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Analysis on dynamic tensile extrusion behavior of UFG OFHC Cu

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Abstract. Dynamic tensile extrusion (DTE) tests with the strain rate order of ~10^5 s^{-1} were conducted on coarse grained (CG) Cu and ultrafine grained (UFG) Cu. ECAP of 16 passes with route B_c was employed to fabricate UFG Cu. DTE tests were carried out by launching the sphere samples to the conical extrusion die at a speed of ~475 m/sec in a vacuumed gas gun system. UFG Cu was fragmented into 3 pieces and showed a DTE elongation of ~340%. CG Cu exhibited a larger DTE elongation of ~490% with fragmentation of 4 pieces. During DTE tests, dynamic recrystallization occurred in UFG Cu, but not in CG Cu. In order to examine the DTE behavior of CG Cu and UFG Cu under very high strain rates, a numerical analysis was undertaken by using a commercial finite element code (LS-DYNA 2D axis-symmetric model) with the Johnson - Cook model. The numerical analysis correctly predicted fragmentation and DTE elongation of CG Cu. But, the experimental DTE elongation of UFG Cu was much smaller than that predicted by the numerical analysis. This difference is discussed in terms of microstructural evolution of UFG Cu during DTE tests.

1. Introduction

The dynamic tensile extrusion (DTE) technique is a newly developed mechanical test [1]. In the ordinary DTE test, a spherical sample launched at high velocity passes through an open conical die. Due to the smaller die exit diameter than the sample diameter, the sample experiences severe tensile deformation. Therefore, the DTE test can characterize the mechanical response of materials under both high strain rate and high strain circumstances. The DTE technique has been applied to coarse grained (CG) pure metals such as Cu [1], Ta [2], Zr [3], etc. In the case of cubic CG metals (i.e. Cu and Ta), recrystallization hardly occurred during DTE although significant adiabatic heating is expected in association with high strain rate deformation (usually higher than 10^5 s^{-1}). Instead, recovered microstructures were dominant such as elongated grains, micro bands, elongated subgrains, and equiaxed subgrains as a function of deformation. Unlike cubic metals, HCP CG Zr exhibited recrystallization which was rationalized by adiabatic heating over α/β phase transformation temperature.

Extensive and intensive researches during past two decades clearly reveal that ultrafine grained (UFG) materials exhibit very different mechanical and thermal responses from CG materials. There are several studies on mechanical behavior of UFG materials at high strain rates [4]. However, the strain rate employed in those studies (typically 10^3 s^{-1} order) was quite lower than that being attainable in the DTE test. Therefore, the mechanical response and corresponding microstructural evolution of UFG materials at strain rate faster than 10^5 s^{-1} order is hardly reported in literature at present.

Meanwhile, the constitutive models involving external and internal variables are commonly employed to describe the mechanical behavior of materials. In particular, extrapolation of the constitutive models is very helpful to predict the mechanical behavior of materials subjected to extreme conditions where experimental works are difficult. Accordingly, several constitutive models have been developed and most of them has been shown their validity - whether they are empirical or physically-based. In terms of the strain rate and the grain size, comparison of the experimental DTE behavior of UFG materials with such models is expected to extend the validity of the models to more extreme conditions.

In line with the above mentioned, the DTE test were conducted on CG and UFG Cu and their DTE behavior was numerically analyzed. The present study is anticipated to provide further understanding of dynamic mechanical behavior of UFG materials and useful information for constitutive modeling under extreme conditions.

2. Experimental

Commercial OFHC Cu bars (20 mm diameter) were annealed at 900 C for 1 hr. Some annealed bars were subjected to 16 passes equal channel angular pressing (ECAP) with route B_c in order to fabricate equiaxed UFG Cu. The sphere samples of 7.62 mm diameter were machined from the central part of the annealed bars and ECAP-ed bars for DTE tests. DTE tests were carried out by using an all-vacuumed gas gun system which consists of the gas gun, the sample flying barrel, the DTE die chamber, and the sample recovery station ; the details of the DTE equipment are described elsewhere [5]. The velocity of sample in this experiment was ~475 m/sec upon reaching the DTE die. After DTE tests, the sample fragments were soft recovered. The numbers and the order of fragments exiting the die were confirmed by the high speed photography. Besides, the complete fragment recovery was ensured by comparing the weight of all fragments with that of the initial sample. A routine microstructural observation were made on CG and UFG Cu before and after the DTE tests with optical microscopy, scanning electron microscopy, transmission electron microscopy, and electron backscattered diffraction (EBSD).

