4.1 RECENT PROGRESS IN THE DEVELOPMENT OF DUCTILE-PHASE TOUGHENED TUNGSTEN FOR PLASMA-FACING MATERIALS: W-Ni-Fe COMPOSITES – C. H. Henager, Jr., R. J. Kurtz, T. J. Roosendaal, B. A. Borlaug, E. A. Nyberg, C. A. Lavender (Pacific Northwest National Laboratory[1]), G. R. Odette, K. H. Cunningham, and F. W. Zok (University of California, Santa Barbara)

OBJECTIVE

The objective of this study is to fabricate a lamellar W-Ni-Fe composite based on tungsten heavy metal alloys suitable for model material development for fusion reactor studies of ductile-phase toughening.

SUMMARY

A promising approach to increasing fracture toughness and decreasing the DBTT of a W-alloy is by ductile-phase toughening (DPT) [1-3]. In this method, a ductile phase is included in a brittle matrix to prevent fracture propagation by crack bridging. W-Ni-Fe alloys consisting of nearly spherical W-particles embedded within a Fe-Ni-W ductile matrix are being manipulated by hot-rolling to create lamellar W/Fe-Ni-W composites with anisotropic fracture properties.

PROGRESS AND STATUS

Background

Tungsten (W) and W-alloys are the solid materials of choice for plasma-facing components (PFCs) of future fusion reactors, such as the International Thermonuclear Experimental Reactor (ITER) and Demonstration Power Plant (DEMO), due to their high melting point, strength at high temperatures, high thermal conductivity, low coefficient of thermal expansion, and low sputtering yield [4-8]. However, W and most W-alloys exhibit low fracture toughness and a high ductile-brittle transition temperature (DBTT) that would render them as brittle materials during reactor operations [4, 6, 9]. The DBTT for unirradiated W-alloys typically ranges from 573K to 1273K (300 to 1000˚C) and in a reactor environment radiation hardening would further elevate this range [6, 10, 11]. W-alloys toughened by engineered reinforcement architectures, such as ductile-phase toughening (DPT), are strong candidates for PFCs. In DPT, a ductile phase is included in a brittle matrix to prevent fracture propagation. This is accomplished by the formation of an intact bridging zone behind the crack tip, which provides reinforcement, resulting in an increase in the remote load stress intensity for continued crack growth with increasing crack length [12, 13]. The principles of DPT are illustrated in Figure 1, which shows an actual and schematic illustration of ductile bridging ligaments stretching across an open crack in a brittle matrix material, such as W [12, 13]. For a brittle material containing a suitable volume fraction of a ductile phase, a highly effective resistance curve toughening mechanism develops as the crack extends. This reduces the crack tip stress intensity factor so that: $\boldsymbol{K_{Tip}} < \boldsymbol{K_{Applied}}$. The crack opening (u) increases with increasing distance behind the crack-tip until the reinforcement breaks at a critical u*.

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[1] PNNL is operated for the U.S. Department of Energy by Battelle Memorial Institute under Contract DE-AC06-76RLO 1830.

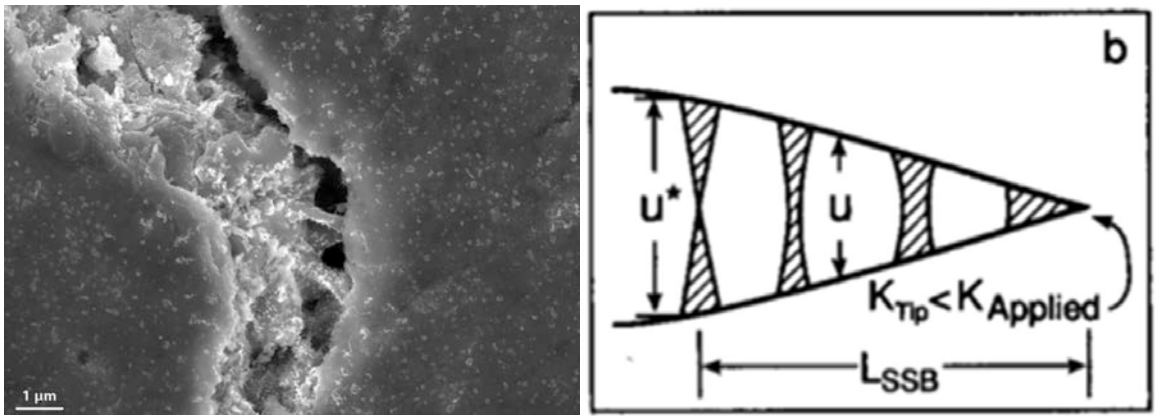


Figure 1. a) SEM image of W-Cu fracture where the ductile phase (Cu) is effectively bridging the crack. b) A steady-state bridging zone shown schematically in 2D [13].

