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Room temperature creep–fatigue response of selected copper alloys for high heat flux applications

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Abstract

Two copper alloys, dispersion-strengthened CuAl25 and precipitation-hardened CuCrZr, were examined under fatigue and fatigue with hold time loading conditions. Tests were carried out at room temperature and hold times were imposed at maximum tensile and maximum compressive strains. It was found that hold times could be damaging even at room temperature, well below temperatures typically associated with creep. Hold times resulted in shorter fatigue lives in the high cycle fatigue, long life regime (i.e., at low strain amplitudes) than those of materials tested under the same conditions without hold times. The influence of hold times on fatigue life in the low cycle fatigue, short life regime (i.e., at high strain amplitudes) was minimal. When hold time effects were observed, fatigue lives were reduced with hold times as short as two seconds. Appreciable stress relaxation was observed during the hold period at all applied strain levels in both tension and compression. In all cases, stresses relaxed quickly within the first few seconds of the hold period and much more gradually thereafter. The CuAl25 alloy showed a larger effect of hold time on reduction of high cycle fatigue life than did the CuCrZr alloy.

1. Introduction

Copper alloys are favored candidates for high heat flux applications in fusion reactor systems, particularly in near-term systems such as ITER (International Thermonuclear Experimental Rector) which will operate in a pulsed mode. In these applications, these alloys will experience severe thermal cycles, and fatigue damage becomes a major design issue. The fatigue life of pure copper and its alloys has been evaluated primarily using continuous cycling [1,2]. However, under normal operating conditions, there will be extended hold periods during the loading cycles which must be accounted for in component fatigue life assessment. Hold times are known to be damaging at elevated temperatures due to thermally activated deformation processes [3]. The current work shows that hold periods can be damaging even at modest temperatures, well below those typically associated with creep.

In this study, the influence of hold periods during fatigue loading was examined for the two preferred copper alloys, dispersion-strengthened (DS) CuAl25 and precipitation-hardened (PH) CuCrZr. The fatigue response with hold times was investigated at room temperature by introducing hold times at the peak strains in both the tension and compression parts of the loading cycles.

2. Experimental procedure

Two copper alloys, DS GlidCop^{TM} CuAl25 (Low Oxygen Copper Clad (LOCL)) (Cu–0.25wt%Al), and PH Outokumpu CuCrZr (Cu–0.65wt%Cr–0.10wt%Zr)

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were investigated. GlidCop™ CuAl25 (supplied by OMG Americas, formerly SCM Metals Inc.) was in the as-extruded (i.e. wrought) condition in the form of 15 and 20 mm diameter rods. This alloy has a high density (2.2×10^{22} m^{-3}) of alumina particles with an average diameter of 8.7 nm. The grain size of this alloy is <1 μm [2]. Outokumpu CuCrZr alloy (supplied by Outokumpu Oy) was solution annealed at 960 °C for 3 h in vacuum, water quenched, and prime aged (PA) at 460 °C for 3 h in vacuum, and then water quenched, and is referred to as Outokumpu CuCrZr PA. This heat treatment yielded a very high density (2.6×10^{23} m^{-3}) of very small (2.2 nm) precipitates and an average grain size of ~75 μm [4].

Subsize fatigue specimens with 3.1 mm gauge diameter and 7.0 mm gauge length were tested at room temperature in ambient air. Gauge sections of all fatigue specimens were mechanically polished longitudinally to remove surface oxidation before testing. Fatigue tests were performed on a Model 1332 Instron closed-loop servo-hydraulic test frame with constant total strain amplitude in fully reversed ($R = -1$) strain control. An MTS 3.00 mm gauge span extensometer with a full scale of 5% (Model 632.29F-20) was used to measure and control total axial strain. Fatigue tests without hold were performed with a sine waveform at a frequency of 0.5 Hz. Fatigue tests with tension and compression hold (TCH) times were carried out using a trapezoidal waveform with either a 2 or 10 s hold at the peak tension and compression strains. The strain rates during the ramping portions of the cycle in hold time tests were the same as those used in continuous fatigue tests. A check of elastic modulus was carried out before each fatigue test to ensure proper stress–strain responses of the material and testing system. Stress–strain hysteresis loops were recorded at intervals throughout the experiments. Fatigue properties were measured from stabilized hysteresis loops taken at half the fatigue life. The fatigue life, N_f was defined as the number of cycles that produced a 50% drop in the saturated tensile load or the number of cycles at specimen fracture.

