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Hold-time effects on the fatigue life of CuCrZr alloys for fusion applications

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Abstract

The fatigue and creep–fatigue response of copper alloys is of interest due to the cyclic thermal–mechanical loading processes a fusion first wall will experience during operation. Creep–fatigue experiments were performed on a CuCrZr alloy with an overaged heat treatment at room temperature to determine the effects on fatigue life of a 10 s hold period applied at the maximum tension and compression points in the fatigue loading cycle. The hold period produced a reduction in the number of cycles to failure. This reduction was largest at the lowest strain amplitudes and the longest fatigue lives, the region of most interest for component design. Stress relaxation was observed during the hold periods even at room temperature where thermally-activated creep processes are not expected. The large reduction in fatigue life is apparently due to a change in the crack initiation mode from transgranular with no hold period to intergranular with a hold period.

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1. Introduction

Copper and its alloys are of prime interest for high heat flux applications in near-term fusion systems such as ITER. These systems must operate in a pulsed mode to allow for plasma heating. This means that the component temperatures and mechanical loading conditions will fluctuate making fatigue a major materials failure mode. Fatigue caused by the cyclic thermal stresses is identified to be the dominant failure mode. The first wall and diverter materials, for which copper alloys are the prime candidate, will be most affected by this process. Several studies of the fatigue response of copper and copper alloys indicate that they have marginal, but acceptable fatigue endurance properties under continuous cycling conditions [1–6]. However, the most recent studies of the creep–fatigue performance, which include hold-time effects, indicate that the hold process can substantially degrade material fatigue life [7,8]. This reduction in fatigue life is found to be most apparent in the long life, high cycle fatigue regime where cyclic failure lives can be reduced by a factor of more than three. It is also found that the reduction in fatigue life requires only a short hold period of 10 s or less, much shorter than the anticipated on/off cycles in ITER of 1000 s/100 s.

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An analysis of the fatigue loading performance with hold-times also indicates that copper and its alloys show a large, up to 15%, relaxation in stress during the hold period at constant applied strain amplitude at room temperature. This temperature, $0.22T_m$, is well below temperatures typically associated with thermally-induced creep and stress relaxation. This study examines the underlying microstructural aspects that control both the stress relaxation process and the changes in fatigue crack initiation and early growth. This information is critical for assessing the impact of cyclic loading with extended hold periods on fatigue failure modes.

2. Experimental procedures

The material used in the present investigations was a precipitation hardened copper alloy, CuCrZr. The alloy was supplied by Outokumpu (Finland) with a composition of Cu–0.73% Cr–0.14% Zr. The alloy was examined in three heat treatment conditions – prime aged (PA): solution annealed at 1233 K for 3 h, water quenched and then heat treated at 733 K for 3 h; heat treatment 1 (HT1): prime aged plus an additional anneal in vacuum at 873 K for 1 h and water quenched; and heat treatment 2 (HT2): same as HT1, but aging for 4 h rather that 1 h. Details of the resulting microstructures are given elsewhere [9]. Of these three heat treatment conditions, HT2 was found to have the most sensitive response to hold-time during creep–fatigue loading. Thus, this study concentrated on the CuCrZr alloy HT2 condition.

Fatigue and creep–fatigue tests were carried out on cylindrical specimens and several interrupted tests were performed on rectangular specimens [8]. Fatigue loading was done at room temperature in strain control mode. The flat specimens were fine polished with 0.02 μm alumina oxide and the specimen surfaces were examined using optical microscopy to monitor the crack initiation and early growth during the interrupted tests.

3. Results

The results of the strain controlled tests on CuCrZr HT2 at room temperature are shown in Fig. 1 in terms of total, elastic and plastic strain amplitudes with and without 10 s hold periods; TCH stands for tension and compression hold. The tests were performed at 0.2%, 0.3% and 0.4% total strain amplitudes. These curves indicate that the inclusion of a hold period in maximum tension and compression of 10 s results in lower creep–fatigue cyclic lives especially for the specimens tested at lower strain amplitudes. In the case of the 0.2% strain amplitude, the fatigue life is reduced by approximately 15 000 cycles due to the application of a periodic hold period of 10 s, while this reduction in cyclic life decreased to only 2000 cycles at 0.4% strain amplitudes. The fatigue test with hold-time strain always had the larger plastic strain amplitude than that without hold-time. It should be noted that the transition life, the point where the elastic and plastic portions of the total strain are equivalent, is about 16 000 cycles for the HT2 condition. This result is consistent with the fact that the material, following overaging, has lower strength [9].

