Deformation feature and properties of Zr based bulk metallic glass treated by laser shock peening

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Laser shock peening is promising surface treatment technique to improve the mechanical properties of metals material through introducing a deep compressive residual stresses region. In this work, LSP was employed to treat Zr based bulk metallic glasses (BMGs). In contrast to the work softening in BMGs, laser shock peened BMG shows significant hardening in the plastic deformed region. Furthermore, the plastic deformation region exhibits unique deformation features, which is dependent on the thickness of the samples. The deformation morphology under the impacted region was also studied. The mechanism for the hardening and formation of unique deformation features is discussed.

Keywords: Metallic glasses, Laser shock peening, Plastic deformation, Vickers hardness

Introduction

Bulk metallic glasses (BMGs) are well known for their high strength and high elastic stain limit. However, the applications of BMGs in structural materials are impeded by the catastrophic brittle fracture at room temperature, owing to the highly localised deformation in shear bands and the work softening behaviour.[1,2] Recently, great efforts have been made to enhance the plastic deformation capability of BMGs. Apart from the composite strategy, several attempts have been made to improve the plasticity of monolithic BMGs, including prior cold rolling,[3,4] and shot peening.[5] The improved plasticity is attributed to the induced residual stress and the implanted shear bands. However, subsequent studies showed that shot peening produced a soft layer (tens of micrometres), which may sacrifice the fatigue property of BMG.[6,7]

Similar to but having more advantages over shot peening, laser shock peening (LSP) has been widely used to improve wear resistance and fatigue performance in metallic materials.[8–10] In the LSP process, a shock wave is generated and propagates into the target through the interaction of a pulsed high intensity laser beam and absorption layer on the metallic target surface. Laser shock peening appears to achieve a much greater depth of residual stress (typical on the order of 1–2 mm) than conventional shot peening (less than 0·25 mm). Furthermore, LSP produces a high strain rate deformation caused by shock wave (normally 10^5–10^7 s^{-1}). These also provide a unique condition for the study of deformation behaviour of BMG deformed under high rates, as well as the interaction mechanism between shock wave and metallic glass materials. However, less attention has been paid on the LSP effect on the BMGs up to now.[11] In this work, LSP was applied to treat a Zr based BMG. The deformation feature and properties evolution in the BMG after LSP were investigated.

Experimental procedures

Bulk metallic glass of composition $Zr_{47\cdot9}Ti_{0\cdot3}Cu_{39\cdot3}Ni_{3\cdot1}Al_{9\cdot4}$ (at-%) was prepared by arc melting the elemental constituents in argon atmosphere, followed by drop casting into cylindrical rods with 5 mm in diameter. Before casting, the arc melted buttons were remelted at least five times to ensure compositional homogeneity. The structure of the as cast alloys was characterised by X-ray diffraction and differential scanning calorimetry with a heating rate of 20 K min^{-1}. The samples are cut into 0·5 or 2 mm in thickness, grinded and polished under standard metallographical procedure to a mirror finish.

Laser shock peening was performed with a Q-switched high power Nd : YAG pulse laser operating at 1064 nm wavelength and a maximum of 2·5 J output energy per shot can be achieved through a two-step amplification system. The full width at half maximum is approximately 7·32 ns. The original laser beam size is about 12 mm in diameter and a focusing lens was used to adjust the beam size to 2 mm such that the laser intensity was above 7 GW cm^{-2} at the specimen surface. The target surface is glued with an Al foil as an absorption layer, confined by a 4·00 mm thick K9 glass against the laser irradiation. An appropriate thickness of the Al foil ($\sim$60 μm here) was chosen to ensure that only the upper part of the Al foil was melted and ionised by the laser energy. The K9 glass is fully clamped with