The DTE behavior of CG and UFG Cu was numerically analyzed by using a commercial finite element code (LS-DYNA 2-dimensional axis-symmetric model [6]). The Johnson - Cook model was employed in the numerical analysis. Five unknown parameters in the Johnson - Cook model were obtained by conducting tensile tests at 10^{-3} s^{-1} and 1 s^{-1} and compression tests at ~4000 s^{-1} on CG and UFG Cu ; tensile tests and compression tests were carried out on a hydraulic universal testing machine and a split Hopkinson pressure bar tester, respectively. In the numerical simulation process, the 2D R-adaptive re-meshing was done in order to prevent severe distortion of the mesh. That is, a completely new mesh was created every 1 μsec in order for the elements to keep a regular shape and a characteristic dimension. The new mesh is initialized from the old mesh by a least square approximation. The simulation results were compared with the experimental ones in terms of total DTE elongation (sum of the axial elongation of individual fragment) and the number and the dimension of fragments.

3. Results and Discussion

3.1. Summary of microstructure evolution

Microstructural evolution during DTE was described in detail in Ref. [5], so its summary is provided in this section. Before DTE, in the case of CG Cu, the average grain size was ~ 120 μm, and texture was weak. Meanwhile, UFG Cu consisted of equiaxed grains of the average size of ~0.35 μm with a high angle boundary faction ~0.66. The strong texture of {111} <110> was developed by ECAP with route B_c.

Soft-recovered fragments of CG and UFG Cu after DTE are shown in Fig. 1a ; the conical fragments (fragment 1 for each sample) are the remnants remained in the DTE die. CG Cu was fragmented into 4 pieces while UFG Cu was fragmented into 3 pieces. The average DTE elongations of the three runs for each sample were ~490 % and ~340 % for CG Cu and UFG Cu, respectively ; DTE elongation = $(\Sigma d_i - d_o)/d_o$ where d_i is the axial length of the i^{th} fragment and d_o is the initial sample diameter.