The fracture surfaces of failed specimens were examined using a Hitachi S-4700 Scanning Electron Microscope (SEM) operated at 10 kV.

3. Results

Fatigue life data for GlidCop™ CuAl25 are plotted in Fig. 1. The introduction of a combined tension and compression hold at peak strains reduces the fatigue life compared to continuous cycling (i.e., without hold time). The effect of hold time is evident even with a hold period of 2 s. The fatigue life is shorter with a longer hold period, particularly at lower strain amplitudes. The magnitude of life reduction is larger in the low strain amplitude, long life regime than in the high strain amplitude, short life regime.

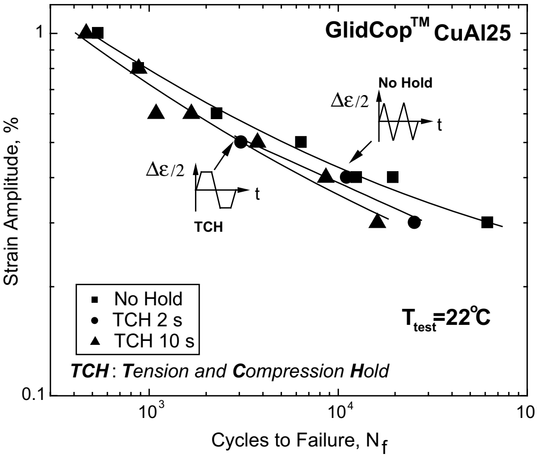

Fig. 1. Strain amplitude vs number of cycles to failure for CuAl25 without hold time and with hold time of 2 and 10 s.

Fig. 2 shows the strain-life behavior of the CuAl25 alloy with the relative contributions of the elastic and the plastic components for continuous cycling and hold time fatigue tests. The elastic strain component dominates the fatigue response for most strain amplitudes examined. The plastic strain component is significant only at higher strain amplitudes. The transition fatigue life, that is, the cycle when the elastic and plastic strain amplitudes are equal, occurs at a fatigue life of approximately 650 cycles in continuous cycling fatigue and is nearly the same for the hold time tests. The plastic strain amplitudes in hold time tests are higher over the entire strain ranges compared to those with continuous

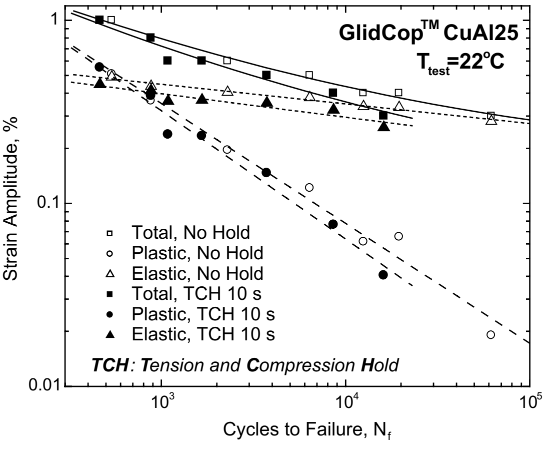

Fig. 2. Strain amplitude vs number of cycles to failure for CuAl25 with and without hold time in terms of total, plastic and elastic strain amplitudes.

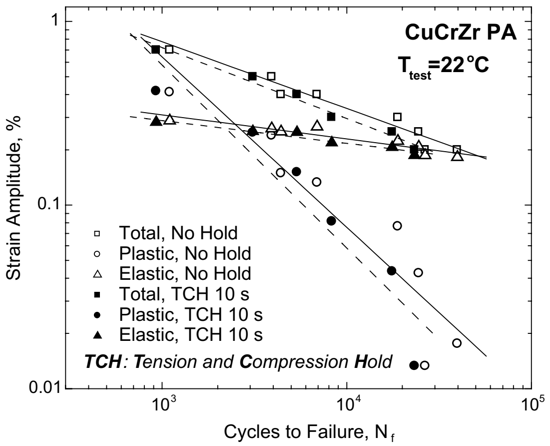

Fig. 3. Strain amplitude vs number of cycles to failure for CuCrZr with and without hold time in terms of total, plastic and elastic strain amplitudes.

