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jmr&t Journal of Materials Research and Technology

www.jmrt.com.br

Original Article

Evolution of hardness in ultrafine-grained metals processed by high-pressure torsion☆

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ARTICLE INFO

Article history:
Received 13 May 2014
Accepted 11 June 2014
Available online 19 July 2014

Keywords:
Hardness
High-pressure torsion
Homogeneity
Severe plastic deformation

ABSTRACT

The processing of metals through the application of high-pressure torsion (HPT) provides the potential for achieving exceptional grain refinement in bulk metals. Numerous reports are now available demonstrating the application of HPT to a range of pure metals and simple alloys. In practice, excellent grain refinement is achieved using this processing technique with the average grain size often reduced to the true nano-scale range. Contrary to the significant grain refinement achieved in metals during HPT, the models of the hardness evolution are very different depending upon the material properties. For a better understanding of the material characteristics after conventional HPT processing, this report demonstrates the hardness evolutions in simple metals including high-purity Al, commercial purity aluminum Al-1050, ZK60A magnesium alloy and Zn-22% Al eutectoid alloy after processing by HPT. Separate models of hardness evolution are described with increasing equivalent strain by HPT. Moreover, a new approach for the use of HPT is demonstrated by synthesizing an Al–Mg metal system by processing two separate commercial metals of Al-1050 and ZK60A through conventional HPT processing at room temperature.

☆ Paper presented in the form of an abstract as part of the proceedings of the Pan American Materials Conference, São Paulo, Brazil, July 21st to 25th 2014.

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http://dx.doi.org/10.1016/j.jmrt.2014.06.002

1. Introduction

The processing of metals through the application of severe plastic deformation (SPD) provides the potential for achieving exceptional grain refinement in bulk metal solids [1]. There are numbers of publications to date demonstrating the significance of SPD techniques but, in general, equal-channel angular pressing (ECAP) [2] and high-pressure torsion (HPT) [3] are accepted as the major SPD methods [4]. For ECAP processing, a sample, in a rod or bar shape, is pressed through a die constrained within a channel so that the microstructure receives shear straining leading to grain refinement to grain sizes in the submicrometer range. For processing through HPT, a sample, in the shape of a disk, is subjected to a high applied pressure and concurrent torsional straining so that the severe deformation leads to submicrometer grains or even true nanometer grains within the metal sample [3]. Accordingly, the present report describes recent published data on simple metals and common alloys processed by HPT.

The essential principles in HPT processing are that the strain introduced within the HPT disk sample is markedly inhomogeneous. Specifically, when a disk is processed by HPT, the equivalent von Mises strain, ε_{eq}, is given by a relationship of the form [5,6]

$$\varepsilon_{eq} = \frac{2\pi N r}{h\sqrt{3}} \tag{1}$$

where N is the number of HPT revolutions and r and h are the radius and height (or thickness) of the disk, respectively. Therefore, it is apparent that the torsional straining imposed within the disk sample is dependent upon the distance from the center of the disk, $r = 0$, where there is theoretically no straining by the torsional processing. This implies that there is an inevitable inhomogeneity both in microstructures and hardness in the disk sample processed by HPT. Nevertheless, it is demonstrated experimentally that both sufficiently high numbers of HPT turns and high applied pressures lead to homogeneous microstructures and hardness throughout the disk [7,8].

Although there is significant grain refinement through HPT processing, the models of hardness evolution into homogeneity are not consistent between the different metals and alloys [9,10]. The present report is initiated to provide recent experimental results on the hardness evolution observed in a series of representative metals and alloys including high-purity Al, commercial purity aluminum Al-1050, ZK60A magnesium alloy and Zn-22% Al eutectoid alloy after they are processed through HPT. These materials are selected because, as also shown in a recent report summarizing the hardness evolution models for metals after HPT [9], high-purity Al [10–18] and Zn–Al alloy [10,19–22] demonstrate unique softening behaviors after HPT compared with most common metals which generally exhibit strain hardening during deformation.

The present report demonstrates two separate contents. In the following two sections, the three separate models of hardness evolution are displayed showing recent experimental results in the metals processed through HPT processing. In the last section, as a new approach for the use of HPT, a potential of improving the upper limit of hardness is demonstrated in the Al–Mg system when processed from two separate commercial metal disks of Al-1050 and ZK60A through conventional HPT processing.

2. Separate models of hardness evolution through HPT

2.1. *Commercially pure Al-1050 aluminum alloy and ZK60A magnesium alloy*

In this section, two different materials of commercial purity aluminum Al-1050 and ZK60A magnesium alloy are selected for demonstrating the general model of hardness evolution through HPT where it is observed in most metals showing strain hardening.

A separate billet was machined from an as-received bar of a commercial purity (99.5%) aluminum Al-1050 containing 0.30% Fe and 0.25% Si [23,24] and an as-extruded bar of ZK60A, respectively. These billets of the alloys were sliced and polished to have final disk shapes with a diameter of 10 mm and a thickness of ∼0.8 mm. All disks were processed at room temperature in quasi-constrained HPT conditions [25,26] with the procedure described earlier [12]. A series of the disks was processed for both alloys under a compressive pressure of $P = 6.0$ GPa and a rotation speed of 1 rpm for total revolutions of $N = 1/4$, 1 and 5 turns.

After processing, Vickers microhardness measurements were conducted on the polished surfaces of both the Al-1050 and ZK60A disks. For the Al-1050 disks, the measurements were taken over the total surface of each disk with an increment of 0.6 mm between the datum points on both axes, X and Y. The measured microhardness values, Hv, were used to construct a three-dimensional color-coded contour map for each disk in order to show the distributions of the local microhardness on the surfaces of the HPT disks after 1/4, 1 and 5 turns. For the ZK60A alloy, the measurements were conducted along the diameters on the polished surfaces of the processed disks. As described earlier [12], each Hv value at the selected representative position along the disk diameter was calculated from four separate cruciform positions lying at a distance of 0.15 mm so that the individual positions were separated by incremental distances of 0.3 mm. For both metals, in order to remove the influence of the possible hardness gradation through the disk thickness direction [18,27], all measurements were conducted on the surfaces at the mid-sections through the disk heights.

Fig. 1 shows the microhardness variation in the three-dimensional color-coded contour maps for the Al-1050 disks processed by HPT for (a) 1/4 turn, (b) 1 turn and (c) 5 turns where the Hv values are presented by unique colors given at the right in the figure [23,24]. For references, the average Hv value of ∼25 was measured as the initial hardness in the as-received condition before HPT processing [28]. It is apparent that high hardness with Hv ≈60–65 was recorded at the peripheral regions of r ≈3–5 mm in the disk after processing for 1/4 turn as shown in Fig. 1(a) and there is a sharp drop in hardness toward the center of the disk with the minimum Hv value of ∼45 at $r = 0$. After HPT for 1 turn as shown in Fig. 1(b), the