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Hardness – strength relationships in fine and ultra-fine grained metals processed through constrained groove pressing

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ABSTRACT

Fine grained (FG) and ultra-fine grained (UFG) materials processed by severe plastic deformation exhibit beneficial hardness and tensile properties. Constrained groove pressing (CGP) were employed for fabrication of FG and UFG sheet metals and accomplished into different types of metals and alloys, such as commercial pure aluminum, AA3003 aluminum alloy, commercial pure copper, nickel, titanium and low carbon steels. Tensile and hardness characteristics in the FG and UFG sheets have been assessed with the aim of evaluating the hardness – strength relationship frequently established for coarse-grained metals and alloys ($\sigma_{UTS}/H_V = 3.45$). However, it was revealed that the FG and UFG materials do not obey widely used hardness – strength relationships in the conventional coarse grained structures. A new multiplicity factor less than 3, depending on the chemical composition of processed materials, is proposed in this study. This is attributed to different strain hardening response of the FG and UFG materials with slight work hardening before necking instability. In fine grained and ultra-fine grained structures failure does not occur in (or right after) the onset of necking point. That is, tensile deformation sustains significantly up to fracture point due to the role of superplasticity mechanisms.

1. Introduction and background

Mechanical properties of polycrystalline metals depend strongly upon the internal grain structure. It has been established that materials become stronger with controlling the grain size at ambient temperature through the Hall – Petch relationship [1–2]. For the aim of industrial applications, grain refinement is performed via implementation of thermo-mechanical processing through elevated temperature straining which leads to fine equiaxed grains. The "bottom-up" and "top-down" are two complementary approaches which have been introduced for fabrication of UFG metals [3]. In the first approach, ultra-fine grained material is processed with assembling individual atoms or nanoparticles such as inert gas condensation [4] and ball milling followed by solid state consolidation [5]. However, the production scale is limited and some degrees of residual porosity remains in the processed materials. In the second approach, UFG material is produced using large plastic straining of a coarse-grained fully-dense bulk solid. Severe plastic deformation (SPD) imposes very large strains into the bulk solid metals leading to producing exceptional grain refinement without any considerable changes in the overall dimensions of the sample [6–8].

Over recent years, UFG materials have been developed through SPD for producing "nano" structures in metals and alloys with superior properties for various structural and functional applications [6,7,9–13]. Several techniques have been introduced in the literature for SPD including; equal-channel angular pressing (ECAP) [14,15], high-pressure torsion (HPT) [16,17], multi-directional forging (MDF) [18], accumulative roll-bonding (ARB) [19], twist extrusion (TE) [20,21], and constrained groove pressing (CGP) [22,23]. Among these SPD techniques, ECAP, HPT, MDF, and TE are utilized for fabrication of FG and UFG component from bulk form metals. The ARB and CGP methods are two main SPD processes of sheet metals. CGP is an especially attractive process, as is easily implemented for processing of large FG and UFG sheets using a hydraulic press. Compared with ARB, in the CGP process a uniform simple shear deformation is applied to the component and the problem of un-bonded regions between the layers in ARB process is eliminated [23–25]. Present paper deals exclusively with

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the production of FG and UFG sheets from different metals and alloys utilizing the CGP process. At follow, the previous studies on the capability of CGP for fabrication of FG and UFG structures in different polycrystalline materials are reviewed.

CGP of commercial pure aluminum were studied by Shin et al. [22], Krishnaiah et al. [23], Zrnik et al. [26], Shirdel et al. [27], Hosseini et al. [28], Morattab et al. [29], Borhani et al. [30], Sajadi et al. [31], and Satheesh Kumar et al. [32]. These researchers have reported significant improvements of tensile strength and hardness up to two times with grain refinement to ~500 nm upon more than four CGP passes. Khakbaz et al. [33,34] investigated the tensile flow behavior (strain rate sensitivity, work hardening and fracture behavior) of CGP AA3003 aluminum alloy upon different processing passes. The characteristics of CGP copper were evaluated through studies by Krishnaiah et al. [25], and Rafizadeh et al. [35]. Also, studies on the CGP of Cu-Zn alloys were performed by Peng et al. [36–38], and Mou et al. [39]. Satheesh Kumar et al. [40,41] and Thirugnanam et al. [42] examined the capability of CGP process in developing fine-grain structures and mechanical characteristics in commercial pure nickel and titanium, respectively. SPD of low carbon steel sheets at ambient temperature was carried out by Khodabakhshi et al. [43–45] with utilizing CGP process up to four passes. This was followed by Alihosseini et al. [46]. In all mentioned SPD metals and alloys, grain refinement through SPD leads to considerable enhancement of mechanical properties. However, the severity of grain size reduction and subsequently the improvements of tensile strength and hardness are affected by the chemical composition of the examined sheets.