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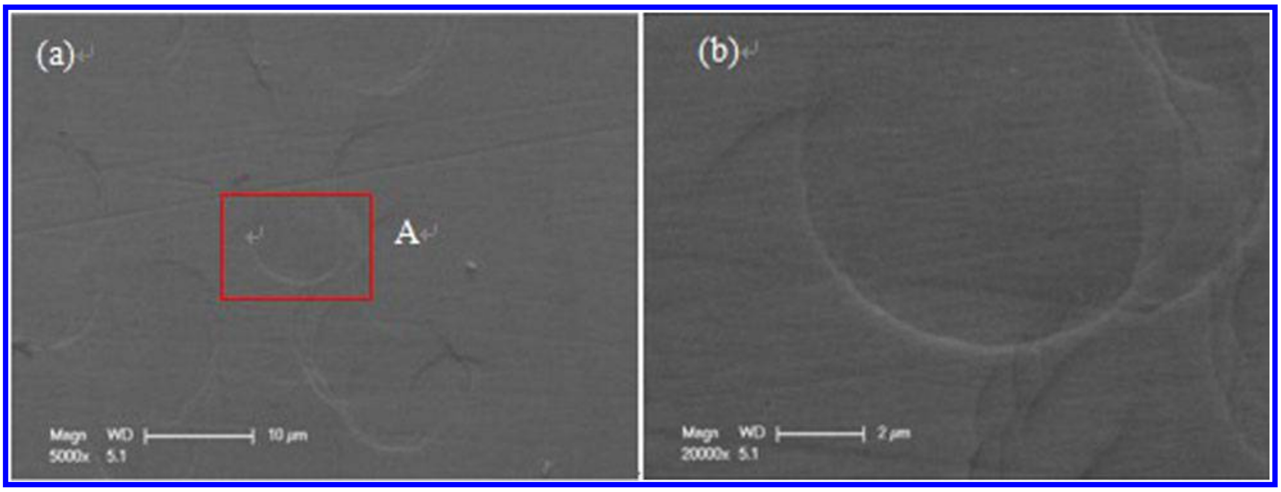


1 *a* SEM morphology of thick sample after LSP and *b* high magnification micrograph corresponding to *a*

the target without a cushion at the back surface by a specially designed holder. After LSP, the detailed morphology of the impacted areas was observed by optical microscopy, scanning electron microscopy (SEM) and atomic force microscopy (AFM). The hardness was measured by Vickers indenter.

Results and discussion

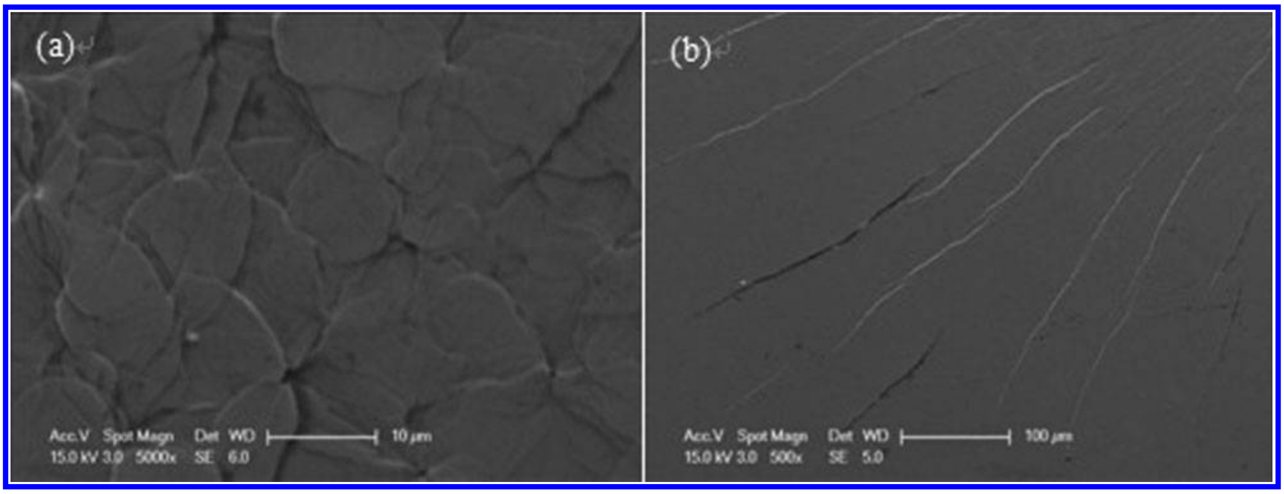
The amorphous structure of the as cast $Zr_{47\cdot9}Ti_{0\cdot3}Ni_{3\cdot1}Cu_{39\cdot3}Al_{9\cdot4}$ BMG is confirmed by X-ray diffraction. Glass transition temperature (T_g), crystallisation temperature (T_x) and the supercooled liquid region [($\Delta T_x = T_x - T_g$)] of the BMG are characterised to be 702, 762 and 60 K, respectively, through differential scanning calorimetry measurements at the heating rate of 20 K min^{-1}.