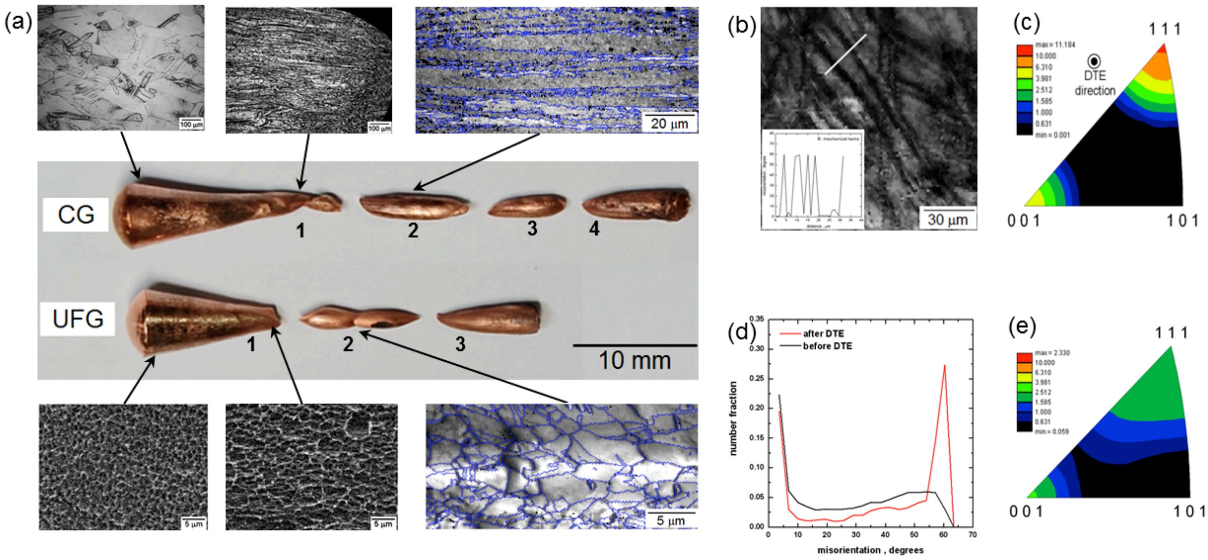

Fig. 1 (a) DTE fragments of CG Cu and UFG Cu in sequence exiting the DTE die and corresponding microstructures; the DTE direction is from left to right, (b) mechanical twins observed in fragment 2 of CG Cu ; the inset is a plot of misorientation distribution across the white line, (c) EBSD IPF of fragment 2 of CG Cu, (d) boundary misorientation distribution of fragment 2 of UFG Cu, and (e) EBSD IPF of fragment 2 of UFG Cu.

Microstructure of fragments of CG Cu exhibited severely elongated grains without evidence of dynamic recrystallization (DRX). Instead, mechanical twins were frequently observed (Fig. 1b); mechanical twinning dissipates energy and therefore delays formation of RRX enclaves [7]. A double fiber texture of strong <111> and moderate <100> parallel to the deformation axis was developed (Fig. 1c), as typically observed in uniaxially processed FCC metals and alloys such as wire drawing [8]. Unlike CG Cu, fully recrystallized grains of ~3.5 μm were observed in fragment 2 of UFG Cu. Correspondingly, the frequency of 60° misorientation remarkably increased due to reformation of annealing twins during DRX (Fig. 1d). The EBSD inverse pole figure (IPF) of fragment 2 of UFG Cu (Fig. 1e) shows the moderate <100> and weak <111> fiber textures which coincide with the recrystallization texture of uniaxially deformed Cu.

3.2. Constitutive behavior

Fig. 2 shows true stress - strain curves of CG Cu (Fig. 2a) and UFG Cu (Fig. 2b) at different strain rates. As usual, regardless of the strain rate, CG Cu exhibited extensive strain hardening after low stress yielding while near-perfect plasticity without strain hardening after high stress yielding occurred in UFG Cu. The deformation behavior of CG Cu and UFG Cu was modeled by using the Johnson - Cook (J-C) model by considering thermal softening associated with adiabatic heating ;

$$\sigma = \left(\sigma_o + B\varepsilon^n\right)\left(1 + C\ell n\frac{\dot{\varepsilon}}{\dot{\varepsilon}_o}\right)\left[1 - \left(\frac{T - T_r}{T_m - T_r}\right)^m\right] \tag{1}$$

$$T = T_r + \frac{\beta}{\rho C_p}\int_0^{\varepsilon_p}\sigma(\varepsilon, \dot{\varepsilon}, T)d\varepsilon \tag{2}$$

where σ is the stress, σ_0 is the yield stress, $\dot{\varepsilon}$ is the strain rate, $\dot{\varepsilon}_0$ is the reference strain rate (usually 1 s^{-1}), T is the material temperature, T_m is the melting temperature, T_r is the reference temperature at which σ_0 is measured, β is the heat conversion coefficient (0.9 for metals), ρ is the density, and C_p is the specific heat at constant pressure. σ_0, B, C, n, and m are the constants to be determined from the experimental data; their values for the present case are listed in Table 1. As seen in Fig. 2, the curves predicted by the J-C model with the parameters in Table 1 (black lines) shows good agreement with experimental ones (red lines).

