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Effect of the Soft Surface Layer on Fatigue Strength of Low Temperature Aged Al-2mass%Cu Alloy

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Fatigue strength of Al-Cu alloy was examined by a repeated tensile mode when the specimens were aged and reversion annealed. The specimen quenched from 723K and aged fully around room temperature showed fatigue strength which depended on the existence of soft layer, while the specimen quenched from 723K and aged in the same way showed fatigue strength independent of the existence of the soft layer. Fatigue strength of the specimen, of which the soft surface layer was removed, was the same for either quenching temperature. Fatigue strength became higher when the soft surface layer was thickened with reversion annealing for 600s at 323K after aging. The soft surface layer was thought to increase fatigue strength of the aged Al-Cu alloy as well as Al-Zn alloy.

1. INTRODUCTION

A little softer surface layer has often been found in Al-Zn alloys when they are aged after quenching because of the difference of GP zone growth depending on the part of the specimen(1-5). Fatigue strength, which is known to be sensitive to the surface condition, was studied on the alloy when various heat treatments were given and various third elements were added, and it was revealed that the soft surface layer in the Al-Zn alloy increased fatigue strength, at least in the repeated tensile mode(6-8).

Existence of soft surface layer has also been observed in Al-Cu alloy(9). This alloy, as Al-Zn, is one of the typical age-hardenable alloys, but its low temperature age hardening is caused by plate shaped GP zones(10,11) while spherical GP zones are responsible to the age hardening in Al-Zn alloy. Relation of the precipitation microstructure in Al-Cu alloy to fatigue strength was examined by Suzuki et al. Difference in fatigue strength was found between the alloy which had a microstructure of GP zones and the one which had a microstructure of θ' phases (12).

This paper reports the effect of the formation of soft surface layer on the fatigue strength in repeated tensile mode when GP[I] zones are produced in the Al-2mass%Cu alloy during the aging around room temperature.

2. EXPERIMENTAL PROCEDURES

2.1 Specimen

Al-2.0mass%Cu (nominal composition) alloy was made by melting in atmosphere pure metals, 99.996%Al and 99.999%Cu, in a high alumina crucible. Ingot, 15mm in diameter and about 150 mm in length, was homogenized for 180ks at 753K, hot forged at 753K to a plate of 5mm in thickness. Strips of 1.1mm thick and of 0.7mm thick were made by cold rolling the plate with several intermediate annealings at 753K. Specimens for hardness test, 7mm in width and 60mm in length, were cut out from the strip of 1.1mm thick and strain annealed for coarsening the grain to about 3mm in diameter. Specimens for fatigue test, 4mm in width and 13mm in length, were cut out from the strip of 0.7mm thick and polished mechanically and electrolytically to the thickness of 0.6mm.

Quenching was done by drawing by hand the specimen which had been placed for 3.6ks in the slit between aluminum blocks maintained at a prescribed temperature (quenching temperature, T_Q) and immersing it into iced water quickly. Aging was done in an ethanol bath at an aging temperature, T_A, and reversion annealing in an silicon oil bath at a reversion temperature, T_R, both to the precision of ±0.5K.

Electrolytic polishing was given to the specimens after aging/reversion in a perchloric acid-ethanol (1:4) solution at 276K to remove surface layer, the voltage and current density being 20V and $500A/m^2$.

2.2 Hardness Test

Hardness was measured at room temperature in the same way as reported previously(1-3), with a Vickers microhardness tester for indentation loads between 0.25N and 2.9N, and with an ultra microhardness tester (Akashi MZT-1) for indentation loads below 0.10N.

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2.3 Fatigue Test

The specimens which had just been heat treated and the ones whose surface layer, 20 to 30μm, was removed after the heat treatment was attached to a fatigue tester (Shimadzu UF15) and number of cycles before the failure was measured under the repeated tensile loads at 30Hz in the stress ratio of 1.