Thick (2 mm) and thin (0·5 mm) samples were peened by a single pulse laser. An indent with the diameter of ~1·8 mm formed, respectively, on the peened surface of the Zr based BMG sample after laser shock, which indicates that the materials have undergone a significant plastic deformation. The detailed surface features of the thick sample (2 mm thick) shocked by a single pulse laser are shown in Fig. 1. Inhomogeneous plastic deformation can be found on the indent surface, which is characterised by the numerous random distributed half-round areas, with the diameter of 5–20 μm. These features are consistent with our previous results for the sample alloy with 5 mm thickness.[11] The morphology of the deformed region for the thin sample after peening is shown in Fig. 2. Random distributed half-round deformation regions are also found at the central part of the indent (Fig. 2*a*). However, another deformation feature, radial deformation steps, is dominated in other parts of the indent. They show lengths in scale of hundreds of micrometres and spacing in scale of 100 μm. Furthermore, AFM was used to make a further study on the deformation feature on the impacted surface. Figure 3 shows two typical morphologies of the radial deformation steps. It can be found that the step height is in the order of hundreds of nanometres, which tends to decrease with increasing the radial distance from the centre of the indent. The height of the radial steps is higher than that of the half-round steps. This is due to the lower number density of the former, thereby each radial step accommodates more plastic strain during the formation of the indent.

The above results show that the shock peened BMG revealed a sample thickness dependent of deformation morphology. The thick sample is dominated by half-round steps, while the thin sample shows two kinds of steps, half-round and radial shaped, with the latter located on the outer regions within the indent surface. The thickness dependent of deformation feature could be related to the shock propagation process in the different samples. Upon the forming of the plasma shock wave, an elastic and plastic compression wave starts to move into the sample. The elastic wave is reflected at the free sample end as a tensile wave and comes back to the plastic front. Then this elastic tensile wave is reflected again at the plastic front as a compression wave, moves back, and so on. With a coupling pressure analytical method, the pressure transmitted to the BMG through shock wave was estimated to have a peak value about 8·2 GPa and full width at half maximum about 35 ns.[11,12] Moreover, the time (t), when the elastic precursor wave reaches the free back end of the sample, is calculated by

