IMPACT OF GRAIN BOUNDARY MODIFICATIONS ON FRACTURE TOUGHNESS OF TUNGSTEN BASED NANOMATERIALS

Daniel Kiener[1]*, Michael Wurmshuber[1], Markus Alfreider[1], Julius Keckes[1], Michael Burtscher[1], Reinhard Pippan[2]

[1]Department Materials Science, Montanuniversität Leoben, Jahnstr. 12, 8700 Leoben, Austria, [2]Erich Schmid Institute of Materials Science, Austrian Academy of Sciences, Jahnstr. 12, 8700 Leoben, Austria
** Presenting Author email: Daniel.kiener@unileoben.ac.at*

Abstract
Nanostructured materials commonly excel with respect to their strength, but their ductility and toughness remain limiting factors for deployment in safety related applications. In this work, using grain boundary engineering concepts in conjunction with severe plastic deformation for microstructural refinement, we aim to develop nanostructured and nanocomposite materials that overcome these limitations. Since material volumes are limited, we utilize small scale testing approaches to examine the respective material properties such as strength, ductility and fracture toughness. We detail on the one hand challenges and recent advancements in small scale fracture experiments, and on the other hand the effectiveness of the mentioned grain boundary engineering approaches to design outstanding nanomaterials overcoming strength-ductility-toughness limitations.

1. Introduction
Since the early works of Hall and Petch, we are accustomed to the fact that reduced grain sizes provide increased strength. While this concept was exploited in recent years extensively down to nanostructured materials that commonly offer several GPa of strength, it was at the same time also realized that this gain in strength comes along with a dramatic loss in ductility, as well as fracture toughness. This behavior is rooted in the fact that the governing plastic deformation mechanisms change, from intergranular dislocation based plasticity to grain boundary dominated mechanisms. As such, plasticity is frequently limited to grain boundary regions, and failure occurs early by localization at grain boundaries.

To overcome this grain boundary failure limitation, we attempt to utilize grain boundary engineering to enhance the grain boundary cohesion, thereby delaying the localized interfacial failure to higher stress and strain levels, respectively, aiming for the activation of supporting intergranular plastic deformation contributions before interfacial failure takes place.

2. Results
We used severe plastic deformation, namely high pressure torsion, as method to synthesize grain boundary modified W based nanomaterials and nanocomposites. By starting from pure powders as input materials, we were able to conveniently add different grain boundary cohesion enhancing doping elements, such as C or B, to the W base material. Furthermore, nanocomposites with enhanced ductility were realized by adding various amounts of Cu powders to the mixture. As such, by this process composition and doping element can be conveniently adjusted before compacting and refining to the final bulk nanostructured material. Furthermore, by an adequate heat treatment, segregation of the doping element is promoted to increase its local concentration and efficiency at the interfaces. We find that the studied materials display, besides very high strengths, appreciable amounts of ductility, even though grain sizes in the range from 150 nm to 10 nm are examined for the bulk and composite materials, respectively.

To study the deformation and fracture characteristics of the synthesized materials, we conducted miniaturized fracture experiments on notched focused ion beam fabricated bending beams. Thereby, we refer to an elastic-plastic fracture data analysis, where the required current crack length is deduced from either partial unloadings, continuous stiffness measurements, image analysis of the recorded in-situ SEM videos, or a combination thereof.

We find that for varying sample sizes in the ufg material condition, see Figure 1 top, there is a prevalence of grain boundary mediated failure, but at the same time a pronounced size effect on the apparent fracture toughness, see Figure 1 bottom. Classically valid quantities are obtained for dimensions roughly equivqalent to 25 times that of the estimated plastic zone size, as suggested for bulk standards. Below this, an apparent or component dependent toughness is measured that first increases, and then drops for even smaller specimens.

We will discuss the benefits and drawbacks of the different approaches to measure current crack lengths, as well as the reasons underlying the observed size dependent fracture toughness.

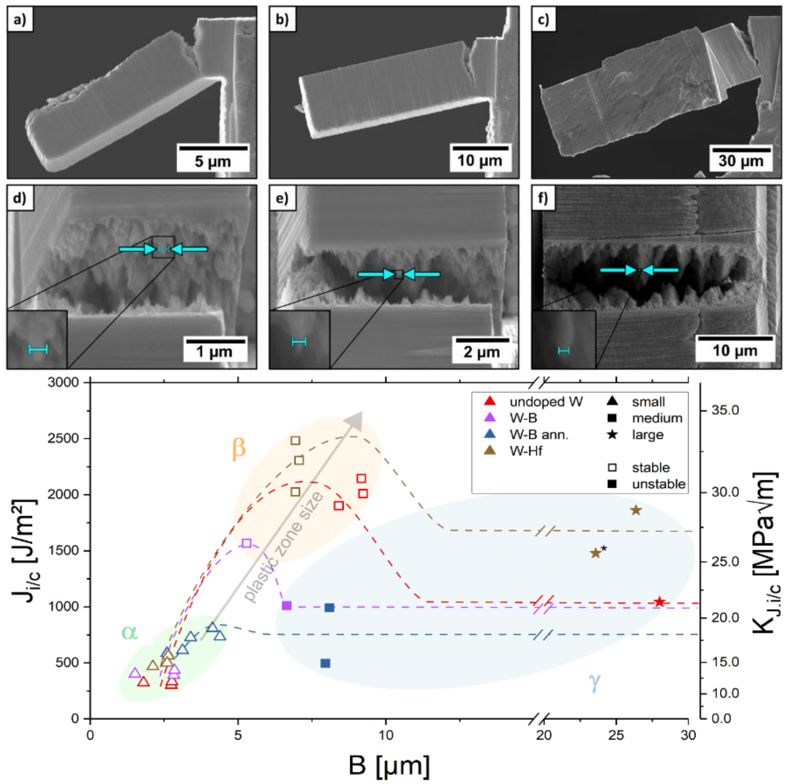

Fig.1 – Differently sized bending beam fracture specimens (top) and the resulting size dependent fracture toughness for different grain boundary modification variants (bottom). From M. Wurmshuber *et al*., Acta Mater. 250 (2023) 118878.

Moving on past these more experimental/analytical considerations, we will detail the effectiveness as well as limitations of this grain boundary engineering approach (Figure 1, bottom) in enabling us to design grain boundary engineered tough nanomaterials and nanocomposites.

3. Conclusions

Grain boundary segregation engineering of nanostructured and nanocomposite W-based materials is demonstrated as a versatile way to move forward in tailoring novel nanomaterials with enhanced ductility and outstanding fracture toughness.

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