3. Results and Discussion

Figure 1 shows variation of electric resistivity and hardness with aging time (t_A) when Al-2%Cu alloy was aged at 293K after quenching from 823K. Resistivity and hardness, both increase with t_A at first and saturate at about 30ks of t_A. Only GP[I] zones are thought to be formed in such an alloy as is aged around room temperature to the state where resistivity and hardness no longer change[10,11]. Thickness of the soft surface layer was estimated by measuring hardness in the central region of grains (apart from grain boundary) with various indentation loads. Figure 2 shows variation of hardness with load for the specimen just aged for 600ks at 293K and the ones aged in the same way and electropolished by several tens μm. Hardness of the specimen as-aged is constant at the load larger than 0.49N but becomes lower at 0.25N, which indicates that the surface layer is somewhat softer than the interior and that hardness of the interior is uniform.. Electropolishing by 10μm increases hardness at evry load but the hardness at 0.25N is still lower than that at 0.49N indicating soft surface layer remaining. Further polishing by 10μm removes the difference in hardness with load, showing absence of soft surface layer. This uniform hardness was the same as that obtained when still further electropolishing by 30μm was done. Thickness of the soft surface layer (t_h) is, therefore, considered to be larger than 10μm and smaller than 20μm. Similar results are shown in Fig.3 for T_Q = 723K but t_h in this case is 20μm or larger, a little thicker than that for T_Q = 823K.

Figure 4 shows relation of the number of stress cycles before failure (N) to the stress amplitude (σ) for the Al-2%Cu specimen heat treated in the same way as the one in Fig.2. Symbols with rightward arrow mean that the specimens did not fail at that number of cycles. σ-N curve for the specimens whose surface layer about 20μm was removed by electropolishing coincides with that for the specimens not electropolished, that is, any difference is not observed in fatigue strength between them. σ-N curve is also shown in Fig.5 in the case of lower quenching temperature, T_Q = 723K, where the t_h was thicker than 20μm.. There is observed an increase in fatigue strength of the specimens not electropolished relative to that of the specimens elctropolished but the

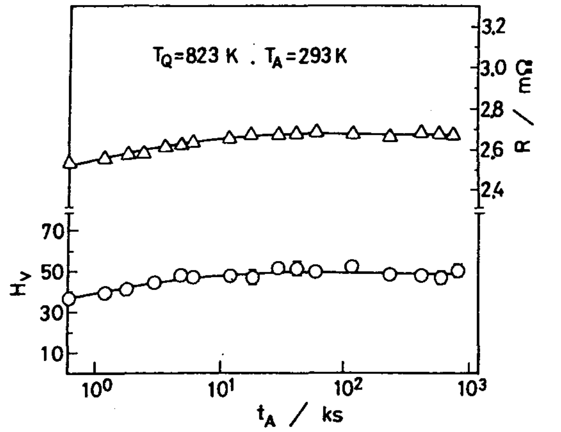

Fig.1 Isothermal curve in resistance and hardness of the Al-2mass%Cu alloy during aging at 293K after quenching from 823K.

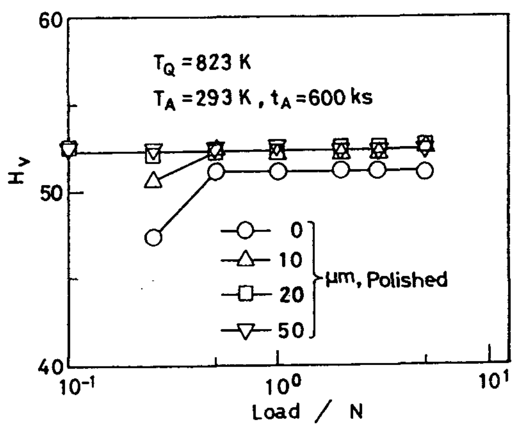

Fig.2 Variation of dependence of hardness on the indentation load when various thickness of surface layer was removed from the specimen aged for 600ks at 293K after quenching from 823K.

