https://doi.org/10.15407/tpwj2019.10.02

INFLUENCE OF LASER POWER AND WELDING VELOCITY ON THE MICROSTRUCTURE OF Zr-BASED BULK METALLIC GLASS WELDED JOINTS*

HAIYAN WANGA[1], **MA YANYIB**[2], **ZHANG YUPENGA**[1],
DONG CHUNLINA[1], **YI YAOYONGA**[1] and **XI HUAIA**[1]
[1]Guangdong Provincial Key Laboratory of Advanced Welding Technology, Guangdong Welding Institute (China-Ukraine E.O. Paton Institute of Welding), Guangzhou, 510650, China
[2]School of Materials Science and Engineering, Shenyang University of Technology, Shenyang, 110870, China

Laser welding is employed to weld $Zr_{67.8}Cu_{24.7}Al_{3.43}Ni_{4.07}$ bulk metallic glass, and the effects of laser power and welding velocity on the microstructures of bulk metallic glass joints are studied. Owing to the high speed and high-energy density of laser welding, the weld fusion zones remain amorphous structure. Some nano-grains are formed in weld fusion zones and of benefits for the improvement of microhardness. Crystallization happens in heat-affected zone and deteriorates the hardness of materials. The joint welded with laser power of 600 W and velocity of 110 mm/s exhibits the lowest degree of crystallization. Larger laser power or slower welding speed would cause excessive heat accumulation in heat-affected zone. 10 Ref., 1 Table, 3 Figures.

Keywords: *Bulk metallic glass; laser welding; microstructure; crystallization*

Zr-based bulk metallic glass (BMG) with specific long-range disordered structure have many promising merits [1], such us high strength, high hardness, and excellent corrosion resistance, etc. These outstanding properties make them promising candidates for potential applications in the field of consumer electronics, medical apparatus, automobile industry and so on. However, as BMGs belong to metastable materials, the relatively weak glass forming ability and the demand for quenching process limits their development of large-scale products. Therefore, to extend the engineering applications, many researches on various welding technologies for BMGs have been carried out, including friction stir welding, explosion welding, and diffusion welding, etc. Among these technologies, laser welding has attracted extensive interests owing to their superiorities of fast welding velocity, deep welding penetration and high energy density [2]. It can fulfill the demands of BMGs' welding for high solidification and thermal quench rate in both weld fusion zone (WFZ) and heat-affected zone (HAZ). Li, Kim and Kawahito et al. utilized laser or pulsed laser welding to realize $Zr_{45}Cu_8Al_7$, $Cu_{54}Ni_6Zr_{22}Ti_{18}$ and $Zr_{55}Al_{10}Ni_5Cu_{30}$ BMGs joints, respectively [3–5]. The reported studies reveal that crystallization easily happens in WFZ and HAZ, so it is critical to control the laser energy input to prevent heat accumulating in welding zone, which depends on the two significant parameters in laser welding, i.e., laser power and welding velocity.

Herein, this work used laser beam to weld $Zr_{67.8}Cu_{24.7}Al_{3.43}Ni_{4.07}$ BMGs. The influences of laser power and welding velocity on the microstructure of welding joints were studied and the optimal parameters were obtained to realized high-quality $Zr_{67.8}Cu_{24.7}Al_{3.43}Ni_{4.07}$ BMG joints.

Experimental. The $Zr_{67.8}Cu_{24.7}Al_{3.43}Ni_{4.07}$ BMGs with sizes of 60 mm×20 mm×1 mm were prepared by arc melting Zr, Cu, Al and Ni metals with a purity above 99.9 %. Before welding, the BMGs were polished by 2000 mesh silicon carbide papers, and cleaned by absolute ethyl alcohol to remove the oxide and residues on welding surface. Then, the BMG plates were welded by TRUMPF TRU DISK10002. The movement of laser beam was controlled by TRUMPF PFO 33, and the diameter of focus spot was about 0.2 mm. Five samples with various laser powers

Welding parameters for $Zr_{67.8}Cu_{24.7}Al_{3.43}Ni_{4.07}$ BMGs

Sample No.	Laser power P (W)	Welding velocity, mm/s
1	600	90
2	600	100
3	600	110
4	570	100
5	630	100

*Based on presentation made at Conference «Polyweld-2019» (23–24 May 2019), NTUU «Igor Sikorsky KPI».

and welding velocities were obtained. Table shows their corresponding parameters in detail.

After welding, the samples were cut along the direction perpendicular to the weld, and inlaid, polished and polished successively. The cross-sectional surfaces were etched by chemical solvent of 3 ml HF, 50 ml HNO_3 and 60 ml H_2O.

