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The effect of high-pressure torsion on the microstructure and properties of magnesium

Roberto B Figueiredo[1,2], Shima Sabbaghianrad[2], Terence G Langdon[2,3]

[1] Department of Materials Engineering and Civil Construction, Universidade Federal de Minas Gerais, Belo Horizonte, MG 31270-901, Brazil
[2] Departments of Aerospace & Mechanical Engineering and Materials Science. University of Southern California, Los Angeles, CA 90089-1453, USA
[3] Materials Research Group, Faculty of Engineering and the Environment, University of Southampton, Southampton SO17 1BJ, UK

E-mail:figueiredo@demc.ufmg.br, ssabbagh@usc.edu, langdon@soton.ac.uk

Abstract. High-pressure torsion provides the opportunity to introduce significant plastic strain at room temperature in magnesium and its alloys. It is now established that this processing operation produces ultrafine-grained structures and changes the properties of these materials. The present paper shows that the mechanism of grain refinement differs from f.c.c. and b.c.c. materials. It is shown that fine grains are formed at the grain boundaries of coarse grains and gradually consume the whole structure. Also, the processed material exhibits unusual mechanical properties due to the activation of grain boundary sliding at room temperature.

1. Introduction

Magnesium exhibits poor formability at room temperature due to the limited number of slip systems readily available. Basal slip and twinning play a major role in accommodating plastic deformation but these mechanisms can only withstand a few percent strain. It has been shown that the maximum strain during compression of pure magnesium with grain size of ~24 µm is in the range of 15%~20% [1]. The maximum elongation of as-cast magnesium in tension is ~5% [2]. EBSD *in situ* tensile [3] and compression [4] testing have shown that slip is accommodated by basal slip and twinning and very limited non-basal slip takes place at low temperatures.

However, recent papers have shown a change in deformation behavior of pure magnesium when the grain size is reduced below a certain level. Hall-Petch breakdown was reported in pure magnesium with grain sizes of several microns [5]. An increase in strain accommodation during low strain-rate compression of magnesium takes place in samples with ~2.7 µm [1]. Finally, a recent paper has shown that grain refinement of magnesium processed by high-pressure torsion leads to a remarkable increase in elongation during tension [2]. This change in deformation behavior is attributed to the onset of grain boundary sliding at room temperature in fine-grained pure magnesium [1, 2, 5].

Thus, high-pressure torsion provides the opportunity to produce magnesium samples with extreme ductility at room temperature. For this, a homogeneous distribution of ultrafine grains must be achieved throughout the sample. The mechanism of grain refinement in pure magnesium processed by severe plastic deformation at high temperatures differs from other metallic materials with b.c.c. and f.c.c. structures [6-8]. However, very limited information is available on microstructure evolution of magnesium processed by severe plastic deformation at room temperature. A recent paper reported the grain structure of pure magnesium [2] at different stages of processing but the area analysed was limited. The present paper aims to evaluate the grain structure at different stages of HPT processing considering larger areas and evaluate the texture evolution.

2. Experimental material and procedures

The material used in this research was commercial purity magnesium. Cylindrical billets with 10 mm diameter were machined from a cast slab. Discs with ~1.0 mm thickness were cut from billets and ground to ~0.85 mm. High-pressure torsion was carried out using quasi-constrained anvils. The nominal pressure was 6.0 GPa and the samples were processed at room temperature at 1 rpm. Samples were processed to 1/8, 1/2 and 10 turns.

The processed discs were ground and polished to a mirror-like finish using diamond suspensions. A final polishing step with colloidal silica polishing was required to obtain clear EBSD images. EBSD characterization was carried out using a JEOL JSM-7001F scanning electron microscope operating at 7 kV. The microstructure was characterized at mid-radius position of the discs.

Miniature tensile specimens with ~1.0 mm gauge length were machined by spark-erosion from discs processed by 10 turns of HPT. The gauge areas of the specimens were located near the mid-radius positions of the discs. Tensile tests were carried out at constant cross-head displacement rate with initial strain rates in the range 10^{-5} – 10^{-1} s^{-1}. Engineering stress vs. strain curves were determined from the load vs. displacement data.