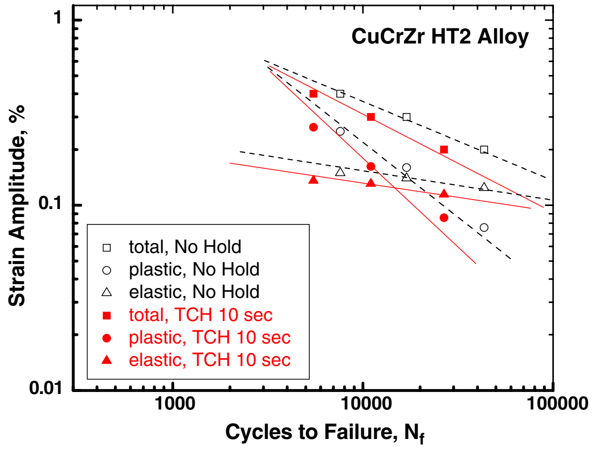

Fig. 1. Strain amplitude versus fatigue life for CuCrZr HT2 with and without 10 s hold in terms of total, plastic and elastic strain amplitudes.

Fig. 2 shows the cyclic stress responses of the CuCrZr HT2 alloy for pure fatigue and hold period tests. In the early fatigue stage, the CuCrZr HT2 alloy shows slight initial cyclic hardening, followed by softening until reaching a plateau in the stress responses. The saturated cyclic condition is reached earlier at higher strain levels than at lower strain levels, while the saturated stress regime is longer at low strain levels. For the materials tested at the same strain level, the saturated stress is nearly the same with and without hold-time. The difference is the number of cycles at which the stress levels drop drastically signaling failure. The stress drop occurs earlier in the hold-time tests than for no hold tests.

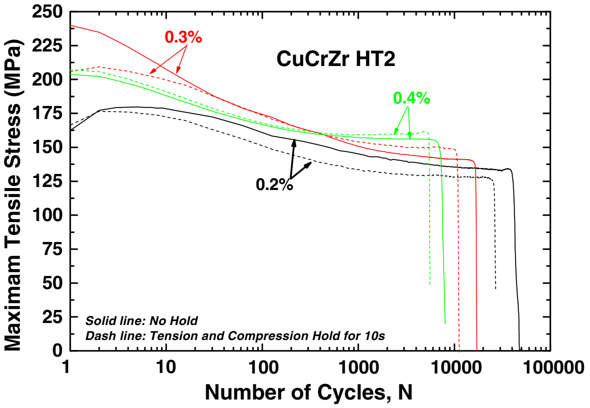

Fig. 2. *S–N* curves for CuCrZr HT2 with and without 10 s hold tested at different strain amplitudes; fatigue life is plotted with log scale.

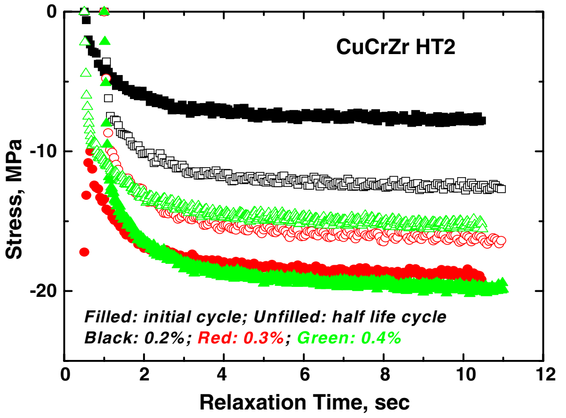

Fig. 4. The stress versus time for the hold period at maximum tension for the initial loading cycle and for a typical cycle at half-life.