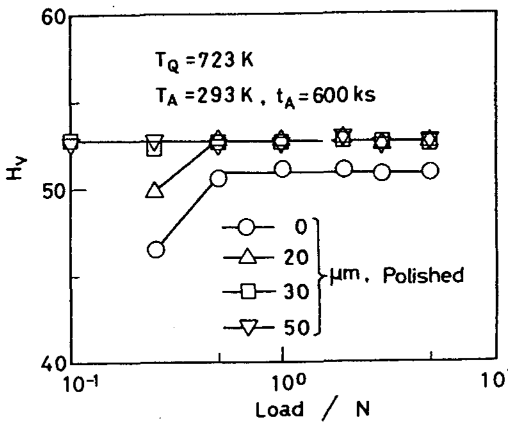

Fig.3 Variation of dependence of hardness on the indentation load when various thickness of surface layer was removed from the specimen aged for 600ks at 293K after quenching from 723K.

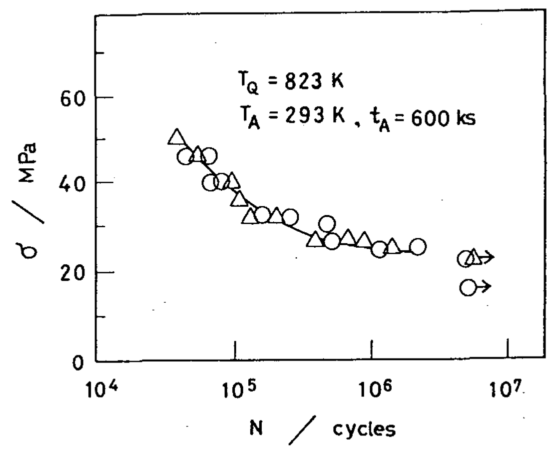

Fig.4 σ-N plot for the specimens aged for 600ks at 293K after quenching from 823K. △: surface removed, ○: surface not removed.

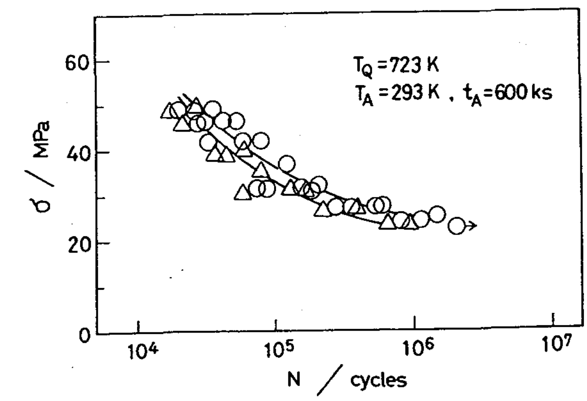

Fig.5 σ-N plot for the specimens aged for 600ks at 293K after quenching from 723K. △: surface removed, ○: surface not removed.

difference is not so distinguished as in the case of Al-Zn alloy(6-8) where t_h, more than 50μm, is remarkably thick.

Fatigue strength of the Al-Cu specimen was examined when the soft surface layer was thickened by giving reversion heat treatment after aging. Fig.6 shows change of dependence of hardness on the indentation load when isochronal annealing for 600s at every ten degrees was given to the Al-2%Cu alloy specimen aged and electropolished. Additional formation of soft surface layer is observed in the early stage of the annealing. Al-2%Cu alloy specimen was annealed for 600s at 323K after aging in the same way as in Fig.4 to form soft surface layer 40μm thick. Only the surface layer was softened and hardness of the interior remained the same, Hv = 52, as was before this reversion annealing. σ-N curve for these specimens in Fig.7 shows considerable increase in fatigue strength compared with that for the specimens as-aged.

Increase in fatigue strength with reversion might be explained, not by the increase in the soft surface layer, but by the change in the microstructure of the alloy because some GP[I] zones should be coarsened while some zones are resolved during annealing at such a low temperature as is fairly low relative to the solvus temperature of 2%Cu alloy, 393K(10). Moreover changes during repeated loading should be taken into account(13,14). To examine these effects fatigue test was carried out for the specimens whose soft surface layer, about 30μm in thickness, was largely removed by electropolishing after the same aging and annealing as in Fig.7. The σ-N curve for the specimens electropolished, in Fig.8, is clearly lower than that before electropolishing and almost coincident with the one obtained for the specimens as-aged. Similar result to Fig.8 was shown in Fig.9 for the same experiment with the specimens quenched form lower temperature, 723K. It is reasonable, therefore, to consider that the

