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Regular Article

Tunable elastic heterogeneity caused by deformation-induced magnetization in flexible metallic glass

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ABSTRACT

In this letter we explore the magnetization effect on mechanical properties of a ductile $Fe_{83}C_1B_{11}Si_2P_3$ metallic glass (MG). We firstly demonstrate that magnetic anisotropy can be systematically created by plastic deformation using high-load Berkovich indentation, and then provide compelling evidence by subsequent spherical nanoindentation which reveals tunable magnetization-induced submicron elastic heterogeneity. A new mechanism of magnetomechanical interaction, different from the alteration of "flow defect", is proposed for explaining the apparent softening in the region without plastic deformation. Our studies have significance for modification and controlling of the microstructure and mechanical properties of MGs with respect to magnetic effect.

The nanoscale structural and mechanical heterogeneity of metallic glasses (MGs) has been revealed and intensively studied by atomic force microscopy [1,2], nanoindentation [3] and other techniques [4,5]. Due to their metastable nature, the local structure and mechanical properties of MGs can be tuned by adjusting their thermal/mechanical histories through methods with a few thermo-mechanical variables, such as plastic deformation [6,7], changing cooling rate [8] and heat treatment [8,9]. For example, it was reported that severe plastic deformation caused by cold rolling [10,11], indentation [12] and high pressure torsion [13] can significantly soften MGs. Usually, such a property change was attributed to the introduction or annihilation of "flow defect" in the amorphous structure, such as free volume [14], shear transformation zone (STZ) [15], liquid-like region [4], flow unit [16] and so on [5]. However, it is noteworthy that the variation of "flow defect" is not the only mechanism that causes softening in MGs. For those with a nonzero magnetostriction coefficient (λ), magnetization can also change the microstructure and thus the mechanical properties [17–19]. In general, the magnetization can be induced by applied stress and/or magnetic field [17–19]. However, the magnetization effect on the microstructure and mechanical properties of macroscopically homogeneous MGs has been scarcely studied. In this letter, we use nanoindentation to study the magnetization effect on the mechanical properties of a model ductile $Fe_{83}C_1B_{11}Si_2P_3$ MG ribbon [20]. Submicron elastic heterogeneity is revealed in the stress-concentrated region without plastic deformation, and a mechanism of magnetomechanical interaction is proposed for explaining the obvious softening phenomenon.

$Fe_{83}C_1B_{11}Si_2P_3$ MG ribbon with good ductility with a thickness of 40 μm was fabricated in argon atmosphere with the single copper roller melt-spinning method at the wheel speed of 20 m/s. The fully amorphous structure of the ribbon was confirmed through X-ray diffraction (see Fig. S1 in the supplementary material). Different from the free surface, the side of the ribbon contacting with the roller during the preparation is full of surface irregularities and contains uncertain internal stress inhomogeneity. To create magnetic domain patterns in a controlled manner, a pattern of micro-indents was made on the flat and clean untreated free surface of the as spun ribbon through Berkovich indentation on the TI 950 TriboIndenter system (Hysitron Inc., Minneapolis, MN). The surface morphology and magnetic domain structure within the indentation pattern were examined by the Dimension Icon® Magnetic Force Microscopy (MFM) under the LiftMode with a constant lift height of 150 nm. The mechanical properties inside the high-load indentation pattern were then measured with the low-load spherical indention with a tip radius *R* of 184 nm at room temperature.

Fig. 1(a) shows the load-displacement (*P*-*h*) curves stemming from the programmed loading-holding-loading profile [the inset of Fig. 1(a)] with the Berkovich sharp indenter at the maximum load of 1 N. Consequently, significant shear bands (SBs) can be observed near the side of the triangle residual indentation at the surface of $Fe_{83}C_1B_{11}Si_2P_3$ ribbon suggesting plastic deformation [Fig. 1(b)]. A square pattern with four residual indentations labeled as 1, 2, 3 and 4 was created by

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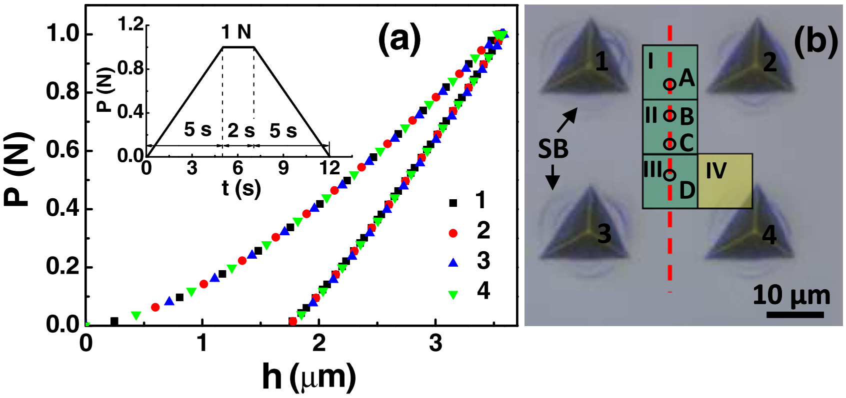

Fig. 1. (a) The *P-h* curves for four indentations of the square pattern with the inset showing the load-time (*P-t*) procedure for each indention. (b) The optical microscopic image of the pattern with the indentations spaced as 30 μm. The indentations are labeled as 1, 2, 3 and 4. The squares I, II, III and IV mark the regions detected with MFM. The circles A, B, C and D mark the nanoindentation positions, and the dashed line is the guide line. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

positioning the indentations 30 μm apart [Fig. 1(b)]. It is worth noting that the *P-h* curves for all the indentations override each other implying the uniformity of the MG ribbon at the micrometer scale.

