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JMST-1108; No. of Pages 8
ARTICLE IN PRESS
Journal of Materials Science & Technology xxx (2017) xxx–xxx
Contents lists available at ScienceDirect
Journal of Materials Science & Technology
journal homepage: www.jmst.org

# Bimodal microstructure – A feasible strategy for high-strength and ductile metallic materials

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ARTICLE INFO

*Article history:*
Received 20 June 2017
Received in revised form 26 August 2017
Accepted 31 August 2017
Available online xxx

*Keywords:*
Nanocrystalline and ultrafine-grained metals
Mechanical milling
Severe plastic deformation
Bimodal microstructure
Strength and ductility

ABSTRACT

Introducing a bimodal grain-size distribution has been demonstrated an efficient strategy for fabricating high-strength and ductile metallic materials, where fine grains provide strength, while coarse grains enable strain hardening and hence decent ductility. Over the last decades, research activities in this area have grown enormously, including interesting results on *fcc* Cu, Ni and Al-Mg alloys as well as steel and Fe alloys via various thermo-mechanical processing approaches. However, investigations on bimodal Mg and other *hcp* metals are relatively few. A brief overview of the available approaches based on thermo-mechanical processing technology in producing bimodal microstructure for various metallic materials is given, along with a summary of unusual mechanical properties achievable by bimodality, where focus is placed on the microstructure-mechanical properties and relevant mechanisms. In addition, key factors that influencing bimodal strategies, such as compositions of starting materials and processing parameters, together with the challenges this research area facing, are identified and discussed briefly.


## 1. Introduction

It has been a long-standing goal for materials scientists to develop structural materials with simultaneous high strength and ductility [1–4]. However, strength and ductility are usually exclusive, and achieving high-strength and ductile materials remains a great challenge. Bulk nanostructured (NS) materials and ultrafine-grained (UFG) metals have motivated considerable attention due to their interesting physical and mechanical properties, e.g., extremely high strength in comparison with their coarse-grained (CG) counterparts. However, bulk NS/UFG metallic materials usually have rather low uniform ductility, which hinders greatly their industry applications [1–3].

Recent progress in developing strategies that strive to increase tensile ductility of bulk NS/UFG metallic materials while increasing/maintaining strength simultaneously has been discussed and briefly reviewed in several papers [3–6]. The proposed strategies could be divided into two groups, i.e., so-called 'mechanical' strategies and 'micro-structural' strategies [4]. The former is in terms of employing mechanical characteristics of the NS materials, such as their work hardening ability and/or strain rate sensitivity, which can be varied via changing testing parameters, such as temperature and/or strain rate [4–6]. The latter is based on the idea of intelligent microstructural design via tailoring micro/nano structure to derive sufficiently high ductility from nanostructured metallic materials and have been already discussed in some reviews [6–9].

Versatile 'microstructural' approaches proposed to improve ductility include: (i) bimodal/multimodal grain-size distribution [10–12]; (ii) generation of precipitation through ageing of severely deformed alloys [13,14]; (iii) introduction of nanoscale twins [15,16]; (iv) through transformation [17]; and (v) control of the grain boundary character [18]. It may be noted that except for the bimodal grain size approach, the applicability of other methodologies is strongly dependent on the system/composition of the alloys [19]. Even the bimodal grain size approach is indirectly dependent on the composition if SPD processing followed by controlled recrystallization annealing is used to produce bimodal microstructure, as suggested by Zha et al. in their work on high solid solution Al-Mg alloys [11,12].

A strategy for enhancing ductility of UFG/NS metals via designing a bimodal microstructure was demonstrated in 2002 by Wang

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https://doi.org/10.1016/j.jmst.2017.11.018
1005-0302/

Please cite this article in press as: M. Zha, et al., J. Mater. Sci. Technol. (2017), https://doi.org/10.1016/j.jmst.2017.11.018

et al. [1] in UFG Cu processed by cryo-rolling (CR) and short-time annealing. The strategy efficiently employs the moderate population of larger grains to achieve a strain hardening rate much higher than what would be expected, while the high strength could be maintained as a result of the existence large population of UFG/NS grains [1,5]. Since then, considerable experimental effort has been devoted to developing bimodal metallic materials for simultaneously high strength and ductility. The challenge for producing desired microstructure remains, but with recent technological advancements, it is becoming increasingly more feasible to control and engineer the grain structure of materials to very fine details, at least at small length scales.

This paper summarizes the approaches developed to achieve bimodal microstructure and highlights some recent results on such developments with a focus on the microstructure-mechanical properties relationship of these bimodal materials, and relevant mechanisms.

## 2. Strategies for bimodal microstructure

Two basic and complementary approaches, i.e., so called "top-down" and "bottom-up" approaches are usually involved in developing bimodal microstructures in UFG/NS metals. The "top-down" approaches refer to taking a bulk solid with a relatively coarse grain size to produce a bimodal grain structure through severe plastic deformation (SPD) techniques followed by appropriate heat treatment (e.g., through annealing and/or recrystallization) under controlled conditions [2,11,12,20]. The most frequently used SPD methods include but not limit to CR, high-pressure torsion (HPT), equal-channel angular pressing (ECAP)). Regarding the "bottom-up" approaches, bimodal materials are usually fabricated by mechanical milling plus consolidation of milled powders mixed with certain volume fractions of as-received coarse grained powders [18,21–24].

