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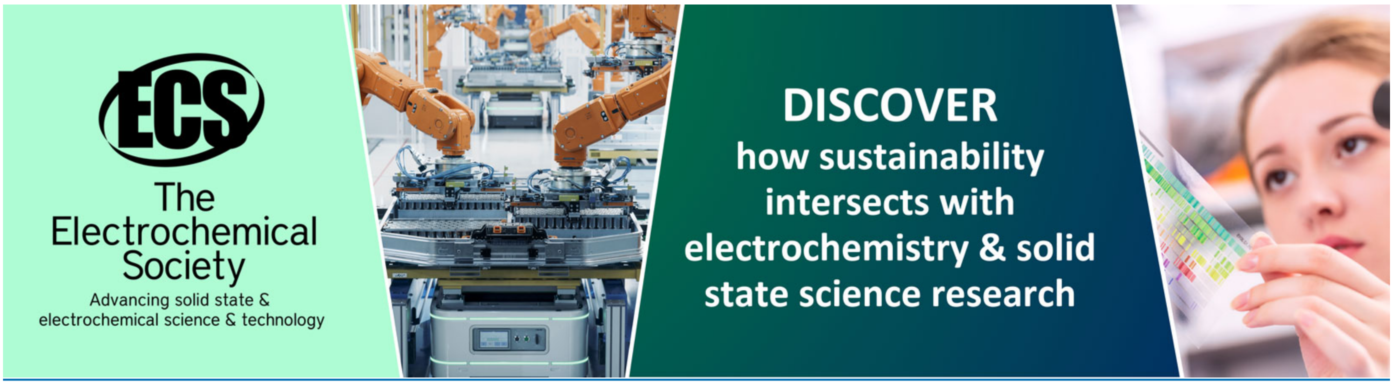

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Influence of grain orientation on evolution of surface features in fatigued polycrystalline copper: a comparison of thermal and uniaxial mechanical fatigue results

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Abstract. Surface state plays a major role in the crack nucleation process of pure metals in the High-Cycle-Fatigue (HCF) as well as in the Ultra-High-Cycle-Fatigue (UHCF) regime. Therefore, in studies dealing with HCF or UHCF, special attention is paid to the evolution of surface degradation during fatigue life. The accelerating structures of the future Compact Linear Collider (CLIC) under study at CERN will be submitted to a high number of thermal-mechanical fatigue cycles, arising from Radio Frequency (RF) induced eddy currents, causing local superficial cyclic heating. The number of cycles during the foreseen lifetime of CLIC reaches 2×10^{11}. Fatigue may limit the lifetime of CLIC structures. In order to assess the effects of superficial fatigue, specific tests are defined and performed on polycrystalline Oxygen Free Electronic (OFE) grade Copper, a candidate material for the structures.

Surface degradation depends on the orientation of near-surface grains. Copper samples thermally fatigued in two different fatigue experiments, pulsed laser and pulsed RF-heating, underwent postmortem Electron Backscattered Diffraction measurements. Samples fatigued by pulsed laser show the same trend in the orientation-fatigue damage behavior as samples fatigued by pulsed RF-heating. It is clearly observed that surface grains, oriented [1 1 1] with respect to the surface, show significantly more damage than surface grains oriented [1 0 0].

Results arising from a third fatigue experiment, the ultrasound (US) swinger, are compared to the results of the mentioned experiments. The US swinger is an uniaxial mechanical fatigue test enabling to apply within several days a total number of cycles representative of the life of the CLIC structures, thanks to a high repetition rate of 24 kHz. For comparison, laser fatigue experiments have much lower repetition rates. The dependence of surface degradation on grain orientation of samples tested by the US swinger was monitored during the fatigue life. Results are presented and compared to the ones arising from the two other test methods.

1. Introduction

The need for high accelerating gradients imposes considerable constraints on the materials of the accelerating structures of the future compact linear collider (CLIC) for high energy physics under study at CERN. The design accelerating fields (100 MV/m) will be the highest ever achieved in accelerating devices [1]. The surfaces exposed to high pulsed Radio Frequency (RF) currents will be subjected to cyclic thermal stresses, arising from cyclic Joule heating. This may well cause surface roughening and degradation by fatigue after the 10^{11} cycles foreseen after 20 years of operation [1]. The negative influence of increased surface roughness on RF-Performance or electrical breakdown resistance must be considered as a limiting factor. As OFE copper is traditionally the standard material for RF applications, it is considered in the present study as the basic structural material for the accelerating structure.

