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Fracture toughness and fatigue crack growth characteristics of nanotwinned copper

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Abstract

Recent studies have shown that nanotwinned copper (NT Cu) exhibits a combination of high strength and moderate ductility. However, most engineering and structural applications would also require materials to have superior fracture toughness and prolonged subcritical fatigue crack growth life. The current study investigates the effect of twin density on the crack initiation toughness and stable fatigue crack propagation characteristics of NT Cu. Specifically, we examine the effects of tailored density of nanotwins, incorporated into a fixed grain size of ultrafine-grained (UFG) copper with an average grain size of 450 nm, on the onset and progression of subcritical fracture under quasi-static and cyclic loading at room temperature. We show here that processing-induced, initially coherent nanoscale twins in UFG copper lead to a noticeable improvement in damage tolerance under conditions of plane stress. This work strongly suggests that an increase in twin density, at a fixed grain size, is beneficial not only for desirable combinations of strength and ductility but also for enhancing damage tolerance characteristics such as fracture toughness, threshold stress intensity factor range for fatigue fracture and subcritical fatigue crack growth life. Possible mechanistic origins of these trends are discussed, along with issues and challenges in the study of damage tolerance in NT Cu.

Keywords: Nanotwins; Fracture toughness; Fatigue crack growth; Damage tolerance; Nanocrystalline copper

1. Introduction

Reducing the grain size of a material to enhance its strength has long been a strategy used in microstructure design [1–6]. In conventional microcrystalline metals and alloys (average grain dimensions typically bigger than 1 μm), grain refinement generally results in an increase in the resistance to fatigue crack initiation. In high cycle fatigue, this trend is reflected as a higher fatigue endurance limit (which is elevated with higher strength); the endurance limit is typically measured through cyclic-stress-controlled experiments on initially smooth laboratory specimens [7]. When the average grain size is refined to values typically below 100 nm, the resulting nanostructured metals exhibit significantly elevated strength and strain rate sensitivity and much lower activation volume, as well as improved resistance to corrosion, fatigue crack initiation for long life as seen in the fatigue endurance limit, and monotonic and cyclic wear [8–13] in comparison to microcrystalline metals and alloys [3,5,6]. However, such beneficial effects of grain size reduction are also commonly accompanied by reductions in ductility. The drop in ductility is ascribed to significant constraints encountered in accommodating plastic strain through the generation and accumulation of dislocations in the nanograined (NG) metals [3,5,6,14]. Furthermore, grain refinement into the nanocrystalline regime is known to degrade different metrics of damage tolerance including fracture toughness and the resistance to stable subcritical crack growth under monotonic and cyclic loading, especially at lower values of stress intensity factor range (the so-called near-threshold regime with crack growth rates typically smaller than 10^{-6}

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mm cycle^{-1}) where most of the fatigue fracture life is expended [7,8,10,15].

In addition to these effects on mechanical properties, grain refinement, especially in the nanocrystalline regime, is also known to have a deleterious effect on electrical conductivity [16–19] and resistance to electromigration [20].