Experimental

Fe-Ni-W alloys, purchased as green bodies consisting of W-7%Ni-3%Fe[2], are being prepared for testing using hot-rolling to provide a range of microstructures with anisotropic fracture behavior. The starting alloy shown in Figure 2 is formed using liquid phase sintering methods and exhibits an isotropic structure consisting of W-Ni-Fe spheres embedded in a Fe-Ni-W matrix. The W-spheres are 99.7% W, 0.2% Ni and 0.1% Fe by wt%. The matrix, which is basically a Ni-based superalloy, is 56.9% Ni, 29.3% W, and 13.8% Fe by wt%.

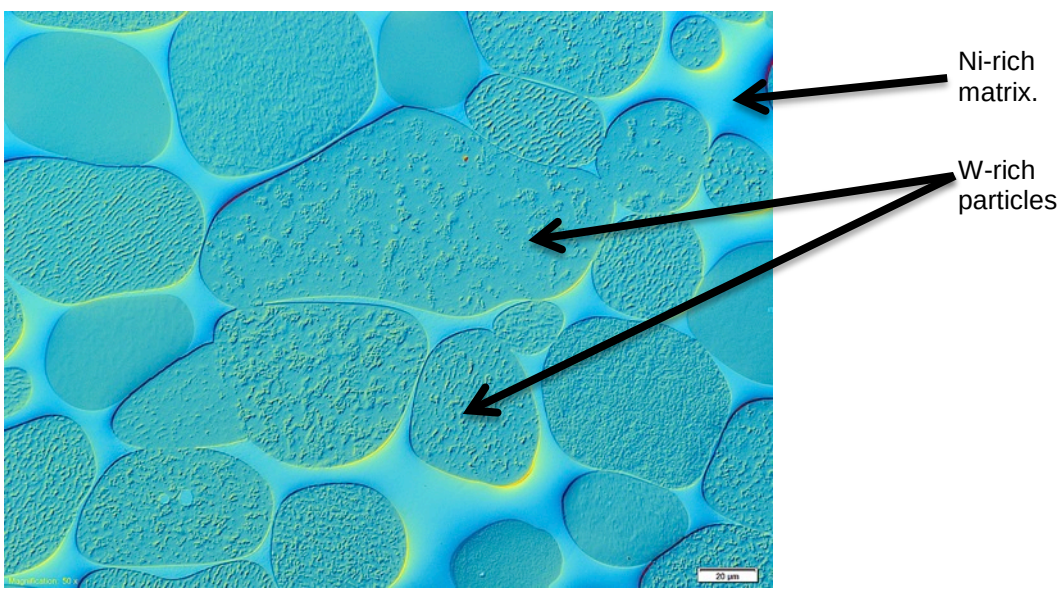


Figure 2. W-Ni-Fe alloy showing W-rich particles and Ni-rich ductile matrix.

These alloys are being successively hot-rolled at 1150˚C for two passes with 5% reduction per rolling pass after initial sintering. Then the alloys are rolled at 900˚C in 11% reduction passes to the final reductions (Fig. 3), noting that after three passes the materials are annealed at 900˚C for 1 hour in argon. Figure 3 shows optical images of the as-rolled materials at different reduction percentages. Samples continue to be rolled to higher reductions but are not yet available for imaging.

