Characterization of fatigue failed aged Cu-Ni-Si alloys

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Abstract. The precipitation hardenable and non-toxic Cu-Ni-Si alloys are good alternatives to Cu-Be and Cu-Co-Ni-Be alloys due to their high strength and high conductivity that can be attained by not only alloying but also thermo-mechanical routes. In this study, the fractographic analysis was carried out to understand the fatigue failure of aged 2.55Ni-0.55Si-0.25Zr-0.25Cr (wt-%) alloy which is a member of Corson family. In fatigue tests, a constant amplitude loading was applied at a stress ratio ($R = \sigma_{\min}/\sigma_{\max}$) of -1 and different stress levels (400, 350, 200 and 175 MPa) were used. The fracture response of the alloy was discussed depending on the applied stress levels and microstructural features. It was concluded that (i) Ni,Zr-rich precipitates and Cr-rich precipitates at the grain boundaries caused crack nucleation at all stress levels and (ii) the interaction between Ni-rich silicides and dislocations at lower stress level resulted in localized shearing and fine striations.

1 Introduction

In electrical, railway and molding industry, age hardenable Cu-Ni-Si alloys are widely used due to their high strength and moderate conductivity [1, 2]. In order to develop their properties, not only the Ni/Si ratio but also thermo-mechanical routes are important factors. Several reports suggest that the addition of elements like Co, Zr, Cr, Ti, V, Al, Mg [3-7] and thermo-mechanical routes [8, 9] enhance the properties further and make modified Cu-Ni-Si alloys good alternative materials to Cu-Be and Cu-Co-Ni-Be alloys that have high toxicity. The enhancement of properties can be attributed to both the formation of nano-sized δ -Ni₂Si precipitates and their interaction with the dislocations within α -Cu matrix. However, several silicides that exist in the microstructure due to alloying may affect the performance under cycling loading [10]. In this study, it is aimed to introduce the effect of microstructural features on the fatigue fracture morphology of an aged Cu-Ni-Si alloy modified with the addition of both Zr and Cr.

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2 Experimental study

In this study, 2.55Ni-0.55Si-0.25Zr-0.25Cr (wt-%) alloy was initially produced as billet material. The solidified bulk material was hot forged at 880 °C and then cooled in air. A conventional heat treatment was applied to the alloy by solid solution annealing at 900°C for 60 min., followed by quenching in water and then aging at 490 °C for 180 min. The aged structure having primary Ni and Zr-rich, Cr-rich and δ-Ni₂Si precipitates is given in Figure 1. The hardness, yield strength and tensile strength values were measured as 215 HV, 520 MPa and 745 MPa, respectively.

Fig. 1. SEM micrograph showing several precipitates within the aged matrix.
Etching reagent : 50 ml HCl + 10 ml HNO₃ + 10 g FeCl₃ + 100 ml H₂O.

As similar to our previous investigation on fatigue behaviour of cast and forged alloy (153 HV) having the same composition [10], the aged one was also tested according to ISO 1099 standard. Prior to loading, the specimens were polished to mirror like finish in order to avoid any surface effect on the fatigue behavior of the material under investigation. For the fatigue tests, a servo-hydraulic machine was used, having a maximum capacity of 250 kN. A constant amplitude loading was applied at a stress ratio ($R = \sigma_{min}/\sigma_{max}$) of -1, while the frequency of the tests was set to 20 Hz. The fracture surfaces were microscopically investigated to specify the fracture morphology depending on the applied stress, ranging between 175 – 400 MPa. The data obtained from the fatigue tests were used to obtain the fatigue strength as shown in Figure 2. Cast and forged alloy displayed a fatigue limit of 179 MPa whereas the aged one had a fatigue limit slightly above 150 MPa. The main reason for the decrease in fatigue limit may be explained by lower work hardening capability of the aged alloy under cyclic loading. The scatter in the data can be attributed to several reasons but mainly to the surface quality of the samples.

Fig. 2. Stress versus number of cycles to failure for the studied alloys.

3 Results and discussion

A general view of the failed alloy (9762 cycle) tested at 400 MPa is given in Figure 3a showing its planar fracture surface that is perpendicular to stress axis. The region indicating the crack initiation is marked by arrow in Figure 3b and the fracture characteristic within this region is completely typical decohesion throughout the grain boundaries in stage I of fatigue. In this region, it was also observed that cracks propagated throughout the heterogeneously-precipitated silicides shown by arrows in Figure 3c. The cross-section of failed surface was also characterized and metallographic images clarified that the several macro cracks formed at lateral direction and the interfaces of metal silicide-matrix led the crack propagation shown by arrow under cyclic loading (Figure 4a). Effect of surface scratches on crack propagation can also be seen clearly in the SEM image given in Figure 4b.

Fig. 3. SEM fractographs showing a general view of failed alloy (a), crack initiation zone (b), decohesion throughout the grain boundaries due to silicides (c). σ : 400 MPa.

Fig. 4. Several macro cracks in the cross-section of failed alloy (a), crack propagation throughout the scratches (b). σ : 400 MPa.