Understanding the hardness–tensile strength relationship for different materials is of scientific interest; (i) reliable hardness–-strength correlations allow firm overall mechanical properties examinations through fast, inexpensive, non-destructive and *in situ* indentation hardness testing instead of elaborate tensile testing, (ii) the hardness testing is among the best options for evaluating mechanical properties of new materials with small processed quantities [47]. Several empirical relationships between hardness and tensile results have been suggested for conventional polycrystalline materials in the published literatures [48–50]. Two widely used assumptions for prediction of strength-hardness relationship can be presented as follow [47,50–52]:

$$\frac{\sigma_{YS}}{H_v}=3 \quad (1)$$

$$\frac{\sigma_{UTS}}{H_v}=3.45 \quad (2)$$

where σ_{YS} is the yield stress, σ_{UTS} is the ultimate tensile strength, and H_v is the Vickers hardness. These relationships, being proposed for coarse-grained polycrystalline materials, are valid for ideal plastic response meaning no changes in the strength due to local plastic deformation during indenting process. However, a correction factor shall be employed while a material exhibit noticeable work hardening behavior [53].

Table 1
Properties of as-received utilized metals and alloys: Yield stress (σ_{YS}, MPa); ultimate tensile strength (σ_{UTS}, MPa); elongation to fracture (e_f, %); mean macro-hardness (H_v, Vickers); and average grain size (*AGZ*, μm).

FG/UFG sample	σ_{YS}	σ_{UTS}	e_f	H_v	*AGZ*
Commercial pure aluminum	45	100	31	25	50
AA3003 aluminum alloy	55	100	36	28.5	30
Commercial pure copper	70	217	41	44	78
Commercial pure nickel	200	349	46	95	34
Commercial pure titanium	325	455	60	125	50
Low carbon steel	204	288	39	98	30

Addressed in the literatures [28,33,44], work hardening behavior of FG and UFG materials processed by severe plastic deformation is totally different with un-processed coarse-grained metals and alloys. Therefore, using Eqs. (1) and (2) for engineering design of practical components, including FG and UFG materials, would result in considerable over-estimation or under-estimation of the materials' strength. In the present study, hardness and tensile data were obtained from the severely plastic deformed metals and alloys through CGP process to assess the hardness–tensile strength relationship for the FG and UFG materials. Moreover, by analyzing the data, empirical equations/predictions were developed for yield stress (σ_{YS}) and ultimate tensile strength (σ_{UTS}) on the bases of Vickers hardness (H_v) measurement.

2. Data collection and modeling procedure

In the present paper, data from previous published studies [22,23,25,28,29,32–35,40–45] on SPD of different metals and alloys through constrained groove pressing process were reviewed and included in the results. To this end, commercial pure aluminum up to six CGP passes [22,23,28,29], AA3003 (Al–Mn) aluminum alloy up to four passes [33,34], commercial pure copper up to three passes [25,35], commercial pure nickel up to three passes [40,41], commercial pure titanium up to three passes [42], and low carbon steel sheets up to four passes [43–45] were investigated. Since deformation behavior of various materials with different chemical compositions is not necessarily similar, the maximum number of employed CGP passes is varied. The experimental data including engineering stress–strain curves, tensile properties (yield stress, ultimate tensile strength, and elongation), Vickers hardness distributions, and microstructural details (grain/cell size) were extracted from previously reported literatures. Tensile tests were performed on the machined samples prepared from the center of SPD sheets according to ASTM Standard E8M [54]. Vickers macro-hardness measurements were carried out from the surface section of SPD sheets at regular distance intervals upon surface finishing treatments and average values for 10 examinations were reported. Microstructural characteristics were monitored through X-ray diffraction (XRD) and transmission electron microscopy (TEM) analysis. Statistical analysis of the collected data (*i.e.* mechanical properties) was performed in order to assess and model the related hardness–tensile strength relationship for these FG and UFG materials.

3. Results and discussion

3.1. Characteristics of the SPD metals and alloys

Table 1 expresses the initial microstructural/mechanical characteristics of the tested commercial pure aluminum, AA3003 alloy, commercial pure copper, nickel, titanium, and low carbon steel sheets before SPD in the annealed condition. The evolutions in the tensile properties of these materials as a function of CGP pass number and equivalent plastic strain after SPD are demonstrated in Fig. 1a–f. As seen, with increasing the CGP pass number (or equivalent plastic strain), σ_{YS} and σ_{UTS} increase continuously and grain structure becomes finer. In all materials, the difference between σ_{YS} and σ_{UTS} reduces indicating decrease in the strain hardening and increase in the strain rate sensitivity. In commercial pure aluminum (Fig. 1a), AA3003 aluminum alloy (Fig. 1b), commercial pure titanium (Fig. 1e), and low carbon steel (Fig. 1f), elongation decreases drastically after first CGP pass, but the rate of elongation descent at following passes fallen considerably. Elongation of commercial pure copper reduces continuously by