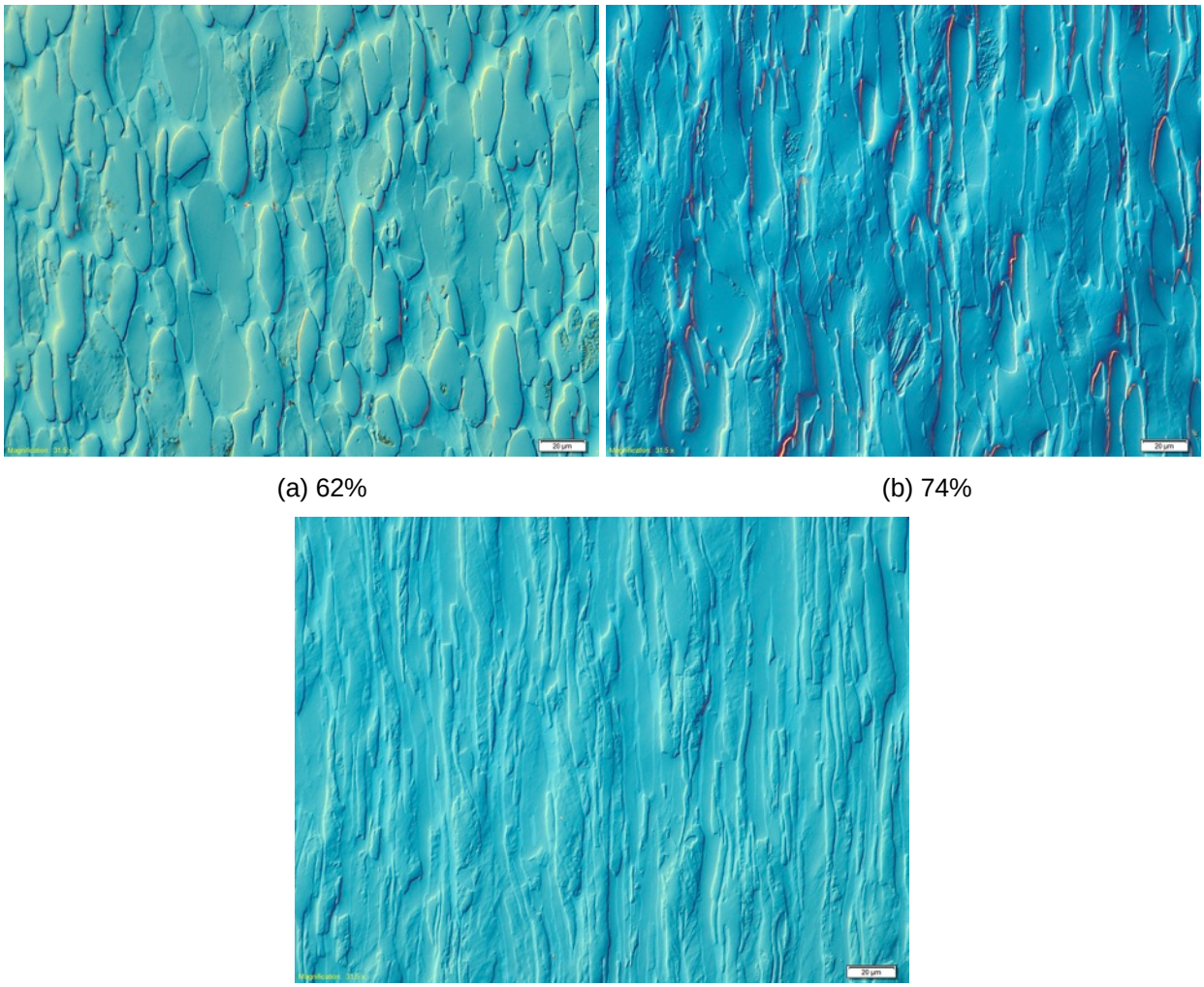
[2] Mi-Tech Metals, Indianapolis, IN, USA.

Discussion

The goal is to achieve a rolled W-Ni-Fe alloy that resembles a lamellar alloy consisting of W-rich lamellae separated by ductile-phase regions. Fig. 3c shows a microstructure of that type. The W-rich lamellae are strong but brittle, while the ductile-phase metallic regions now have a thin, plate-like morphology that should act as a ductile bridging region. Such a material would be oriented with the W-rich lamellae parallel to principal stresses so that surface cracking would be normal to the ductile-phase bridging regions.

Future Work

Additional amounts of reduction are planned so that reductions greater than 90% are achieved and thinner lamellar regions are produced to be able to more completely explore morphological effects on mechanical properties. Fracture toughness samples in the form of 4-point bend bars are being fabricated from these rolled alloys and will be tested at ambient and elevated temperatures. Exploration of alternative alloy compositions that reduce the amount of Ni in the alloy due to neutron activation concerns will follow successful fracture testing.



(a) 62% (b) 74%

(c) 88%

Figure 3. Optical images of hot-rolled W-Ni-Fe alloy with (a) 62%, (b) 74%, and (c) 88% reductions, respectively. A goal is to achieve a rolled reduction of 90% or greater to form a lamellar tungsten alloy with anisotropic fracture properties. These rolled materials will be tested with the specimens oriented so that crack growth was horizontal (right to left) in the image.

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