The microstructures of BMG welding joints were characterized by optical microscopy (OM, ZEISS Ario Imager.M2m). The Vickers hardness of WFZ and HAZ was evaluated by micro-hardness tester (Buehler VH1202) with load and dwell time of 1 kg and 10 s, respectively. The glassy or crystalline structures were identified by transmission electron microscopy (TEM, FEI Titan G2 300).

Results and discussion. Figures 1, *a*–*e*, show the cross-sectional microstructures and morphology of samples 1 to 5, respectively. The three zones of WFZ, HAZ and unaffected base material (BM) can be clearly identified according to the contrasting differences, which are signed in the figures, respectively. As can been observed in Figure 1, *b* to *c*, there are some little pores existing in WFZs, which is mainly caused by the key hole formed during laser welding. As for the microstructures of HAZ, the bright spots are corresponding to the crystallization area, and its proportion can be utilized to evaluate the degree of crystallization [4, 6, 7].

Generally, sample 3 which is welded under laser power and velocity of 600 W and 110 mm/s, respectively, shows the weakest degree of crystallization. To study the effect of welding velocity on the crystallization, samples 1, 2 and 3 are compared. It is obvious that as the welding velocity increases from 90 mm/s to 110 mm/s, the crystallization is successively weakened. This is owing to the relatively larger welding velocity, which is beneficial to promote the heat conduction and thermal quench happening in HAZ [6]. As for the influence of laser power, samples 2, 4 and 5 are taken into considerations. As can be seen from Figure 1, *d*, when the laser power is 570 W, the bottom of the weld is incompletely fused, indicating that the input energy is too low to weld. As the laser power increases to 600 and 630 W, the BMG joints become completely fused, but the degree of crystallization also gets worse and exhibit the largest crystallization area of sample 5.

To understand the difference of microstructures between glassy WFZ and crystalline HAZ, bright-field TEM (BFTEM) and high-resolution TEM (HRTEM) characterizations are employed. Figure 2, *a* and *c* show the typical BFTEM and HRTEM images of HAZs, respectively. Many grains as well as grains boundaries can be observed, and the HRTEM result exhibiting ordered lattice further verifies the crystalline structure of HAZ. Figure 2, *b* and *d* are the typical BFTEM and HRTEM results for WFZs, respectively. Different from Figure 2, *a*, only several nano-grains are identified in Figure 2, *b*. The HRTEM image shown in Figure 2, *d* reveals that the microstructure of WFZ is generally amorphous, and the nano-grain is with a size of about 80 nm in circumscribed circle diameter. The formation of such nano-grains is ascribed to the high speed and high-energy density of laser welding [8], which results in the increasing nucleation rate and quickly drop of temperature during welding to retard grain growth. These nano-grains are regarded as the key to improving the mechanical properties of materials [9, 10], including hardness, strength, plasticity, etc.

To evaluate the mechanical properties of as-welded BMG joints, the Vickers hardness of difference zones for samples 1 to 5 is tested by a micro-hardness tester