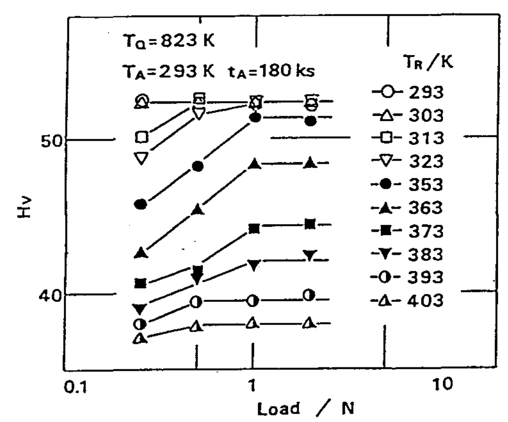

Fig.6 Variation of dependence of hardness on the indentation load during annealing isochronally the specimen aged for 180ks at 293K after quenching from 823K.

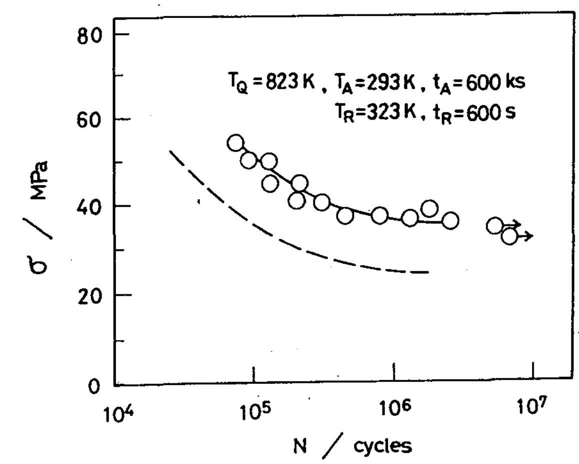

Fig.7 σ-N plot for the specimens annealed for 600s at 323K after aging in the same way as in Fig.4. Dashed curve represents σ-N plot for the specimens as-aged.

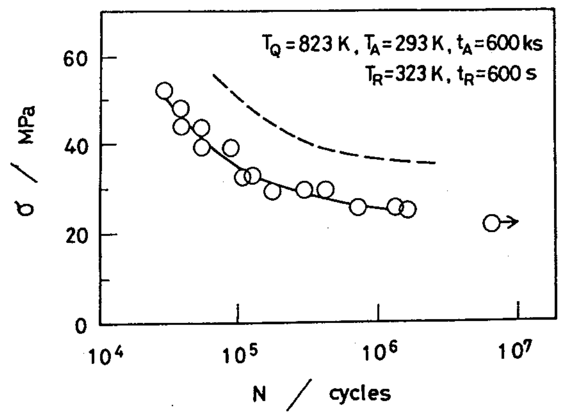

Fig.8 σ-N curve for the specimens whose surface layer about 30μm in thickness was removed by electropolishing after aging and annealing in the same way as in Fig.7. Dashed curve represents σ-N curve for the specimens not electropolished.

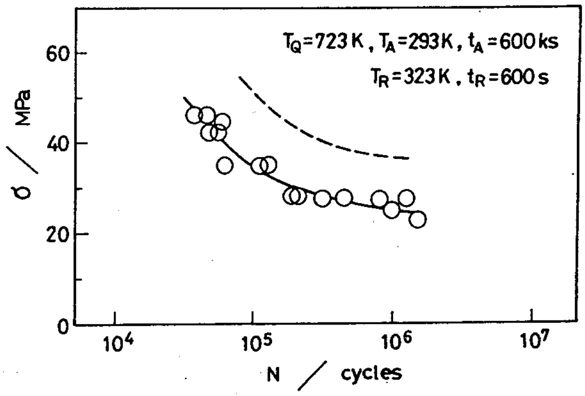

Fig.9 σ-N curve for the specimens whose surface layer about 30μm in thickness was removed by electropolishing after aging and annealing in the same way as in Fig.7 except for T_Q=723K. Dashed curve is for the specimens not electropolished.

increase in fatigue strength with reversion annealing is caused by the existence of the surface layer rather than caused by the change in microstructure.