### *2.1. Strategies based on SPD techniques followed by heat treatment*

The "top-down" approaches are dependent upon SPD processing, and hence avoid the contaminations that are inherent for the materials produced by "bottom-up" approaches, in addition to the advantage that it can be readily applied to a wide range of preselected alloys [25]. Therefore, it is not surprising that considerable effort has been focused on producing bimodal microstructures by "top-down" approaches ever since Wang et al. [1] reported that a bimodal grain size distribution could be generated in UFG Cu processed by CR and short-time annealing, leading to simultaneously high yield strength and large uniform (and total) elongation. In addition, a numerical study showed that both crack bridging in the CG inclusions and crack deflection in the NS matrix can significantly toughen the bimodal NS Cu [26,27].

In addition to pure Cu, several studies on bimodal Cu alloys, e.g., Cu-Al [28], Cu-Ag [19] have also been conducted. For example, by pre-deformation heat-treatment followed by HPT with consequent annealing, controllable bimodal structures of micrometer-grained pre-eutectoid phase embedded on UFG matrix with eutectoid composition were obtained in hypo-eutectoid Cu-Al alloys, which possessed high strength and obvious uniform elongation [28]. Also, by cold rolling and short-time annealing, UFG Cu-Ag alloy with a bimodal grain size was produced, which exhibited high tensile strengths of ~550–620 MPa with decent uniform elongation (from 1 to 10%) [19]. The authors claimed that the superior combination of strength and ductility was resulted from the combined effect from bimodal grain size, dislocation density and solute distribution as well as nano-sized Ag precipitation [19]. Moreover, strength-

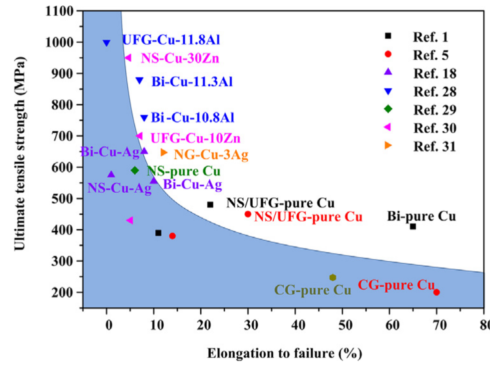


**Fig. 1.** Strength-ductility data taken from literature for bimodal Cu and its alloys. Data for NS/UFG and CG Cu and its alloys are also included for comparison [1,5,19,28–31].

ductility data taken from the literature for bimodal Cu and its alloys as well as for NS/UFG Cu or CG Cu [1,5,19,28–31] are summarized in Fig. 1 for comparison.

In addition to *fcc* Cu and its alloys, by utilizing ECAP either with or without inter-pass annealing, it is possible to achieve a high strength and significant uniform elongation (e.g. UTS ~570–600 MPa, uniform elongation ~11%-14%) [11,12,32–34] in high-solid-solution Al-Mg alloys by producing desired bimodal structures consisting of mixtures of nano-, UFG- and micron grains (Fig. 2) [12]. An excellent combination of strength and ductility of bimodal Al alloys was demonstrated by comparing tensile properties of bimodal Al-7Mg alloy with those of NS/UFG and CG Al alloys from previous studies [11,12,14,18,20,35,36], as shown in Fig. 3. The authors claimed that a high content of solute-Mg is key factor to promote microstructural heterogeneity upon deformation at a moderate to high strain, leading to the formation of a desired bi/multi-modal grain structure. It is mainly because fast dynamic recovery and recrystallization easily occur in *fcc* Al. The addition of high content of solute-Mg can effectively retard dislocation mobility by the friction effect from Mg atoms and hence depress the subdivision of those grains with less active dislocation slip systems. Naturally, non-uniform deformation and heterogeneous microstructure appear. In contrast, either reducing solute-Mg content or increasing the deformation strain would promote a more homogeneous microstructure, e.g., Al-1Mg deformed by similar ECAP conditions to those of Al-7Mg alloy [34] and Al-8.8 at.% Mg processed by HPT [37] both exhibiting relatively homogeneous (sub) grain structures. It seems that the bimodal-grain-size approach depends greatly on alloy composition, and hence, one may conclude that inhomogeneous deformation upon SPD induced by high solid-solution content can be strategized to promote bimodal grain structure in alloys with low melting points and high stacking fault energy (SFE) that restrict the grain refinement down to nanometer range.

In addition to *fcc* Cu and Al alloys, the combination of high strength and high ductility behaviour resulted from a multimodal grain structure was also found in *hcp* metals, such as Ti [2,38], Zr [39,40] and their alloys [41]. For example, by using CR followed by low-temperature annealing, multimodal grain structure was produced in commercial Ti, which exhibited a high yield strength of 926 MPa and uniform elongation of 11% [42]. Moreover, by asymmetric rolling and partial recrystallization, Wu et al. [2] architected a heterogeneous lamella structure, i.e., a special case of bimodal structure, in Ti, which possessed a high strength and large tensile ductility due to an extraordinary strain-hardening rate resulted from back-stress hardening and dislocation hardening [2,38]. Also, through SPD processing followed by thermal annealing, NS/UFG lamellar structure with micrometer-sized equiaxed