A new cracking path formed due to detachment of hard primary silicides (Ni_2SiZr) is shown by arrow in the SEM image given in Figure 5a. Slip bands start to develop in different planes close to the crack tip and striations start to form in stage II of fatigue and after crack initiation, fatigue cracks propagate. Figure 5b shows intermittent striations and as can be seen cracks propagated not only throughout the boundaries/interfaces of matrix-silicide but also throughout the striations far away from crack initiation zone. The fracture surface includes very fine dimples in final fracture zone where local plastic flow is arrested by very fine precipitates (Figure 5c).

Fig. 5. SEM images showing new crack path due to hard silicides (a), crack propagation throughout the intermittent striations (b) and arrested local plastic flows due to fine silicides (c). σ : 400 MPa.

The alloy tested at 300 MPa revealed a dendritic morphology as shown in Figure 6a and it had higher N_f value (10483 cycle) which can be attributed to the plastic deformation capability of its matrix. Twins which are responsible for crack propagation path in α -Cu matrix are shown in Figure 6b. Not only very fine dimples but also localized shearing was observed in total fracture surface (Figure 6c). Theories suggest that fatigue to failure progresses by (i) the interactions between dislocation-dislocation (pile-ups), (ii) the interactions (looping or cutting) between dislocations-precipitates, (iii) accumulation of local stress around the precipitates/boundaries, and all these simultaneously compete and contribute to local hardening due to enhancement of dislocation density or failure of the matrix due to the increase in number of microcrack zones.

Fig. 6. SEM fractographs showing a dendritic fracture morphology in failed alloy tested at 300 MPa (a), crack propagation throughout the twins in the stage I (b), very fine slip bands (c).

The fracture surface of the alloy tested at 200 MPa and failed at 52073 cycle exhibited a different feature compared to those tested at higher stress levels, although its fracture surface exhibited typical zones i.e crack initiation zone, crack propagation zone and final fracture zone. A grid pattern crossing the entire grain from grain boundary to the opposite one and propagating from neighboring grains or twins was observed (Figure 7a). At higher magnification of the patterns, it was observed that these bands were free of precipitates, and these precipitate-free bands could be defined as intensive slip bands, not deformation twins, in which cracks possibly nucleated and propagated during the further stage of fatigue (Figure 7c).

Fig. 7. SEM fractographs showing a grid pattern in failed alloy tested at 200 MPa (a), higher magnification image of patterns (b), crack nucleation and propagation throughout the intensive bands (c).

At the lowest stress level (175 MPa) adopted in the study highest N_f value was recorded (62000 cycle). Although general fracture morphology of the alloy exhibited planar regions indicating no plastic deformation, the dominant macro failure morphology was interdendritic fracture. A “ladder-like structure” was observed in its crack initiation zone shown by a circle in Figure 8a and also inside persistent slip bands, which are much localized and carry most of the plastic deformation in a crystal under continued cyclic deformation. This ladder-like structure was seen on the cross-section of the failed alloy (Figure 9a and b) as well. Among the all tested alloys, a large area of the fracture surface was covered by very fine striations in fatigue crack growth and propagation zone proving the highest fatigue limit value (Figure 8b). As similar to our previous observation cited in ref. 10, the fracture surface had a mixed fracture of dimple and transgranular ruptures in its final fracture region.

Fig. 8. SEM fractographs showing a general view of failed alloy tested at 175 MPa (a), very fine striations in fatigue crack growth and propagation zone (b), mixed fracture in final fracture zone (c).

Fig. 9. Images showing the cracking path by dashed line in the cross-section of failed alloy tested at 175 MPa (a), a “ladder-like structure” shown by arrow (b).

4 Conclusions

This study is an extension of our previous report [10] focusing on the fatigue response of a Zr and Cr modified Cu-Ni-Si alloy tested at different stress levels. In the present study, the alloy was subjected to a conventional heat treatment and exhibited higher mechanical properties compared to its cast and forged condition. Enhancement of the mechanical properties was attributed mainly to δ -Ni₂Si precipitates although both Zr and Cr formed metal silicides within α -Cu matrix. As similar to our previous report [10], rough primary Ni,Zr-rich precipitates and Cr-rich precipitates at the grain boundaries took part in crack nucleation and presence of grain boundaries and also twins supported both crack initiation and propagation at all stages of fatigue, as expected. The brittle characteristics of hard primary silicides under loading formed new cracking paths enhancing the crack propagation especially at the highest stress level utilized (400 MPa). A dendritic fracture morphology was observed on the fracture surface of the alloy tested at 300 MPa and not only very fine dimples but also localized shearing was observed on total fracture surface due to interactions between very fine Ni-silicides and dislocations. At 200 MPa, the existence of precipitate-free bands caused crack nucleation and propagation. At lowest stress level (175 MPa), a “ladder-like structure” was observed both on the fracture surface and also at the cross-section of aged alloy. This structure was an indication of persistent slip bands, that caused fine striations covering the fracture surface at crack growth and propagation zones. All these findings are in agreement with the results cited in several studies related to fatigue behavior of Cu-Ni-Si alloy.

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