The magnetic properties of the pristine and indented surface of the MG ribbon were examined with MFM. The phase image of the as spun ribbon is shown in Fig. 2(a). The phase degree varies between −0.18° and 0.18°, and no magnetic domain pattern is found within the resolution of MFM. The phase images of regions I, II and III marked by the green squares in Fig. 1(b) are shown in Fig. 2(b), (c) and (d), respectively. A strip-like magnetic domain pattern with a width less than 200 nm

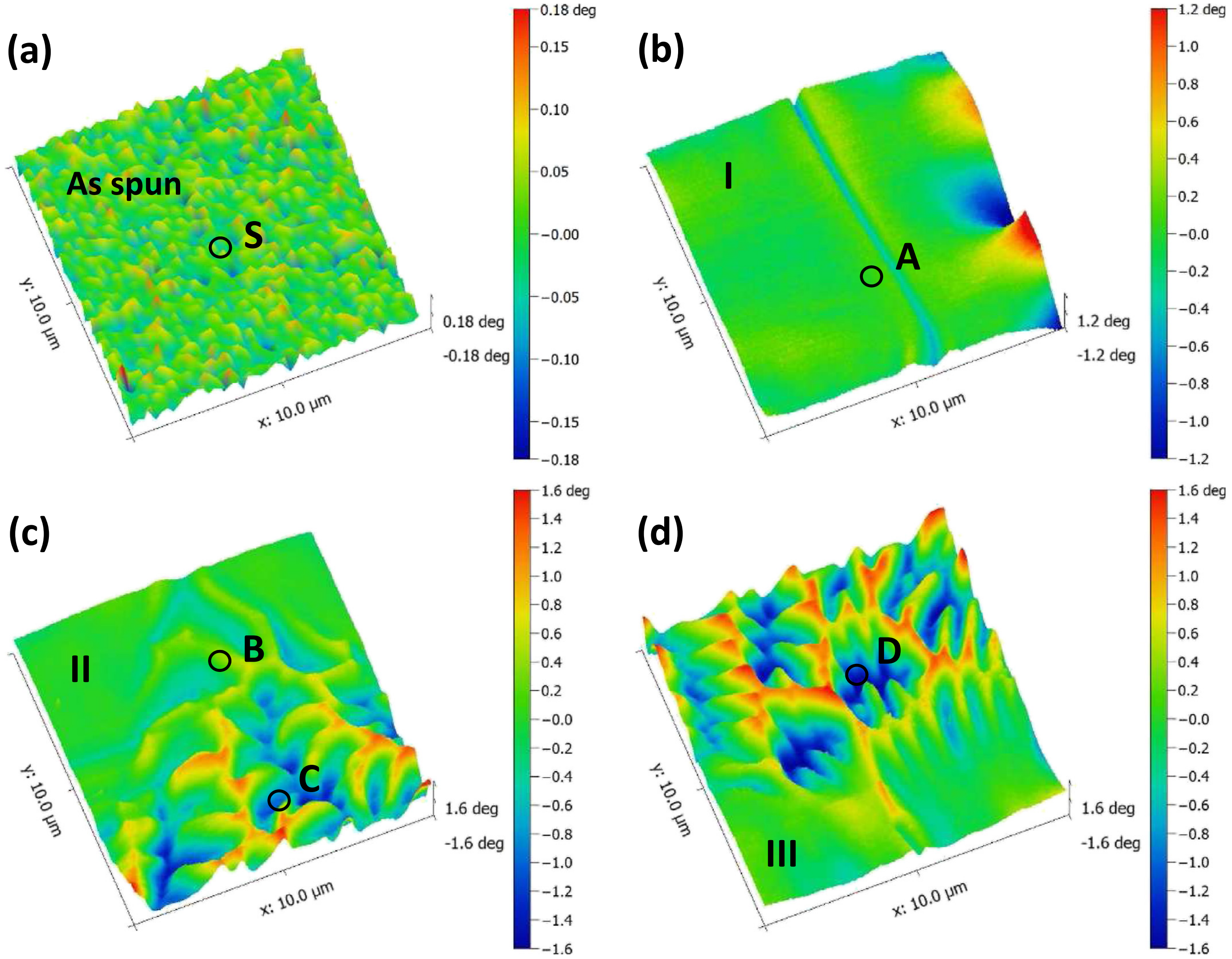

Fig. 2. The phase images of (a) as spun $Fe_{83}C_1B_{11}Si_2P_3$ ribbon, (b) region I, (c) region II and (d) region III of deformed $Fe_{83}C_1B_{11}Si_2P_3$ ribbon detected with MFM. The circles S, A, B, C and D mark the nanoindentation positions.