To date, there is limited information available on the fatigue properties of ultrafine-grained (UFG) and nanograined (NG) materials. Earlier studies included high cycle fatigue experiments performed on nanocrystalline Cu produced by inert gas condensation [21] in order to ascertain the stability of microstructure under cyclic loading. These experiments documented 30% increase in grain size due to repeated, cyclic loading along with the surface being populated with parallel "extrusions" seemingly similar to persistent slip bands (PSBs) observed in coarse-grained (CG) Cu and single crystals [7]. Strain-controlled fatigue tests [22] comparing UFG Cu prepared by severe plastic deformation (SPD) and CG Cu showed that the latter has a longer total fatigue life than the former, and that the surface of the fatigued UFG specimen showed extrusions similar to those found in NG Cu [21]. In addition, cyclic softening was observed in Cu prepared by SPD [23]. However, it has been found [24] that annealing treatment improves the low cycle fatigue life in strain controlled cyclic tests on UFG materials produced by equal channel angular pressing (ECAP). Cyclic softening in UFG Cu produced by ECAP was also ascribed to dynamic recrystallization and subsequent grain growth which was observed after strain controlled cyclic loading on Cu specimens produced by ECAP [25]. Unlike UFG metals prepared from SPD techniques, electrodeposited NG Ni with an average grain size of 40 nm displayed cyclic strain hardening under tension–tension cyclic loading. The deformation was also found to be dependent on the frequency of applied loading [26]. Stress-controlled cyclic loading applied on bulk Ni–18 wt.%Fe alloy with an average grain size of 23 nm and produced by pulsed electrodeposition exhibited an endurance limit of just 13% of the yield stress, which was surprisingly low compared to the trend shown by other metals [27]. Fracture and fatigue studies [28] done on the same bulk Ni–18 wt.%Fe alloy with an average grain size of 23 nm demonstrated limited values of fracture toughness owing to nanovoid coalescence at the grain boundaries. In the near-threshold regime of stable fatigue crack growth, the crack path was found to be non-tortuous as seen through scanning electron microscopy (SEM). Focused ion beam confirmed the results obtained earlier from atomistic simulations [29] that the microcracks are initiated close to the primary crack by the process of nanovoid coalescence. Xie et al. [30] performed experiments on electrodeposited Ni sheets (average grain size 26 nm) and CG Ni in order to determine the difference in the modes of fatigue crack nucleation. It was found [30] that for CG Ni crack nucleation occurred in a diffused manner in that a population of cracks was observed whereas for NG Ni there was one principal crack and dislocation cell structures with an average size of 108 nm were observed along the main crack.

Mirshams et al. [15] found that the fracture toughness of pure NG Ni produced by pulsed electrodeposition decreased with an increase in annealing temperature. Their results were rationalized using the "cluster model" [31]. Here the claim is that a large number of nonequilibrium vacancies formed during the process of recrystallization of nanocrystalline materials would segregate and condense into clusters preferentially residing at the grain boundaries. These clustered vacancies would weaken the material, and the number and size of these clusters would increase with an increase in annealing temperature.

Opposite trends, however, were observed for carbon-doped NG Ni in that the fracture toughness increased with an increase in annealing temperature. Charpy impact energy tests on electrodeposited Co showed that the toughness decreases as the grain size is refined close to 18 nm [32]. This trend has also been corroborated by fracture studies on α-Fe and Al [33], which have shown that fracture toughness decreases with grain refinement. Stress-controlled cyclic loading experiments conducted on electrodeposited Ni showed an improvement in fatigue life and endurance limit with grain refinement in the <100 nm regime. However, stable crack propagation experiments on CG, UFG and NG Ni revealed diminishing fatigue crack growth threshold values with grain refinement [8,10].

The foregoing discussion of prior work clearly illustrates that: (i) there has been very little systematic work on the fracture and fatigue crack growth characteristics of nanograined metals and alloys; (ii) the limited experimental information available to date generally appears to indicate a significant reduction in damage tolerance with grain refinement into the nanocrystalline regime; and (iii) the loss of resistance to fatigue crack growth with grain refinement in NG metals, especially in the near-threshold regime, mirrors the trend observed in their CG counterparts [8,10].

Significant strengthening due to grain refinement arises from the obstruction of dislocation motion at nanoscale grain boundaries. Similar strengthening can also be achieved through the introduction of initially coherent twin boundaries within UFG metals. Recent studies [34–38] have shown that when a polycrystalline ensemble of UFG copper (with average grain size in the range of 100–1000 nm) is populated with initially coherent, mechanically and thermally stable nanoscale twins (where the twin width or spacing is on the order of tens of nanometers), the ensuing structure exhibits deformation characteristics that mirror those of nanograined copper whose average grain size is comparable to the twin spacing in the nanotwinned (NT) copper. In other words, when nanotwins are introduced in the UFG metal during pulsed electrodeposition, the material exhibits strengthening characteristics and strain rate sensitivity comparable to those of a nanograined metal without twins [34,35,38]. The coherent NT boundaries act as barriers to dislocation motion just as grain boundaries do [36,37,39]. The pile-up of dislocations at