3. Results and discussion

Figure 1 shows the inverse pole figures of the grain structure at the mid-radius positions of discs processed to different numbers of turns of HPT. Coarse grains of ~10 μm and ultrafine grains are observed in the material processed to 1/8 turn. This multimodal grain size distribution is typical of magnesium and magnesium alloys processed by equal-channel angular pressing at high temperatures and is attributed to a different mechanism of grain refinement in these materials [6-8]. Inhomogeneous grain size distribution has also been reported in Zr processed by HPT [9] which suggests this might be a common feature in h.c.p. metals. The microstructure of the sample processed to 1/2 turn is largely composed of ultrafine grains although a small number of grains with a few microns are still observed. Processing by 10 turns of HPT does not change significantly the structure but decreases the number of grains larger than 1 μm.

Figure 2 shows the frequency distribution of the grain boundary misorientations at different stages of HPT processing. A high frequency of low-angle boundaries is observed at 1/8 turn but the overall fraction of these boundaries is significantly smaller than observed in b.c.c. or f.c.c. metals processed to low numbers of turns in HPT [10-12]. Further processing leads to an increase in high-angle boundaries and a pronounced peak in distribution is observed around 30º. A high frequency of grain boundaries with this misorientation range is predicted in magnesium with a basal fiber texture [13]. It is worth noting a high frequency of grain boundaries with misorientation in the range 85º-90º which is associated with twinning [14].

