# STRATEGIES FOR IMPROVING DUCTILITY OF BULK NANOSTRUCTURED MATERIALS

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## Introduction

For structural materials used in aerospace, transportation and biomedical etc. industries, enhancing their strength means a reduction of weight. This is particularly attractive under the today's background of energy and environmental crises. Over the past couple of decades, bulk nanostructured (NS) materials with nanoscale grain size have been the subject of widespread research studies [1] because of their ultrahigh strength. However, bulk NS materials usually have low ductility which limits their wide industrial applications.

The reasons for the low ductility of NS materials can be classified into two groups: extrinsic processing artifacts and intrinsic microstructures /deformation mechanisms. The former case includes porosity, insufficient bonding, impurities etc. that may develop during consolidation and/or synthesis of NS materials [2]. The latter case is stemmed from their low strain hardening ability. According to Hart criterion, localized deformation occurs when:

$$\gamma \leq 1\text{-}m \qquad (1)$$

where $\gamma$ is the normalized strain hardening rate, and $m$ is the strain rate sensitivity. Both $m$ and $\gamma$ are small for bulk NS materials, resulting in early necking instability in the presence of tensile stresses. The low strain hardening rate of NS materials is caused by their low dislocation storage efficiency owing to their small grains and/or nearly saturated defect (dislocation) density.

After 2000, many efforts have been paid to improve the low ductility of bulk NS materials, as discussed in review papers by Koch, Ma and Zhao [3-5]. The developed strategies include introducing a bi- or multi-modal grain size distribution, introducing pre-existing nano-scale growth/deformation twins, engineering 2$^{nd}$-phase precipitates in a nanostructured matrix, designing multiple-phase alloys or composites, lowering stacking fault energy by alloying, lowering dislocation density and changing grain boundary nature, utilizing phase-transformation plasticity, reducing processing artifacts, or deformation under conditions including low temperature or high strain rate. These strategies have been demonstrated to have varying degrees of success for improving the poor ductility of NS materials, and attest that it is possible to achieve enough ductility by tailoring and optimizing the microstructures of bulk NS materials .

## Experimentals and Results

Recently, we proposed an improved approach to produce bulk dense bi-modal or multi-modal grain structures with eliminated impurities and other processing artifacts using the cryomilling, degassing and quasi-static forging methods [6]. In this approach, NS metal powders (such as Ni and Ti) processed by cryo-milling were mixed with coarse-grained powders at designated ratios and then quasi-isostatic Ceracon forged to produce large, fully dense samples. As shown in Fig. 1, both high tensile ductility and high strength are achieved for multi- and bi-model Ni samples. The high ductility resulted from significantly reduced processing flaws (i.e. high density (>99.5% theoretical density) and high purity (>99.3%)) as well as a uniform distribution of micro- and NS grains.

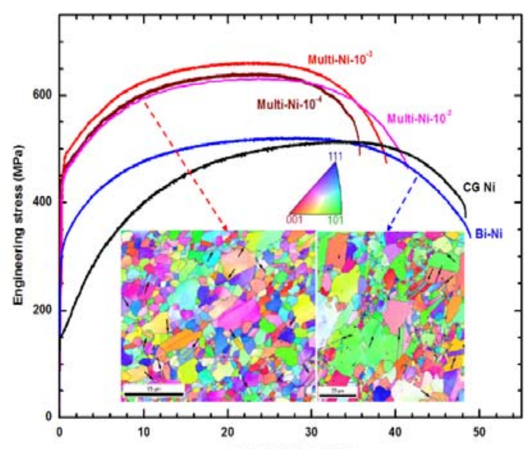


Fig. 1 Tensile engineering stress-strain curves of multi- (Multi-Ni) and bi-model (Bi-Ni) Ni samples prepared by cryomilling and quasi-isostatic forge [6]. The CG Ni was achieved by annealed the multi-Ni sample at 1000 °C for 10 h.

The presence of a high strain rate can also increase the strain hardening rate because the dynamic equilibrium dislocation density under this condition is high, allowing for more dislocation accumulation. Fig. 2 shows the dynamic and quasi-static true stress-strain curves of the nanocrystalline NiFe alloy [7]. Significantly enhanced dynamic deformation strain and strength were observed compared to the quasi-static loading with a strain rate of $1\times10^{-3}$ $s^{-1}$. These observations indicate the advantages of NS materials under some certain service conditions such as high strain-rate conditions.

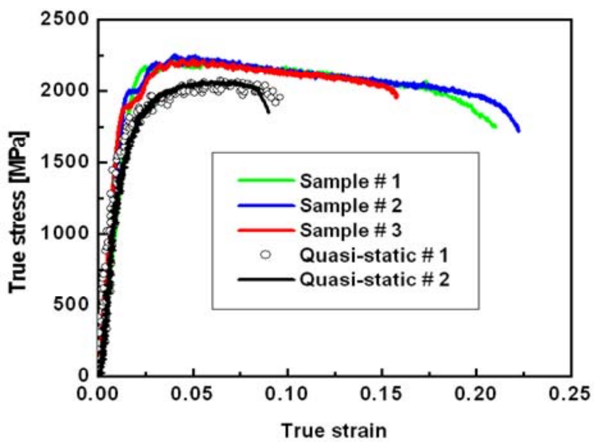


Fig. 2 Dynamic and quasi-static true stress-strain curves of the nanocrystalline NiFe alloy [7]. Three samples were used for the dynamical tests with strain rates ranging from $1\times10^{3}$ $s^{-1}$ to $3\times10^{3}$ $s^{-1}$. Significantly enhanced dynamic deformation strain and strength were observed compared to the quasi-static loading with a strain rate of $1\times10^{-3}$ $s^{-1}$.

By using high pressure torsion (HPT), we engineered Al alloys to contain a nanostructural hierarchy that enables breaking of Al alloy strength record – an aerospace grade 7075 alloy exhibits a yield strength of 1 GPa and total elongation to failure of 9%, as shown in Fig. 3 [8]. The nanostructure was revealed through new high resolution microscopy techniques and comprises a solid solution, free of precipitation, featuring (i) concentrated intragranular solute clusters of sub-nanometre diameter, (ii) 2 geometries of intergranular solute structures on the nanometre scale, (iii) grain sizes tens of nanometres across, and (iv) high density of dislocations. These microstructural characteristics resulted in the both high strength and high ductility [8].

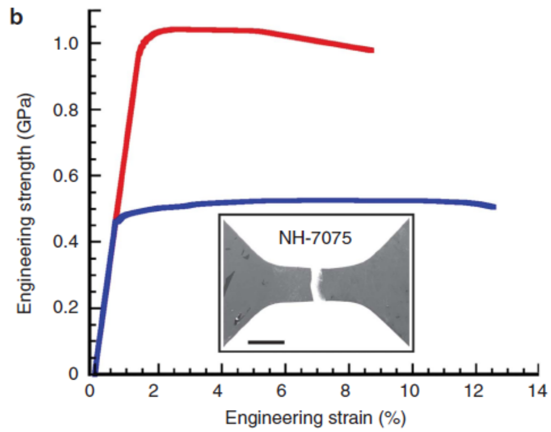


Fig. 3 Engineering stress-strain plot for the nanocrystalline (NH) 7075 and T6-7075 alloy [8]. The inset is the fractured tesnile specimen of the HN-7075 Al alloy.

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