It has been reported that the microstructure of GP zones obtained in the Al-Zn and Al-Cu alloy after full aging depends much on the quenching temperature[15,16]. However, σ-N curves for the specimens quenched from 823K and for the ones quenched from 723K, shown in Fig.8 and Fig.9 respectively, coincide well. This support the explanation that existence of soft surface layer is more responsible to the increase of fatigue strength than the GP zone microstructure.

Figures 10 and 11 shows variation of hardness with depth from the surface for the specimens before and after fatigue test. For the specimens with soft surface layer, a little hardening is observed near the surface after the fatigue test, σ = 17MPa and N = 10^5 cycles, but no hardening in the interior beyond certain depth from the surface. Even after a large number of cycles of repeated loading the surface layer remained softer than the interior. On the other hand dependence of hardness on the depth from surface, either before or after the fatigue test, was not observed at all for the specimens which was electropolished by 30μm, thus they contained no soft surface layer. Hardness near the grain boundary was also examined before and after the fatigue test and the results obtained, Figs.12 and 13, is similar to Figs.10 and 11. Hardening of the soft surface layer during repeated loading cycles, therefore, is considered to be due to the growth of GP zones promoted by vacancies generated during the plastic deformation as well as the strain hardening. Such a change as this in the soft surface layer may act as a kind of

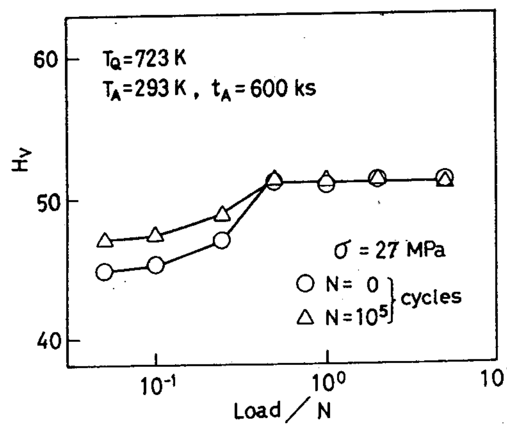

Fig.10 Dependence of hardness on the indentation load before and after fatigue test for the specimen which had been aged for 600ks at 293K after quenching from 723K, thus had a thick soft surface layer.

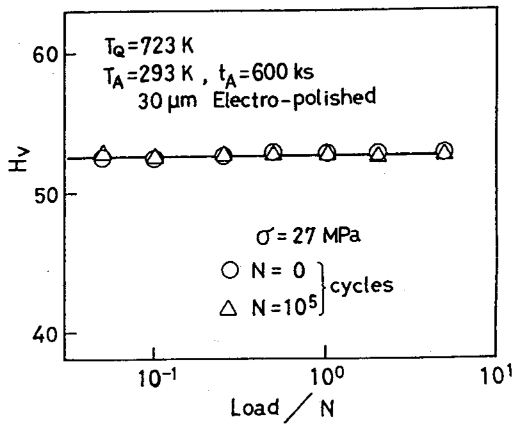

Fig.11 Dependence of hardness on the indentation load before and after fatigue test for the specimen which had been electro-polished after aging in the same way as in Fig.10, thus had no soft surface layer.

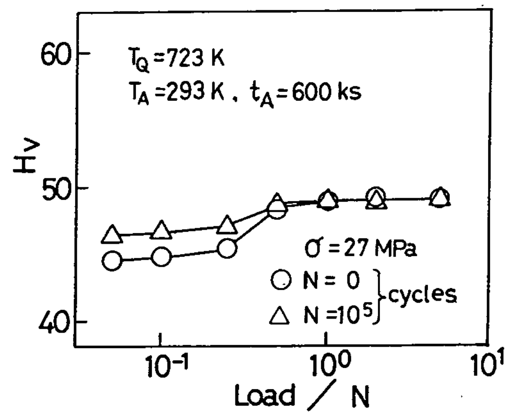

Fig.12 Dependence of hardness near the grain boundary on the indentation load before and after fatigue test for the specimen which had been aged for 600ks at 293K after quenching from 723K, thus had a thick soft surface layer.