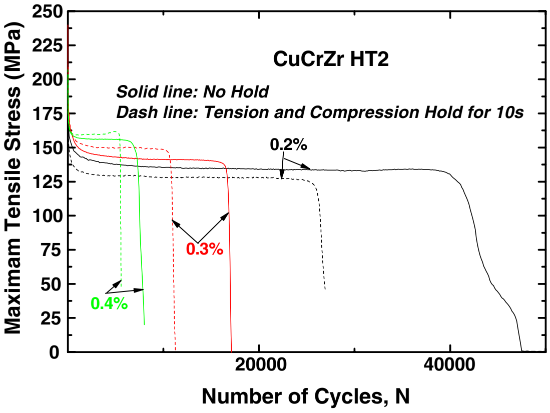

Fig. 3. *S–N* curves for CuCrZr HT2 with and without 10 s hold tested at different strain amplitudes; fatigue life is plotted with linear scale.

The data in Fig. 2 are replotted in Fig. 3 using a linear scale for fatigue life axis to provide a better demonstration of the extent of the saturated stress regime. It is evident that CuCrZr HT2 experiences an extended stress plateau following the initial sharp softening in the early stages of fatigue. For all tests, the stable stress plateau persists for a very large fraction of the fatigue life, followed by an abrupt drop signaling the onset of main crack advance. The time dependences of the stress relaxation during holds at constant strain are shown in Fig. 4. The fast drop in stress with time is notable as is the tendency for all of the relaxation curves to converge at half-life.

In addition to the regular creep–fatigue tests to failure, a number of 'interrupted' creep–fatigue tests were performed. These tests were carried out in strain control mode with strain amplitude of 0.2% and with a tension and compression hold-time of 10 s. The test without hold-time was interrupted at 10000; 20000; 30000 and 42000 cycles, and the test with 10 s hold periods was interrupted at 10000; 20000 and 27000 cycles, The last number of cycles of both tests coincided with a drop in applied stress and main crack formation and extension. At the prescribed number of cycles, the specimen was unloaded for the microstructural examination. Due to the uncertainty of the locations of crack initiation, the entire gage area was photographed so that the origins of the crack initiation site could be pinpointed. Fig. 5 shows the crack evolution in the pure fatigue specimen from 20000 to 42000 cycles. It can be noted that the crack initiates from one of many persistent slip bands (PSBs), and the crack is oriented to the direction of a maximum shear angle. Fig. 6 shows a similar series of views for the hold-time test specimen between 10000 and 27000 cycles. The microstructure indicates that, in the case of the hold period, the main cracks initiated from grain boundaries. Microstructural analysis indicates that cracks initiate at several grain boundaries at a variety of locations, some of which eventually coalesce to form the main crack. It should also be noted that grain boundary triple points seem to provide the predominant point of crack initiation. The different arrangements of slip bands on the opposite sides of the crack indicate that the crack initiates from the grain boundary. Fig. 6 shows the evolution of the crack initiation from AB to C to DE.