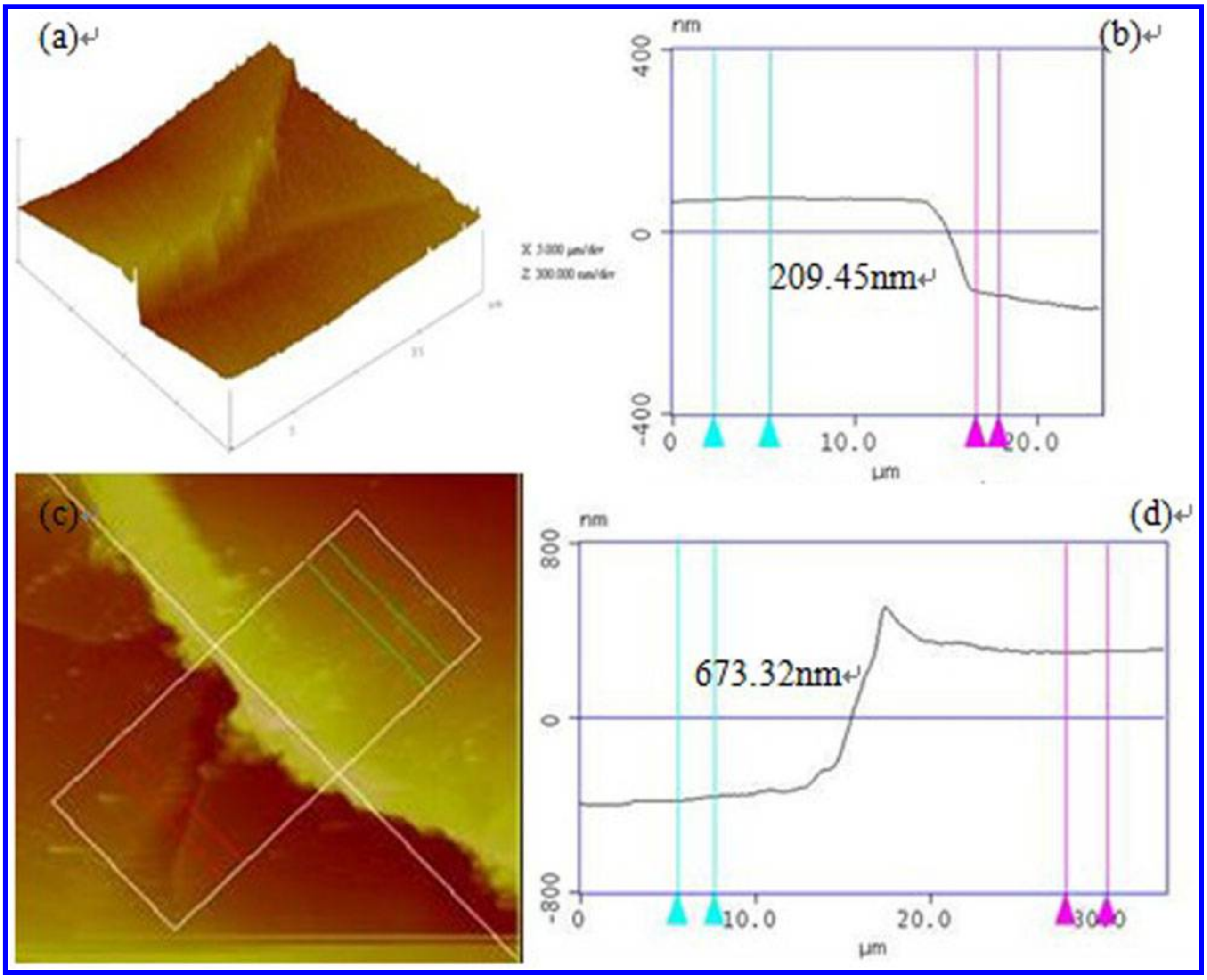
$$t = \frac{h}{c} = h\left[\frac{(1-2v)(1+v)\rho}{(1-v)E}\right]^{1/2} \tag{1}$$

where E is elastic modulus, ρ is the density of the BMG, h is the thickness of sample, v is poisson's ratio. For h=0·5 mm, t is calculated to be ~95·5 ns, which is not far beyond the pulse width of the shock wave. Due to the high peak pressure and the short time duration, the reflected tensile wave may still have a pressure higher than dynamic yield stress of the BMG, which leads to a tensile strain superimposing on the previous compressive strain. This causes complex plastic features on plastic deformed surface. As for the thick sample (h=2 mm), t is ~382 ns, far beyond the pulse width of the shock wave. When the elastic precursor wave approaching the back end of the sample, the energy attenuates greatly due to the long propagation time, and is transferred to the sample. The reflected tensile wave may have a much lower pressure than the dynamic yield stress of the BMG, not giving rise to a tensile strain in the sample. This is thought to be the reason that the deformation feature of the thick sample is dominated by the half-round shape steps.