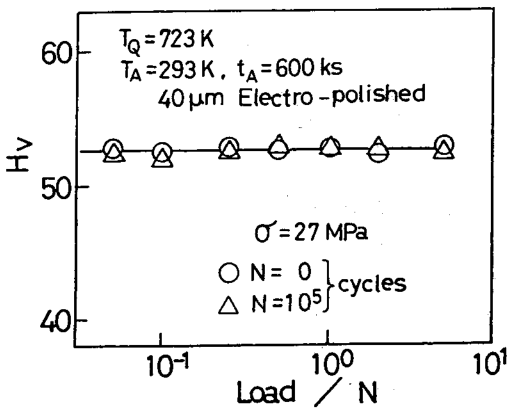

Fig.13 Dependence of hardness near the grain boundary on the indentation load before and after fatigue test for the specimen which had been electro-polished after aging in the same way as in Fig.10, thus had no soft surface layer.

buffer against the nucleation and propagation of fatigue cracks under the repeated tensile loading, but details are not clear at present.

4. CONCLUSION

Age hardening and reversion of Al-2mass%Cu alloy was studied with microhardness test and fatigue test in repeated tensile mode and the following results were obtained:
(1) Fatigue strength does not depend on the existence of soft surface layer when the specimen is quenched from 823K and aged around room temperature. When quenched from 723K and aged, where thicker soft surface layer is formed, specimens with a soft surface layer show higher fatigue strength than the ones without a soft surface layer. Fatigue strength of the specimens without a soft surface layer is identical irrespective of quenching temperature.
(2) Fatigue strength of the age-hardened specimens increases when the thickness of the soft surface layer is increased by annealing for 600s at 323K, where reversion occurs.
(3) In the Al-Cu alloy the existence of soft surface layer increases fatigue strength in repeated tensile mode as in the Al-Zn alloy.

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REFERENCES

(1) M.Ohta, H.Yamada, T.Kanadani, A.Sakakibara and M.Yamada: *J.Japan Inst. Light Metals*, 33(1983), 212.
(2) M.Ohta, T.Kanadani, A.Sakakibara, H.Yamada and M.Yamada: *Phys. Stat. Sol.(a)*, 77(1983), K49.
(3) M.Ohta, T.Kanadani, A.Sakakibara, H.Yamada and M.Yamada: *Phys. Stat. Sol.(a)*, 78(1983), K23.
(4) M.Ohta, T.Kanadani, M.Yamada and A.Sakakibara: *J.Japan Inst Metals*, 50(1986), 887.
(5) A.Sakakibara, M.Yamada and T.Kanadani: Z. Metallkde., 82(1991), 769.
(6) T.Kanadani: *Phys. Stat. Sol.(a)*, 115(1989), K147.
(7) T.Kanadani, T.Matsushima, N.Hosokawa, T.Kaneeda and A.Sakakibara: *Phys. Stat. Sol.(a)*, 124(1991), K97.
(8) T.Kanadani and A.Sakakibara: *Phys. Stat. Sol.(a)*, 141(1994), K93.
(9) A.Sakakibara, T.Kanadani, M.Yamada and M.Ohta: *J.Japan Inst. Light Metals*, 38(1988), 767.
(10) R.H.Betón and E.C.Rollason: *J.Inst. Metals*, 86(1957-58), 77.
(11) J.M.Silcock, T.J.Heal and H.K.Hardy: *J.Inst. Metals*, 82(1953-54), 239.
(12) H.Suzuki, M.Kanno, M.Tsubota, H.Hayashi: *J.Japan Inst. Light Metals*, 27(1977), 503.
(13) T.Eto, A.Sato and T.Mori: *Acta Met.*, 26(1978), 499.
(14) T.Takahashi, Y.Kojima, T.Sato and H.Ohira: *J.Japan Inst. Metals*, 44(1980), 366.
(15) T.Sato, Y.Kojima and T.Takahashi: *J.Japan Inst. Light Metals*, 28(1978), 506.
(16) M.Ohta, T.Kanadani and A.Sakakibara: *J.Japan Inst. Metals*, 47(1983), 375.