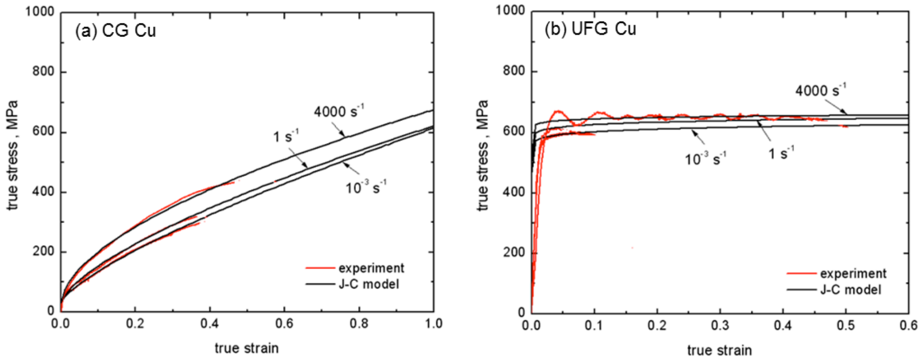

Fig. 2 True stress - strain curves of (a) CG Cu and (b) UFG Cu at different strain rates.

Table 1. The Johnson - Cook parameters for CG Cu and UFG Cu

	σ_0 (MPa)	B (MPa)	n	C	m
CG Cu	32	606	0.67	0.004	1.02
UFG Cu	502	146	0.09	0.009	1.03

3.3. Numerical simulation results

As aforementioned, the present DTE behavior of CG Cu and UFG Cu was numerically by the LS-DYNA FEM code with the 2D R-adaptivity re-meshing and the above J-C model. A simulation example for strain after complete fragmentation at ~60 μsec is presented in Fig. 3. The number of fragment is correctly predicted by simulation, i.e. 4 fragments for CG Cu and 3 fragments for UFG Cu. The simulated total length of CG Cu and UFG Cu was 38.1 mm (DTE elongation ~400%) and 33.8 mm (DTE elongation ~320%), respectively. The simulated DTE elongation of UFG Cu is in reasonable agreement with the experimental one (~340 %). In contrast, for CG Cu, the experimental DTE elongation (~490 %) was larger than the simulated one. As shown in Fig. 1a, the tip of fragment 1 of CG Cu shows macro-shear deformation. A relatively large localized deformation due to macro-shear at the tip may be a reason for error in DTE elongation simulation for CG Cu.

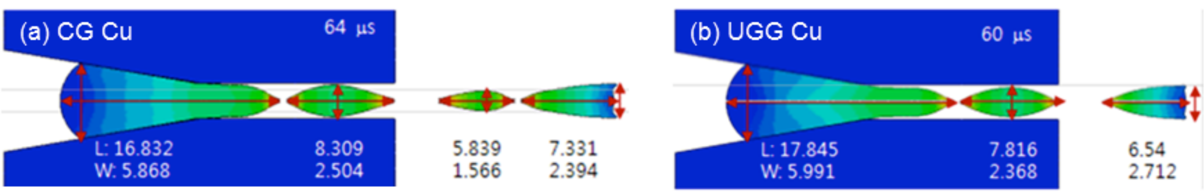

Fig. 3 FEM simulation result showing the number and dimension (in mm) of the DTE fragment of (a) CG Cu, and (b) UFG Cu.