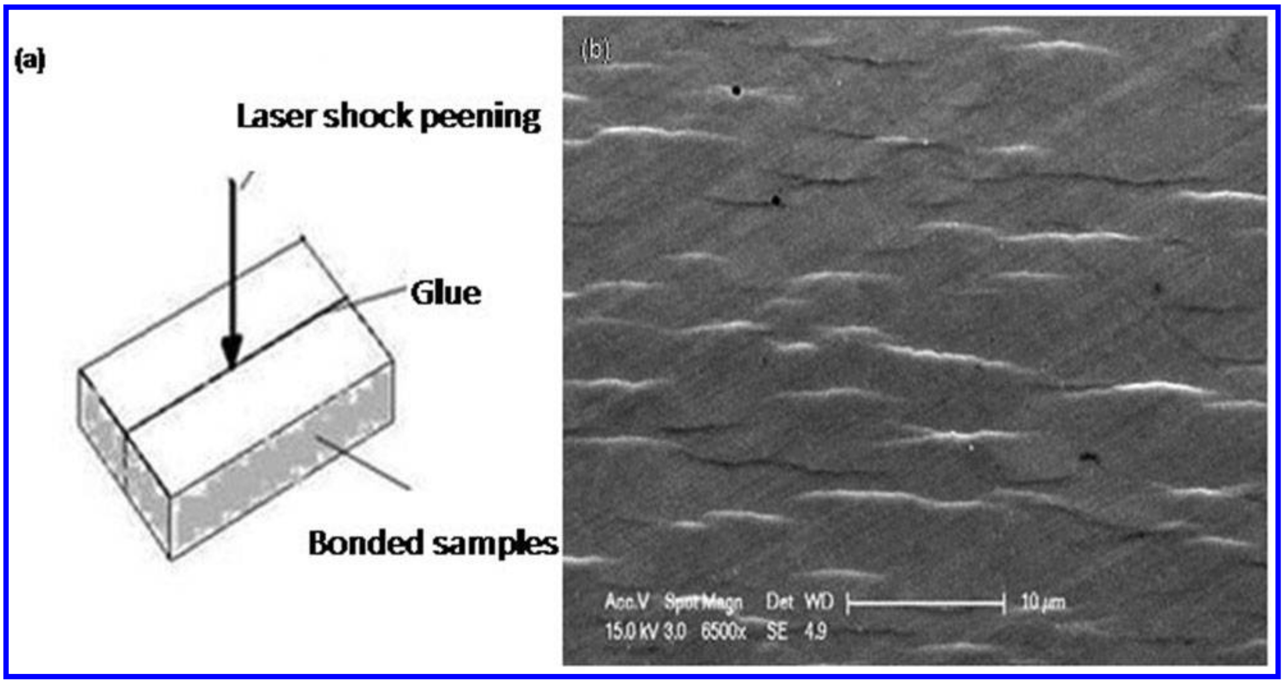


a central part; *b* outer parts
2 Morphology (SEM) of thin sample after LSP

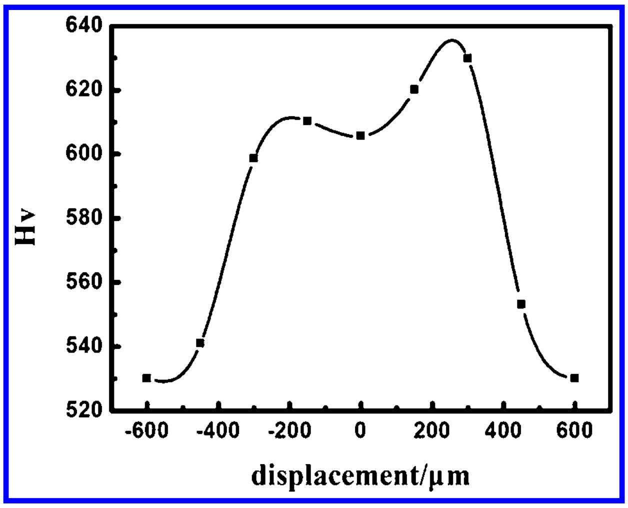
In order to investigate the plastic deformation feature underneath the peened surface, a bonded interface sample (schematically shown in Fig. 4*a*) was employed. The two BMG blocks were polished and bonded by high strength glue with a gap width of about 5 μm. The height of the sample is about 3 mm. The laser beam was focused on the centre of the interface. After LSP treatment, the bonded blocks are separated and observed by optical microscopy and SEM. Typical morphology of the deformed region under the surface is shown in Fig. 4*b*. It can be seen that a large number of shear bands, which is typical plastic deformation feature of BMGs, are found under the surface. The shear bands have an average length of about 10 μm, changing with the depth under the surface. The depth of the plastic deformation region, characterised by the appearance of