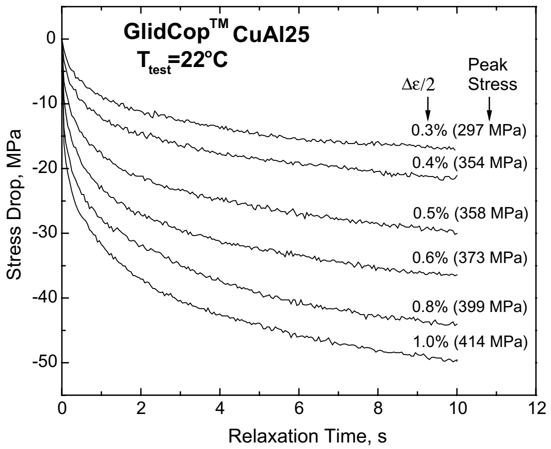

Fig. 4. Stress relaxation curves at various strain amplitudes for CuAl25 in hold time tests with a TCH of 10 s. The peak stresses are shown in parentheses for each applied strain amplitude.

cycling due to the broader hysteresis loops which result from stress relaxation at peak strains during the hold periods. The present fatigue response in continuous cycling is consistent with previous results [1,2].

The effect of hold time on the fatigue life of the CuCrZr alloy is shown in Fig. 3 in terms of total, plastic and elastic strain amplitudes. A 10 s hold period resulted in shorter fatigue lives for the CuCrZr alloy. Again, the hold effect is more prominent in the low strain amplitude, long life regime. The elastic strain component dominates the fatigue response over a wide range of the applied strain amplitudes in CuCrZr. The transition fatigue life for this alloy occurs at approximately 2000 cycles. In all cases, the plastic strain amplitudes with hold times are higher than those for continuous cycling (i.e., without hold time), again due to broader hysteresis curves resulting from stress relaxation.

Stress relaxation was observed at the peak strains in both tension and compression in the hold time tests. The stress relaxation behavior was analyzed for both alloys. Fig. 4 shows the tensile stress relaxation profiles at various strain amplitudes for CuAl25 with a TCH of 10 s. Only the tensile stress relaxation curves are presented since the stress relaxation behavior was equivalent in tension and compression. Significant stress relaxation was observed during hold even at the lowest strain amplitude. The peak tensile stress was reduced by 17 MPa, about 6% of the peak tensile stress at a strain amplitude of 0.3%. The magnitude of the stress drop increased with increasing strain amplitude. The peak stress dropped 50 MPa, a 12% drop from the maximum stress at a strain amplitude of 1%. At each strain level, the stress decreased rapidly in the first few seconds and decreased much more gradually afterwards. Similar stress relaxation behavior was observed in the CuCrZr alloy.

4. Discussion

Creep–fatigue interaction occurs most often at high temperatures with relatively long hold periods, usually longer than a minute, consistent with the known creep processes. For most structural materials, hold time effects are believed to be insignificant at room temperature [3]. In the current study, creep–fatigue damage was observed at room temperature with hold periods as short as 2 s. Hold time effects at such a low temperature with such short hold periods have not previously been reported. This form of creep–fatigue interaction behavior does not appear to be consistent with generally accepted theories of creep–fatigue interaction where secondary creep and creep-induced cavitation play a major role in the failure processes [5–7].

The experimental results clearly indicate that the application of a hold time has a detrimental effect on the fatigue life of the CuAl25 and CuCrZr alloys. The effect is particularly marked at lower strain amplitudes and longer fatigue lives. At higher strain amplitudes and shorter fatigue lives, there is little or no influence of hold times on fatigue life despite substantial stress relaxation during hold periods. The elastic strain component dominates the fatigue response in the long fatigue life regime, and the plastic strain component is significant only in the shorter fatigue life regime. The plastic strain component is always higher in the hold time fatigue tests than that in continuous fatigue tests for both alloys. The additional plastic strain in hold time tests was produced due to stress relaxation during hold periods which acts to broaden the hysteresis loops.

Prominent stress relaxation was observed during both tension and compression holds in all hold time fatigue tests on these two alloys (see Fig. 4). The stress relaxed very rapidly in the first few seconds and then the rate of stress relaxation decreased gradually during the rest of the hold period. The rate of stress relaxation follows a logarithm relation with time, which is typically found in low temperature stress relaxation tests with plastically deforming solids [8,9]. There appears to be a similarity between the stress relaxation behavior of the hold time and primary creep processes. Other studies indicate that primary creep is a prominent deformation mode for copper alloys at intermediate temperatures [10].