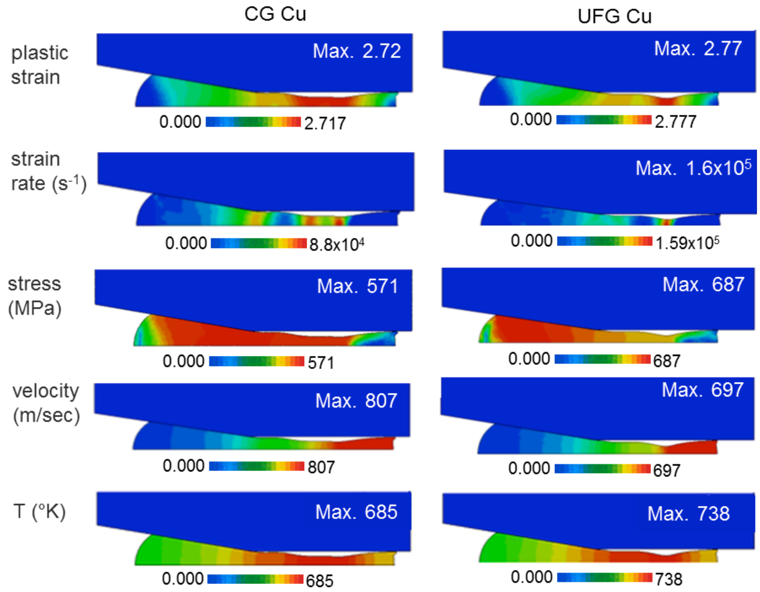

Fig. 4 Comparison of strain, strain rate, stress, velocity and temperature distribution between CG Cu and UFG Cu at 40 μsec.

Distribution of strain, strain rate, stress, velocity and temperature in the CG Cu and UFG Cu samples at 40 μsec was presented in Fig. 4 ; it is worth mentioning that the values of these constitutive variables increased until complete fragmentation (i.e. to ~60 μsec). The maximum strain was developed at the necked region in both sample with the similar value. The strain at the necked region upon fragmentation reached ~5.5. Simulation revealed more localized necking in UFG Cu, possibly causing smaller DTE elongation than CG Cu. In both sample, the strain rate was also maximum at the necked region with 10^5 s^{-1} order which is at least one order or more higher than that achievable by the ordinary Hopkinson test. The maximum strain rate of UFG Cu was slightly higher than that of CG Cu, corresponding to more diffused strain distribution in the latter. The stress imposed by impacting the die was higher in UFG Cu due to its higher yield and flow stresses. The sample velocity was maximum at the exiting tips by the inertia effect. The tip (i.e. maximum) velocity of CG Cu was faster than that of UFG Cu. As expected considerable temperature rise occurred by adiabatic heating. Temperature at the stretched portion in the straight channel was close to or even higher than 700 °K which is about 0.5 T_m. It was locally over 800 °K (~0.6 T_m of Cu) upon fragmentation.

Recrystallization of cold-worked metals and alloys usually occurs above ~0.5 T_m. Therefore the present adiabatic heating is enough for DRX in all DTE samples. However, as shown in Fig. 1a, DRX did not occur in CG Cu. Instead, mechanical twins were often observed as shown in Fig. 1b. It was reported that mechanical twinning does not store the strain energy as much as dislocations [9]. Subsequently, it was demonstrated [8] that, under dynamic loading, mechanical twinning behaves as an active energy dissipation source and therefore it suppresses DRX. UFG Cu was in the higher energy state and contain a larger area of grain boundaries compared to CG Cu due to ECAP. In addition, the critical stress for mechanical twinning increases with decreasing the grain size [10]. These factors are favorable for relatively easy DRX in UFG Cu. Under quasi-static loading which does not accompany DRX, UFG materials usually exhibit very limited ductility with shear mode. Under dynamic loading as the present case, DRX of several μm order grain size occurred in UFG Cu and it resulted in ductile failure with necking, in spite of its inferior DTE elongation to the CG sample.

4. Summary

1. A series of dynamic tensile extrusion (DTE) tests, the newly developed mechanical test at high strain rate, was conducted on coarse grained (CG) Cu and ultrafine grained (UFG) Cu. CG Cu exhibited higher DTE elongation than UFG Cu.
2. During DTE, dynamic recrystallization occurred in UFG Cu. In contrast, the DTE microstructure of CG Cu was manifested by severely elongated grains along the DTE direction with mechanical twins. But no evidence of DRX was found in CG Cu.
3. Numerical simulation employing the mesh adaptivity and the Johnson - Cook model involving thermal softening by adiabatic heating reasonably predicted the fragmentation behavior of CG Cu and UFG Cu in terms of DTE elongation and the number of fragments.
4. Numerical simulation revealed more localized deformation in UFG Cu than in CG Cu. In addition, it predicted significant adiabatic temperature rise over 0.5 T_m. In addition, it revealed that the strain rate of 10^5 s^{-1} order can be achieved by the DTE test.

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