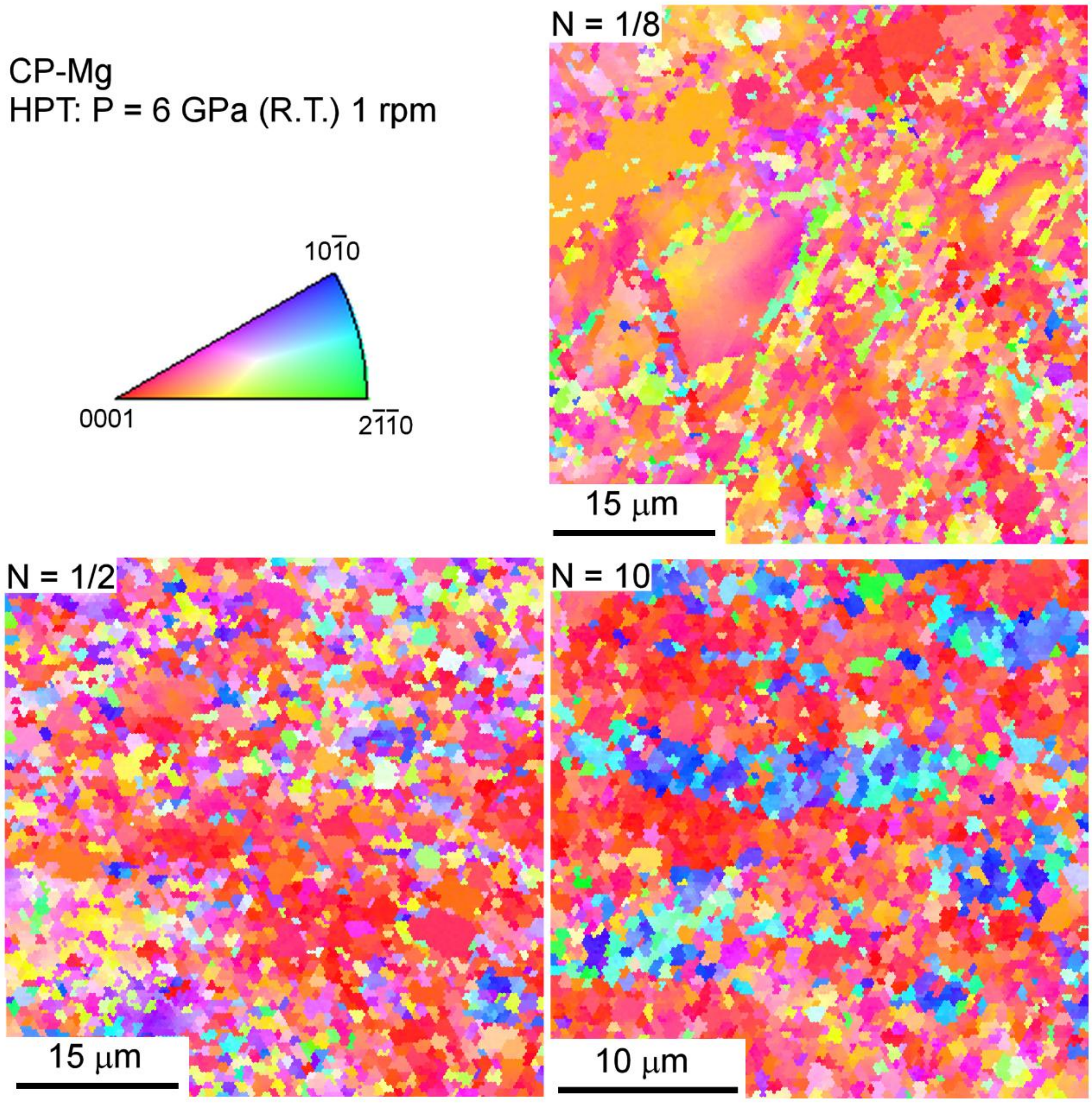

Fig. 1. Inverse pole figure maps of the microstructures at the mid-radius positions of samples processed by 1/8, 1/2 and 10 turns of HPT.

The inverse pole figures of the samples processed to different numbers of turns of HPT is shown in Fig. 3. An alignment of the c-axis with the compression axis is readily observed in the early stage of processing at 1/8 turn and this alignment persists with further processing. This was also observed in an AZ31 alloy processed by HPT [15]. The results also suggest an increase in intensity of texture with increasing numbers of turns. The formation of a basal fiber texture agrees with the high frequency of grain boundaries with misorientations of 30º.

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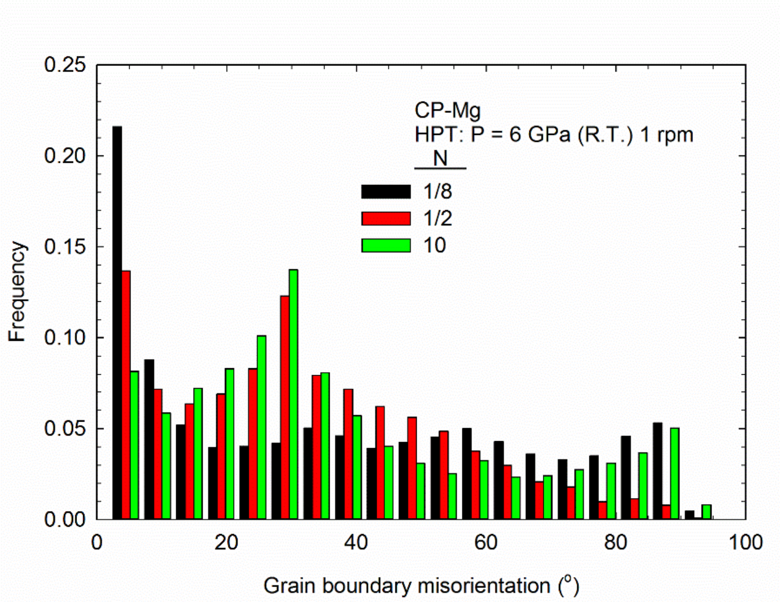

Fig.2. Frequency of grain boundary misorientation distribution at different stages of HPT.