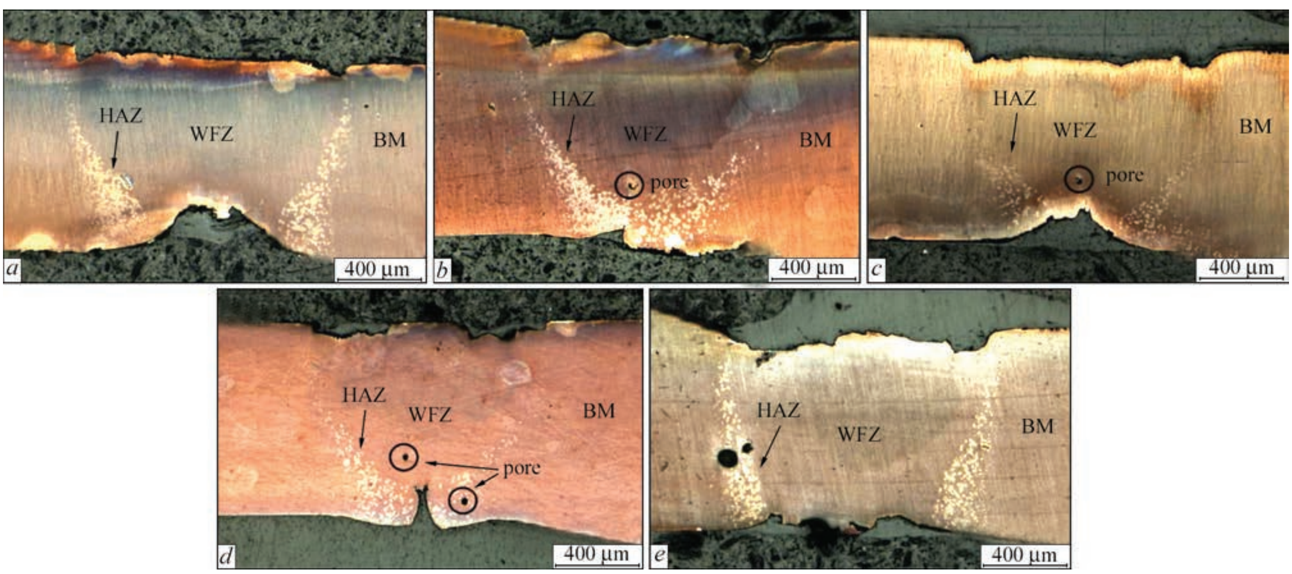

Figure 1. Optical microscopy images for the cross-sections of the welds taken from *a*–*e* samples 1–5

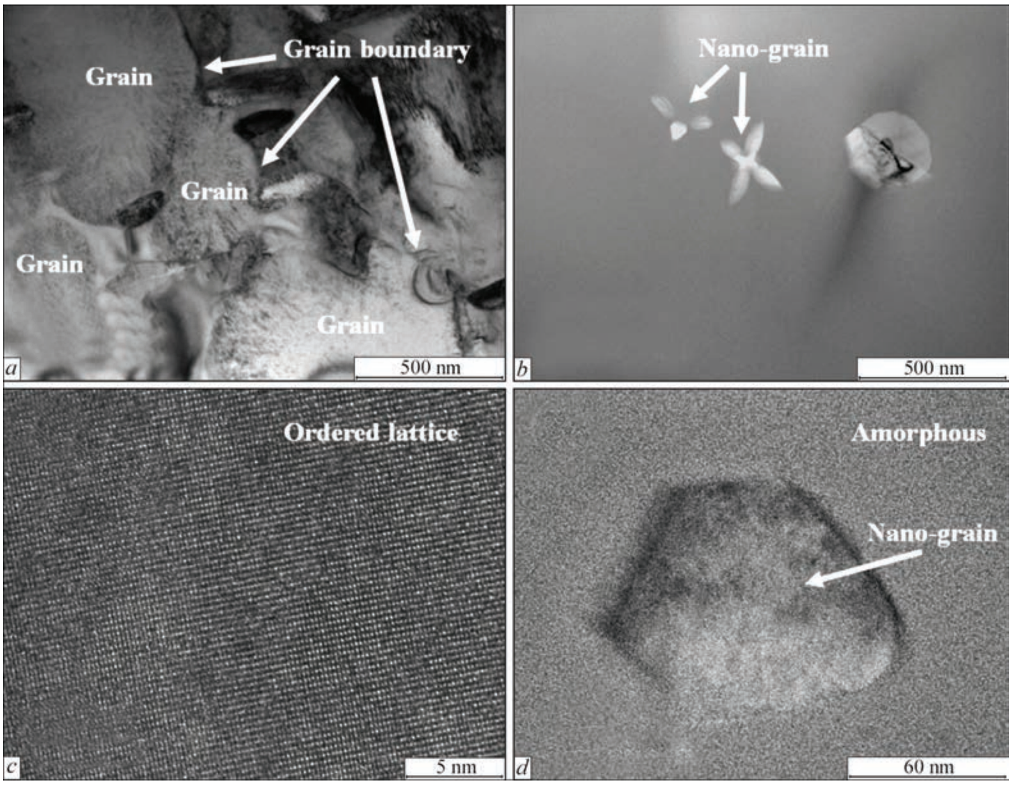

Figure 2. Typical BFTEM images of (*a*) HAZs and (*b*) WFZs, and the corresponding HRTEM images of (*c*) HAZs and (*d*) WFZs for these samples