In both High–Cycle–Fatigue (HCF) and Ultra–High–Cycle–Fatigue (UHCF), the limiting factor for fatigue life is crack initiation. In contrast, during Low-Cycle-Fatigue (LCF), crack propagation plays the major role [2]. Therefore special attention is payed in HCF and in UHCF to the evolution of the surface during cycling when cycle numbers exceed 10^4 [3, 4].

This study focuses on surface degradation as a function of the orientation of surface grains. As shown in [5], copper exhibits highly anisotropic elastic properties. A significant dependence of surface degradation on local orientation can be observed. Two different fatigue experiments were presented in [5] and the results are discussed. Cycle numbers are significantly extended by introducing an additional fatigue technique, the ultra sound (US) swinger. Results will be discussed and compared to [5].

2. Material and experimental procedure

Material

All samples are made of high conductivity–oxygen free–copper min 99.99 % (Cu–OFE REF. UNS C10100 Grade 1) already used in [5]. The state without any heat treatment is “half-hard” (H02 according to ASTM B601). Samples in the “annealed” state were exposed to 1000 °C for 2 h in vacuum. For properties see [5].

Fatigue Devices

In the laser–fatigue device an Excimer–laser irradiates repetitively a disc like specimen under vacuum. The experimental setup is described in detail in [6, 5]. A repetition frequency of 200 Hz, a pulse length of 40 ns and an energy density 0.3 J/cm^2 (which induces a calculated temperature rise of ΔT = 280 K [6]) are chosen in order to ensure that between each cycle the irradiated area can cool completely down to room temperature due to heat diffusion through the specimen into the specimen holder. Therefore there is no steady temperature rise in the specimen. The heating while irradiation induces thermal expansion which is suppressed by surrounding material in lateral direction as well as in depth. This cyclic biaxial stress results in fatigue damage. The estimated thermally induced cyclic compressive strain load is between $\epsilon_{th} = 0$ and 7 x 10^{-3}.

The RF-fatigue device consists of a mushroom cavity which produces well defined temporarily changing magnetic fields. A detailed description of the device can be found in [7, 5]. Pulsed RF magnetic fields (11,4 GHz called X–Band) induce eddy currents with a repetition rate of 60 Hz. During one pulse (1,5 μs) these eddy currents induce heating up to a calculated temperature change of $\Delta T_{max} = 110$ K for the current test setup, which corresponds to a maximal thermal strain of $\epsilon_{th} = 1.8$ x 10^{-3}. As for the laser device the cyclic heating produces cyclic compressive biaxial stress which results finally in fatigue damage. The magnetic field intensity and the cooling system are chosen in the way to ensure the cooling between pulses to be sufficient to reach an average steady state of minimum temperature of $\approx$ 60 °C.

The US swinger (USS) device cycles mechanically an hour glass shaped sample which is mounted on one end to a piezo–electric resonator. The experimental setup is described in detail in [8]. The sample undergoes cyclic uniaxial tension and compression loads with a load ratio R = -1. The calculated resulting stress for the present experiment is 60 MPa hence strain $\epsilon = 6$ x 10^{-4}. The sample dissipates heat during high frequency cycling. Therefore the free sample end is dipped in a water bath, which is constantly recirculated. On the resonator site the leverage is cooled through forced air convection, provided by a high power fan. The resulting steady state sample temperature is below 50 °C.

For details about the determination of grain orientations see [5]

3. Experimental Results

Laser-fatigued samples

An annealed sample has been submitted to laser fatigue. Fig. 1 shows the transition area between a [1 0 0] twin and a [1 1 1] grain after 5 x 10^5 cycles (= test end). A strong difference in roughness can be observed across the twin boundary. The bright contrast of the [1 1 1] grain within the irradiated area arises from roughening effects, since the surface roughness increased during the laser irradiation treatment for this orientation. The dark appearance of the twin [1 0 0] is due to its almost completely smooth surface apart from the adaptation area in the close vicinity of the twin boundary, illustrated with dashed lines. No surface features developed therefore during the thermal cycling for this orientation.

RF-fatigued samples

Fig. 2 shows the surface of the RF-fatigued sample in the area of highest cyclic temperature load after 1 x 10^7 cycles (= test end). RF tests were performed on half–hard samples, showing significantly smaller grains than in the annealed state for the laser discs. Only the grains with the main orientations [1 0 0] and [1 1 1] are indicated. The dark regions [1 0 0] correspond to smoother surfaces whereas bright regions correspond to clearly developed surface features.