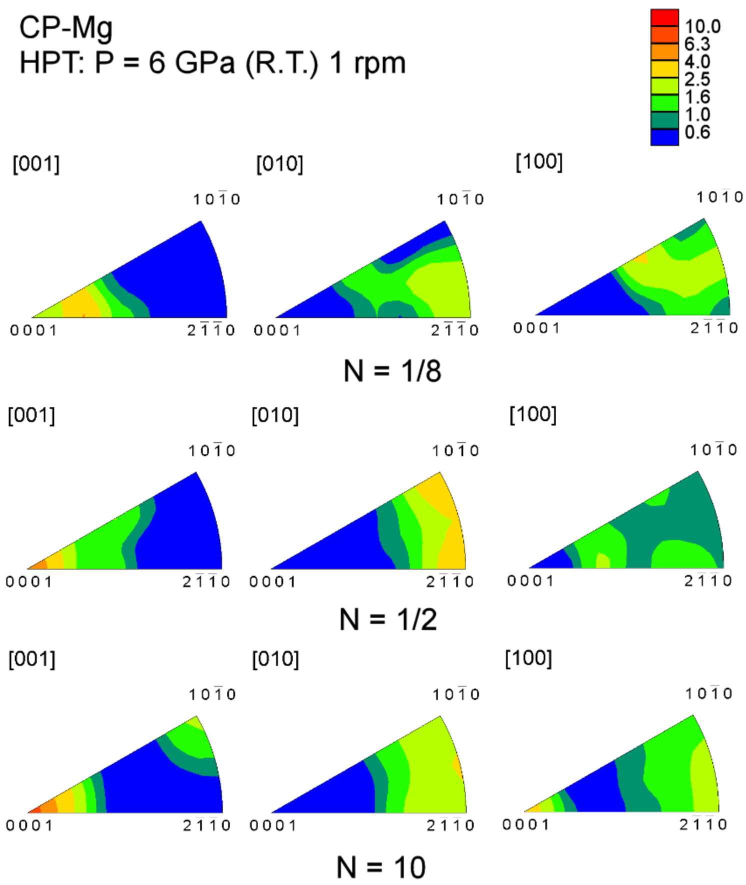

Fig. 3. Inverse pole figures at different stages of HPT processing.

The engineering stress vs. engineering strain curves of the material processed by 10 turns of HPT are shown in Fig. 4. The curves obtained during testing at different strain rates show that this parameter plays a major role in the deformation response of this material. The maximum flow stress observed during testing at 10^{-5} s^{-1} is ~50 MPa and increasing the strain rate to 10^{-1} s^{-1} leads to a 4-fold increase in flow stress. This agrees with the high strain rate sensitivity reported for fine-grained magnesium [1, 2, 5]. Also, the curves show a pronounced increase in elongation with decreasing strain rate which confirms that HPT processing enhances the ductility of magnesium.

