually the valve bridge shown by the arrow mark. This area is often vulnerable to fatigue cracks resulting from repeated combustion force and thermal loads.

Fig.15(b) shows the microstructure of the area pointed by the arrow in Fig.15(a) at about 1200 cycle of durability test. The precipitates have grown in size and oval or spherical in shape. The dislocation density is low. This state of microstructure seems to indicate over-aging. The microstructure of Fig.15(b) is similar to between Fig.12(b) and Fig.12(c) aforementioned by the TMF. From the results, it was able to confirm that the microstructure in the lower deck of the cylinder head has changed during the cold-hot durability test for the actual engine.

5. Conclusion

In this study, the authors tried to determine the effects of aging after T6 treatment on thermal fatigue life for the aluminum alloys A356, often used for major engine parts, and studied the applicability of aging to cylinder head materials. The following conclusions are drawn:

1. Aging after T6 treatment is very effective for fatigue life. As the alloys are aged longer, and tempering is enhanced, fatigue life is lengthened. Strength, however, is reduced and the materials tend to suffer from deformation.
2. The plastic work density per unit time turned out to be useful for estimating low-cycle fatigue lives of the alloys aged for different periods of time after T6 treatment. The index is useful because it can be applied to the cases of different loading conditions, such as strain amplitude.
3. Aging time is very effective for loop-end stress amplitude change rate. The change rate can be expressed as a state of stress relaxation, and there is a significant correlation between the change rate and fatigue life. The change rate should be taken into account in selecting material and determining heat treatment conditions.
4. TEM photos revealed how precipitates interact with dislocation, and the great effects of aging on microstructure in terms of strength and fatigue life.
5. The longer aging time leads to the lower increment of the density of both dislocation and precipitates, This means that the effect of the mechanical and thermal loading is lower on the microstructures in the case of the longer aging time.
6. The choice the condition of heat treatment that leads to the smaller change in microstructure during the test is important to improve the proof against the fatigue failure.
7. Fatigue strength can be optimized by aging an aluminum alloy, to be suitable for such an engine part as a cylinder head. This method was found to have great potential of application to other engine parts.

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