3 Images (AFM) of deformed surface on thin sample after LSP



4 ***a* schematic diagram of bonded interface technique and *b* shear bands pattern underneath deformed surface**



5 Hardness distribution of impacted region after LSP

shear bands is about 1·5 mm. This also proves that the plastic deformation does not reach the bottom end of thick sample, because of the attenuated wave pressure.

Vickers hardness measurements were used to characterise the effect of LSP on the hardness change of the BMG. The hardness distribution of the impacted zone after LSP is shown in Fig. 5. The hardness of the central part of deformed region is found to be higher than that on edges, and the average hardness of the central region ($\sim$0·8 mm diameter) is about 618 HV, which is 17% higher than that of untreated sample.

It is known that crystalline metals show a distinct hardening upon plastic deformation, due to dislocation multiplication. However, metallic glasses normally exhibit work-softening feature. The formation of shear bands was reported to cause the dilatation and softening.[13,14] As a result of shear softening, shot peening, in fact, produces a soft surface layer ($\sim$80 μm) in BMGs.[5] It should be noted that significant hardening occurs in the present BMG treated by LSP, which is promising for the improvement of the fatigue properties in BMGs. The hardening of the BMG may caused by the super high speed densification of the alloy, which overcomes the softening by forming shear bands. To further prove this, the hardness of the LSP treated sample was compared with that of the relaxed samples. The as cast samples were isothermally annealed at 651 K for 6 and 24 h, respectively. The measured hardness as well as that of the fully crystallised sample is listed in Table 1. The peened sample shows a much higher hardness than highly relaxed samples, but is softer than the crystallised alloy. The relaxation of the BMG gives rise to the annihilation of extra free volume and drives the alloy into a metastable equilibrium state. The higher hardness of the peened sample implies a more condensed glassy structure with less free volume. Moreover, the work hardening mechanism of the BMG under LSP may also be related to the residual compressive stresses induced by LSP. Although the residual compressive stress does not increase the hardness obviously,[15] the combined effect of the structural densification and residual compressive stress could contribute to the significant hardening of the BMG.

The deformation feature of the present LSP sample, does not show pile-ups and shear bands around the indent, unlike the deformation morphology of BMGs under indentation.[16,17] The maximum strain rate of the present LSP treatment is estimated to be about $2{\cdot}5\times10^{6}\ \mathrm{s}^{-1}$. However, the unique plastic deformation features can not

Table 1 Vickers hardness of as cast, relaxed, crystallised, and as peened BMG

Sample	As cast	6 h-relaxed	24 h-relaxed	Crystallised	As peened (central)
Hardness/HV	530	542	568	639	618

only be ascribed to high strain rate, as they were not observed in other high speed experiments (e.g. plate impact).[18,19] The formation of the half-round and radial shape steps may be related to collective microscaled deformation during the densification of the BMG. Further study is needed to clarify the mechanism for the novel plastic deformation behaviour in BMGs.

Summary

Bulk metallic glass of composition $Zr_{47\cdot9}Ti_{0\cdot3}Cu_{39\cdot3}Ni_{3\cdot1}Al_{9\cdot34}$ (at-%) has been treated by LSP technology. In addition to forming a millimetre scaled indent, half-round and radial shape deformation steps are formed on the deformed surface, with the type depending on sample thickness. The plastic deformation region has a depth of about 1·5 mm, and is characterised by profuse short shear bands. Significant hardening is achieved after LSP. The mechanism is ascribed to the high speed densification of the material to a more closely packed structure, which overcomes the local softening by shear bands.