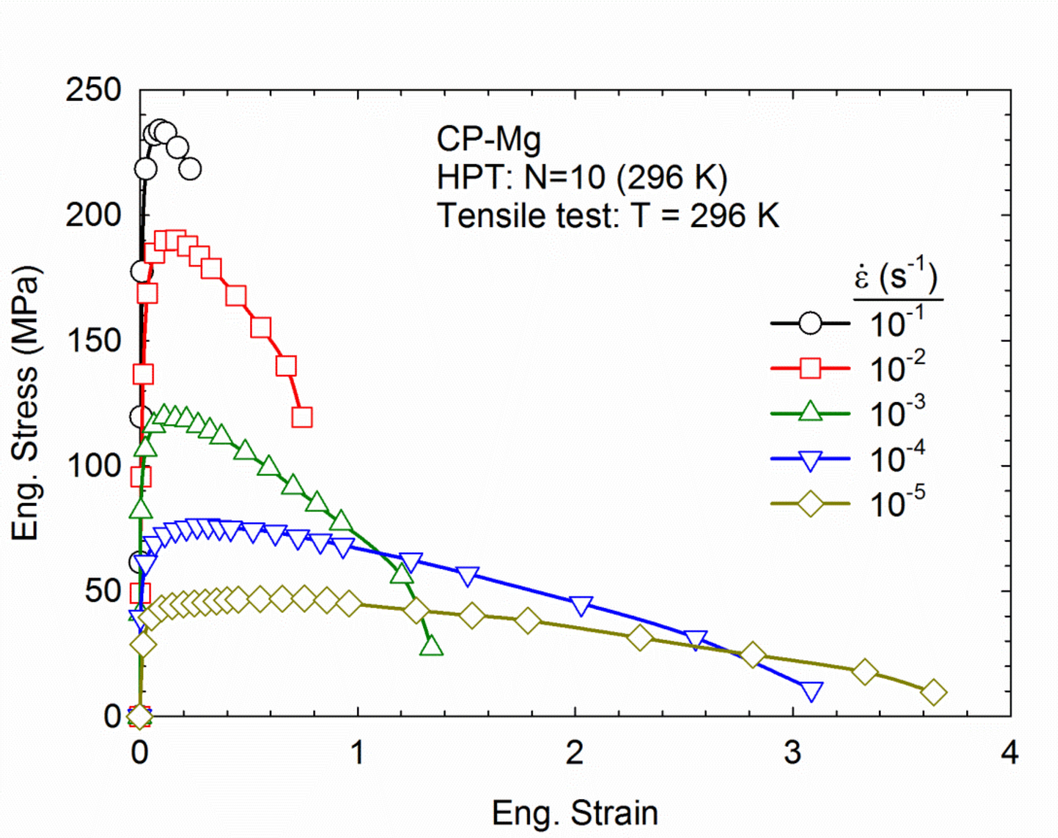

Fig. 4. Engineering stress versus engineering strain for the CP-Mg alloy processed by HPT.

4. Conclusions

The mechanism of grain refinement of magnesium differs from that observed in f.c.c. and b.c.c. metals. A multi-modal grain size distribution is observed in the early stage of deformation and gradually evolves to a homogeneous distribution of ultrafine grains.

The distribution of grain boundary misorientations shows significantly lower frequencies of low-angle boundaries in the early stage of processing compared to aluminium and iron. A high frequency of misorientations around 30º is observed at 1/2 and 10 turns of HPT.

A basal fiber texture with the c-axis aligned to the torsion axis develops in the early stage of HPT processing and persists with increasing numbers of turns.

HPT processing improves the ductility of magnesium.

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References

[1] Figueiredo RB, Poggiali FSJ, Silva CLP, Cetlin PR, Langdon TG. 2016 *J. Mater. Sci.* **51** 3013-24.
[2] Figueiredo RB, Sabbaghianrad S, Giwa A, Greer JR, Langdon TG. 2017 *Acta Mater.* **122** 322-31.
[3] Cepeda-Jiménez CM, Molina-Aldareguia JM, Pérez-Prado MT. 2015 *Acta Mater.* **84** 443-56.
[4] Cepeda-Jiménez CM, Molina-Aldareguia JM, Pérez-Prado MT. 2015 *Acta Mater.* **88** 232-44.
[5] Somekawa H, Mukai T. 2015 *Metall. Mater. Trans. A* **46A** 894-902.
[6] Figueiredo RB, Langdon TG. 2010 *J. Mater. Sci.* **45** 4827-36.
[7] Figueiredo RB, Langdon TG. 2009 *Int J Mater Res* **100** 1638-46.
[8] Figueiredo RB, Langdon TG. 2009 *J. Mater. Sci.* **44** 4758-62.
[9] Wang YB, Louie M, Cao Y, Liao XZ, Li HJ, Ringer SP, Zhu YT. 2010 *Scripta Mater.* **62** 214-217.
[10] Ivanisenko Y, Valiev RZ, Fecht HJ. 2005 *Mater. Sci. Eng. A* **390** 159-65.
[11] Ito Y, Horita Z. 2009 *Mater. Sci. Eng. A* **503** 32-6.
[12] Xu C, Horita Z, Langdon TG. 2010 *Mater. Trans.* **51** 2-7.
[13] del Valle JA, Pérez-Prado MT, Ruano OA. 2002 *Rev. Metall. Madrid* **38** 353-357.
[14] Partridge PG. 1967 *Metall. Rev.* **12** 169-94.
[15] Huang Y, Figueiredo RB, Baudin T, Helbert AL, Brisset F, Langdon TG. 2013 *Mater. Res.* **16** 577-85.