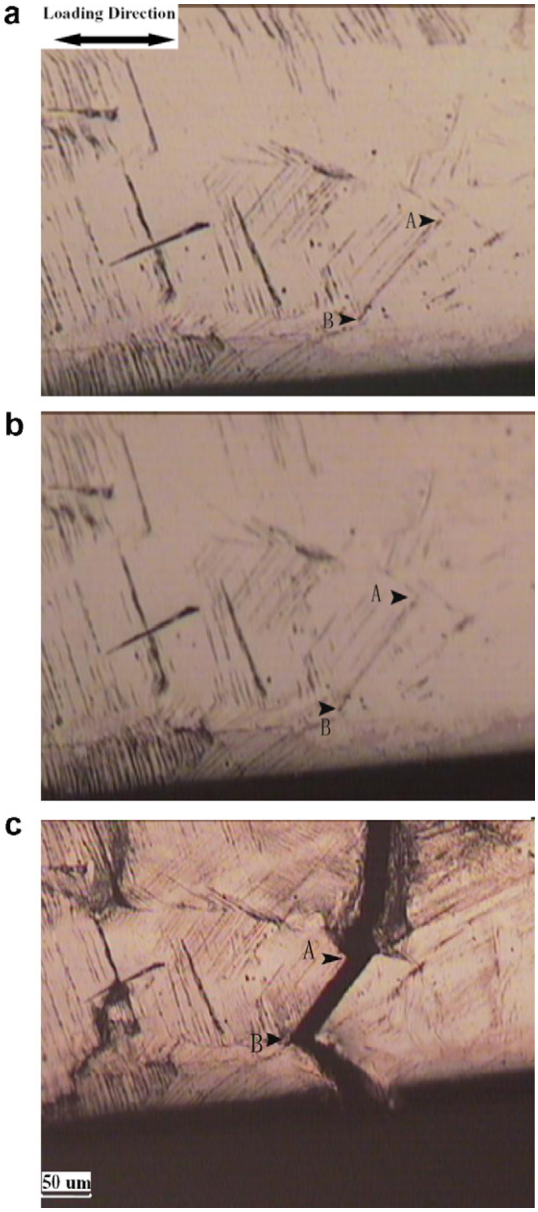

Fig. 5. Crack initiation and progression in pure fatigue (i.e. without hold-time) tests carried out with strain amplitude of 0.2%; crack developments are shown for: (a) 20 000, (b) 30 000 and (c) 42 000 cycles; the marks A and B indicate the crack evolution.

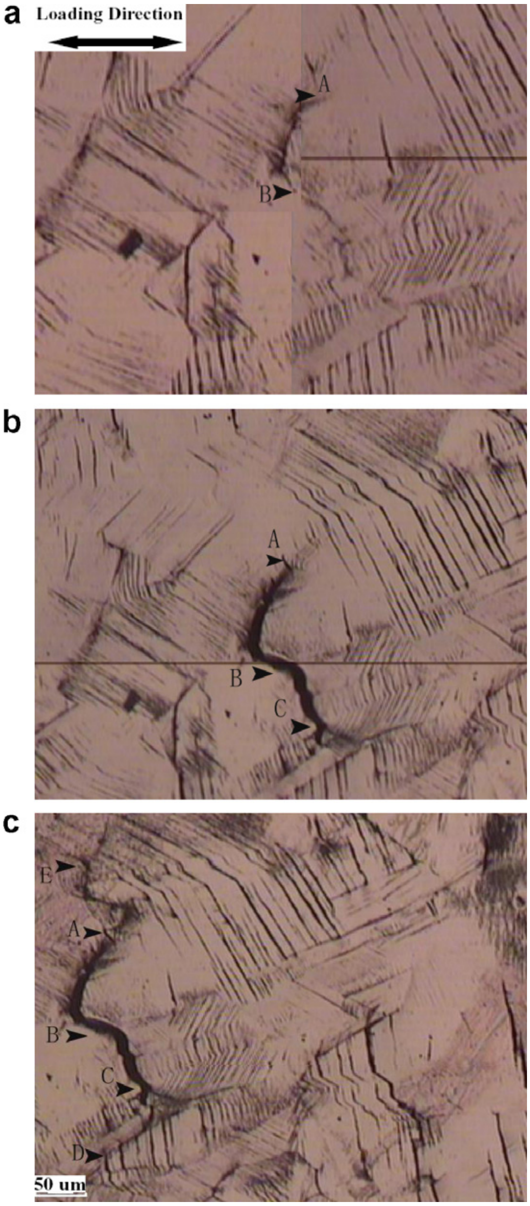

Fig. 6. Crack initiation and progression during creep–fatigue tests carried out with strain amplitude of 0.2% and with a tension and compression hold-time of 10 s; crack developments are shown for: (a) 10 000, (b) 20 000 and (c) 27 000 cycles; the marks A and B to C to D and E indicate the crack evolution.