An increase in the length of a hold time further decreases the fatigue life, at least for the short hold times examined in this study. A substantial decrease in fatigue life takes place at a hold period of 2 s in the CuAl25 alloy. Increasing the hold period to 10 s causes further decreases in life, but the extent of additional life reduction is not as marked as in the first two seconds (Fig. 1). This suggests that the operating damage mechanism during a 10 s hold is likely to be the same as that during a 2 s hold and that a large amount of creep–fatigue damage is generated in the first few seconds when there is a marked decrease in the relaxed stress and creep strain rate.

The effect of hold time on fatigue life was observed in the copper alloys at room temperature, which is about 0.2 T_m (T_m is the melting temperature) for copper. It is generally accepted that the creep deformation is insignificant below 0.3 T_m [11], so creep damage is not normally anticipated at lower temperatures. Nevertheless a significant effect was found here. It was found that cracks initiated and propagated in a predominantly intergranular mode in hold time tests at lower strain amplitudes in the CuCrZr alloy. Fig. 5 compares the fracture surfaces of the CuCrZr alloy at a strain amplitude of 0.2% in a continuous fatigue test and in a hold time test. Intergranular cracking is clearly seen with a hold time of 10 s. When cracks grew larger than a few grain diameters, the propagation mode switched from intergranular to transgranular with clear fatigue striations. At higher strain amplitudes, cracks became increasingly transgranular even in the very early growth stage. Intergranular fracture was observed in both continuous cycling and hold time fatigue tests at lower strain amplitudes, though it appeared more prominently with hold times. This suggests that the creep effect during the hold time facilitates intergranular cracking at lower strain amplitudes. Since the hold periods are short and the temperature is low, dislocation flow mechanisms must be the major mode of deformation. Due to the bulk hardening effect, the failure process may shift from the grain interiors to the grain boundaries. In contrast, the hold time effect is insignificant in the high strain amplitudes, low cycle fatigue regimes when cracks behave in a transgranular fracture mode and grain boundaries are less involved in the fracture process. Due to the small grain size and anisotropic character of the microstructure in the CuAl25 alloy, it was not possible to identify a distinct microstructural difference between fatigue cycling with and without an applied hold time. The precise damage mechanisms associated with the hold time in both alloys requires further investigation.

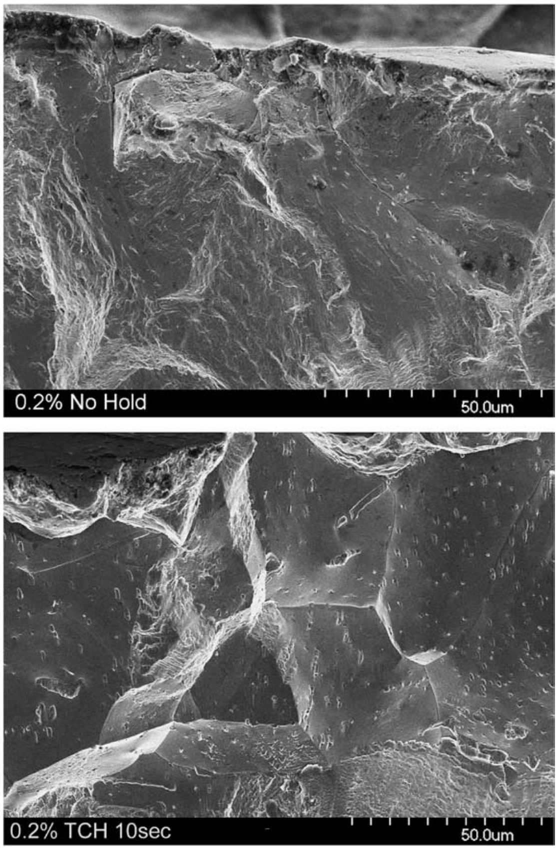

Fig. 5. SEM fractographs of fracture surfaces of CuCrZr alloy at a strain amplitude of 0.2% without hold and with a TCH for 10 s.

5. Conclusions

Fatigue tests with and without hold times were carried out on DS GlidCop^{TM} CuAl25 and PH CuCrZr PA at room temperature. The experiments showed that the introduction of a hold time at peak strains reduced the fatigue life compared to that in continuous cycling fatigue tests. The hold-time effect is evident even with hold times as short as a few seconds. The reduction of fatigue life is more severe at low strain amplitudes than that at high strain amplitudes. At a given strain amplitude, longer hold periods result in fewer cycles to failure in the CuAl25 alloy. Notable stress relaxation was observed during the hold period. The stress relaxation process is characterized by a rapid initial drop in stress in the first one or two seconds, and then a more gradually decrease, consistent with a primary creep process.

Acknowledgements

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