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References

1. W. H. Wang, C. Dong and C. H. Shek: 'Bulk metallic glasses', *Mater. Sci. Eng. R*, 2004, **R44**, 45.
2. C. A. Schuh, T. C. Hufnagel and U. Ramamurty: 'Mechanical behavior of amorphous alloys', *Acta Mater.*, 2007, **55**, 4067.
3. T. G. Nieh, Y. Yang, J. Lu and C. T. Liu: 'Effect of surface modifications on shear banding and plasticity in metallic glasses: An overview', *Prog. Nat. Sci.: Mater. Int.*, 2012, **22**, 355–363.
4. M. H. Lee, K. S. Lee and J. Das: 'Improved plasticity of bulk metallic glasses upon cold rolling', *Scr. Mater.*, 2010, **62**, 678.
5. Y. Zhang, W. Wang and A. Greer: 'Making metallic glasses plastic by control of residual stress', *Nat. Mater.*, 2006, **5**, 857
6. R. Raghavan, R. Ayer, H. W. Jin, C. N. Marzinsky and U. Ramamurty: 'Effect of shot peening on the fatigue life of a Zr-based bulk metallic glass', *Scr. Mater.*, 2008, **59**, 167.
7. L. Wang, H. Bei, Y. F. Gao, Z. P. Lu and T. G. Nieh: 'Effect of residual stresses on the hardness of bulk metallic glasses', *Acta Mater.*, 2011, **59**, 2858.
8. C. S Montross, T. Wei, L. Ye, G. Clark and Y. W. Mai: 'Laser shock processing and its effects on microstructure and properties of metal alloys: a review', *Int. J. Fatigue*, 2002, **24**, 1021.
9. Y. Liao, S. Suslov, C. Ye and G. J. Cheng: 'The mechanisms of thermal engineered laser shock peening for enhanced fatigue performance', *Acta Mater.*, 2012, **60**, 4997.
10. R. K. Nalla, I. Altenberger, U. Noster and G. Y. Liu: 'On the influence of mechanical surface treatments—deep rolling and laser shock peening—on the fatigue behavior of Ti–6Al–4V at ambient and elevated temperatures', *Mater. Sci. Eng. A*, 2003, **355**, 216.
11. Y. P. Wei, B. C. Wei, X. Wang, G. Y. Xu, L. Li, X. Q. Wu, H. W. Song and C. G. Huang: 'A novel micro-scale plastic deformation feature on a bulk metallic glass surface under laser shock peening', *Chin. Phys. Lett.*, 2013, **30**, 036201.
12. X. Wu, C. Huang, X. Wang and H. Song: 'A new effective method to estimate the effect of laser shock peening', *Int. J. Impact Eng.*, 2011, **38**, 322.
13. S. Xie and E. P. George: 'Hardness and shear band evolution in bulk metallic glasses after plastic deformation and annealing', *Acta Mater.*, 2008, **56**, 5202.
14. J. W. Liu, Q. P. Cao, L. Y. Chen, X. D. Wang and J. Z. Jiang: 'Shear band evolution and hardness change in cold-rolled bulk metallic glasses', *Acta Mater.*, 2010, **58**, 4827.
15. L. Y. Chen, Q. Ge, S. Qu and J. Z. Jiang: 'Stress-induced softening and hardening in a bulk metallic glass', *Scr. Mater.*, 2008, **59**, 1210.
16. V. Keryvin: 'Indentation of bulk metallic glasses: Relationships between shear bands observed around the prints and hardness', *Acta Mater.*, 2007, **55**, 2565.
17. J. S. Gu, L. Li, T. H. Zhang *et al.*: 'Characterization of shear bands in two bulk metallic glasses with different inherent plasticity', *Int. J. Modern Phys. B*, 2009, **23B**, 1217.
18. J. X. Meng, Z. Ling, M. Q. Jiang, H. S. Zhang and L. H. Dai: 'Dynamic fracture instability of tough bulk metallic glass', *Appl. Phys. Lett.*, 2008, **92**, 171909.
19. F. Yuan, V. Prakash and J. J. Lewandowski: 'Spall strength and Hugoniot elastic limit of a Zirconium-based bulk metallic glass under planar shock compression', *J. Mater. Res.*, 2007, **22**, 402.