USS-fatigued samples

Fig. 3 shows the surface of a sample submitted to the USS-fatigue device after 2 x 10^{10} cycles (fracture = test end). Dark spots are artifacts of electro polishing before cycling. One can see a central [1 0 0] oriented grain (G1) without surface degradation. It is surrounded by several [1 1 1] oriented grains which show different levels of degradation. There can be distinguished 3 groups of [1 1 1] degradation: grains G2 and G5 show severe surface roughening; grains G3 and G4 show moderate roughening and grain G6 shows no roughening. The in–plane orientation of the [1 1 1] grains differ significantly. For G2 and G5 the first Euler angle (which determines the in plane rotation) is 350°. For G3 and G4 the angle is 212° and 222° respectively, whereas for G6 the angle is 278°. All angles have a statistical accuracy of ± 4°.

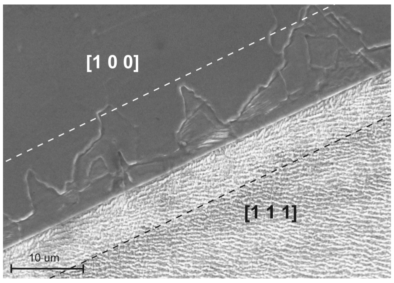

Figure 1. SEM picture of laser fatigued sample. No damage on [1 0 0] grain outside the transition region (dashed line) is observed. The [1 1 1] grain shows severe roughening.

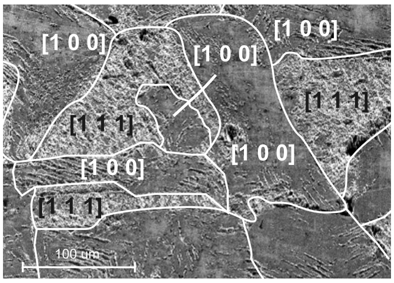

Figure 2. SEM picture of RF fatigued sample. Only grains with the main orientations are indicated. Bright and dark contrast correspond to rougher ([1 1 1]) and smoother ([1 0 0]) surface.

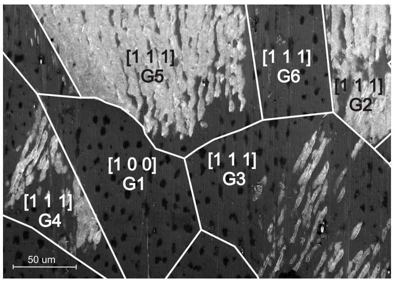

Figure 3. SEM picture of USS fatigued sample. Loading axis is horizontal. Dark spots are artifacts of electro polishing. Only grains with main orientations are indicated.

4. Discussion and Outlook

In [5] it is clearly shown that surface grains oriented in [1 0 0] submitted to thermal fatigue show much less surface degradation than grains in [1 1 1] (see also Fig. 1, 2). Although surface degradation features look quite similar (see Fig. 2, 3), in uniaxial mechanical loading this trend cannot be observed as clearly as in thermal fatigue. By calculating the Schmid factors (SF) for each of the 12 slip systems for different crystallographic orientations one can show that in biaxial case only out–of–plane orientations of surface grains change the SFs. In contrast, in uniaxial case the SF configuration is strongly depending on the in–plane orientations of surface grains. Therefore different surface degradation behaviour of grains differing only in the in–plane orientations can be expected.

While in thermal fatigue the degradation behaviour was clearly observed to be as reported in [5], in uniaxial testing also undamaged [1 1 1] grains were observed (Fig. 3). The group of grains G2 and G5 show severe surface damage whereas the group of grains G3 and G4 show moderate damage. The surface of grain G6 is completely smooth. Differences in the in–plane orientations are corrected, taking into account the three fold symmetry of a [1 1 1] direction. The corrected values show that only the grain G6 differs significantly (38°) whereas the the grains G2-G5 are oriented at 102° ± 10°.

The differences in extend of degradation of the [1 1 1] grains can therefore only be partly described by the in-plane orientation. A complete explanation of the dependency of degradation of the surface through thermal or mechanical cycling on grain orientation is still not established. To this purpose a more detailed Schmid factor analysis and active slip system orientation observation are foreseen.

5. Conclusion

The influence of the grain orientation on the fatigue behavior of surfaces is shown on the base of the main grain orientations [1 1 1] and [1 0 0]. In thermal fatigue both orientations showed very different developments during fatigue life. The [1 1 1] grains showed severe surface deformation whereas the [1 0 0] grains stayed almost unchanged smooth. Introducing a third fatigue device, the uniaxial USS-device, makes it more difficult to assign surface degradation directly to an out-of-plane orientation. The in-plane orientation of the grains becomes highly important because the Schmid factor configuration on the slip systems change significantly. In uniaxial loading it is shown that [1 1 1] oriented grains can show significantly lower surface degradation as compared to the biaxial loading arising from thermal fatigue experiments.

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