4. Discussion

It is generally accepted that, for most structure materials, creep–fatigue interaction usually occurs at elevated temperatures, typically above $0.3T_m$, and hold-time effects are insignificant for materials tested at low temperatures [10]. However, in this study, a major effect of hold-time on fatigue life was observed for CuCrZr alloy with HT2 heat treatment at room temperature, about $0.2T_m$. The materials tested with a 10 s hold suffer a serious reduction of fatigue life, especially at lower strain amplitudes, e.g. 0.2%. This means that the hold-time effect is particularly acute for lower strain amplitudes, and it has smaller impact when the material is deformed at higher strain amplitudes. It should be noted that hold periods result in higher plastic strain amplitudes as would be expected from the stress relaxation response, see Fig. 1. Stress relaxation during hold periods broadens the hysteresis loops indicating that stress relaxation at the maximum tension and compression points with hold periods has a major effect on the plastic deformation processes. This is examined in greater detail elsewhere [7].

The stability of the stress–strain hysteresis during fatigue cycling indicates that a stable microstructure develops during the loading history. Figs. 2 and 3 show an initial hardening followed by a steady softening behavior through cyclic life with a plateau in stress amplitude towards the end of life. The stable hysteresis response is seen for most of the life, see Fig. 3, and is nearly the same stress level regardless of hold period. The major difference in the fatigue hysteresis response is the point of departure from the stable stress level which marks the end of the fatigue life due to the evolution of a major crack. Thus, the formation of the critical crack seems to be the major difference between the pure fatigue and fatigue with hold period response.

It is noteworthy that the biggest effects of hold period are observed in the lowest strain ranges or the longest lives, exactly the conditions of most design interest. The mechanism which causes the hold-time effect is believed to be the different patterns of crack initiation for loading conditions with and without hold-time. Comparing Fig. 5 with Fig. 6, it is evident that cracks initiated and propagated in a predominantly intergranular mode in tests with hold-time. It is further interesting to note in Fig. 5, that the PSBs initiation results in a sharp initial crack which then grows in a much more plastic mode. Blunting can be seen through the rounding of the crack propagation surfaces both above and below the initiating PSBs in this case. The difference between crack initiation modes in tests with and without hold periods suggests that the creep effect during the hold-time promotes the grain boundary damage. This is most apparent at low strain ranges where the time to crack initiation dominates the fatigue life. Thus changes in crack initiation mode, from transgranular to intergranular, can have a major effect on fatigue life. At higher strain ranges, where crack initiation occurs quickly and is a small fraction of the total fatigue life, this effect is minimalized and has a much less apparent effect on fatigue life.

Earlier reports of the hold-time fatigue effect in copper alloys [7] indicate that, in strain controlled tests, the stress relaxes very quickly during the hold period, consistent with the behavior shown in Fig. 4. Most of the stress relaxation occurs in the first few seconds of the hold period, so for a 10 s hold, the level of relaxation is more than 90% of the total relaxation if the hold period were extended to very long times. In fact, other recent work [8] indicates that the influence of hold periods on the reduction of fatigue life is nearly the same for hold periods ranging from 2 s to 1000 s in this material. The fast stress relaxation is associated with a primary creep process, which is found even at moderate temperatures in copper and copper alloys. The results here indicate that this process results in grain deformation modes that concentrate the stress, and thus the damage, at grain boundaries, as opposed to the development of PSBs as the primary damage mechanism. The grain boundary damage seems to be most prominent at triple points, from which most of the cracks initiate and grow.

5. Conclusions

This paper describes the main findings of the study of the room temperature creep–fatigue interaction behavior of a precipitation hardened CuCrZr alloy in the overaged condition (HT2). In the present work, the creep–fatigue interaction was simulated by applying a certain hold-time on both tension and compression sides of the cyclic loading procedure. The tests at lower strain amplitude were interrupted to examine the microstructure evolution and crack initiation.

On the basis of the results reported here, the following conclusions can be drawn:

1. The inclusion of a hold period in tension and compression significantly reduced the fatigue life compared to the continuous cycling fatigue without hold period.
2. The reduction of fatigue life due to hold-time effect is particularly noticeable for the low strain amplitudes and long fatigue lives.
3. The materials experience a very brief stress hardening followed by a brief softening and finally reach a stress plateau during their fatigue lives.
4. The hold-time effect is believed to be due to the creep-induced grain boundary cracks initiation. The crack initiation mechanisms are different for the materials tested with and without hold-

time where cracks for non-hold tests initiate from persistent slip band, while crack for hold-time tests initiate at grain boundaries, the latter mode reducing the fatigue life.

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