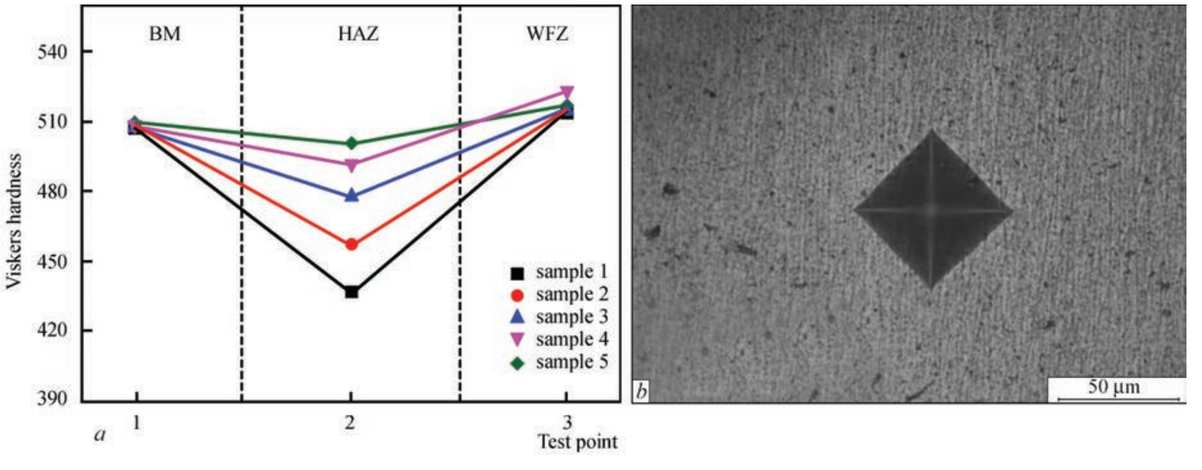

Figure 3. Vickers hardness of different zones for samples 1 to 5, and test point of 1, 2 and 3 are corresponding to BM, HAZ and WFZ, respectively (*a*), the image of typical indentation for each test (*b*)

under the force of 1 kg and dwell time of 10 s, as shown in Figure 3, *a*. Figure 3, *b* displays the typical indentation for each test. According to Figure 3, *a*, the hardness of WFZ as 514~523 *HV* is generally higher than that of BM as 507~509 *HV*, which is attributed to the nano-crystallization happening in WFZ, as revealed in Figure 2, *d*. On the contrary, the hardness of HAZ is greatly decreased to 436, 456.9, 477.4, 491.3 and 500.2 *HV* for samples 1 to 5, respectively. It is considered that the severe thermal crystallization during welding is the main reason for this sharply weakened hardness in HAZ.

Conclusions

In summary, $Zr_{67.8}Cu_{24.7}Al_{3.43}Ni_{4.07}$ BMGs were welded by laser welding, and the effects of laser power and welding velocity on the microstructure, especially the crystallization behavior, of BMG joints were studied. The WFZs' microstructure of all samples remain amorphous generally, but several nano-grains are formed, which is advantageous to improve the Vickers hardness of WFZ. As for HAZ, the joint welded with laser power of 600 W and velocity of 110 mm/s exhibits the lowest degree of crystallization. Larger laser power or slower welding speed would cause excessive heat accumulation in HAZ, and, therefore, result in severe crystallization reaction and deterioration of the mechanical properties of BMG materials.

Acknowledgments. *This work is supported by the following grants: GDAS's Project of Constructing Domestic First-class Research Institutions (2019GDASYL-0103075), GDAS's Project of Science and Technology Development (2017GDAS-CX-01), Science and Technology Planning Project of Guangdong Province (2014B070705007) and Science and Technology Planning Project of Guangzhou (ZWY201704002).*

1. Williams, E., Lavery, N. (2017) Laser processing of bulk metallic glass: A review. *Journal of Material Processing Technology*, **247**, 73–91.
2. Wang, H.S., Chen, H.G., Jang, J.S.C., Chiou, M.S. (2010) Combination of a Nd:YAG laser and a liquid cooling device to $(Zr_{53}Cu_{30}Ni_9Al_8)Si_{0.5}$ bulk metallic glass welding. *Materials Science & Engineering A*, 528(**1**), 338–341.
3. Kawahito, Y., Terajima, T., Kimura, H. et al. (2008) High-power fiber laser welding and its application to metallic glass $Zr_{55}Al_{10}Ni_5Cu_{30}$. *Materials Science & Engineering B*, 148(**1**), 105–109.
4. Li, B., Li, Z.Y., Xiong, J.G. et al. (2006) Laser welding of $Zr_{45}Cu_{48}Al_7$ bulk glassy alloy. *Journal of Alloys & Compounds*, 413(**1**), 118–121.
5. Kim, J.H., Lee, C., Lee, D.M. et al. (2007) Pulsed Nd:YAG laser welding of $Cu_{54}Ni_6Zr_{22}Ti_{18}$ bulk metallic glass. *Materials Science & Engineering A*, 449(**13**), 872–875.
6. Wang, G., Huang, Y.J., Shagiev, M., Shen, J. (2012) Laser welding of $Ti_{40}Zr_{25}Ni_3Cu_{12}Be_{20}$ bulk metallic glass. *Materials Science and Engineering A*, **541**, 33–37.
7. Wang, H.S., Chen, H.G., Jang, S.C. (2010) Microstructure evolution in Nd:YAG laser-welded $(Zr_{53}Cu_{30}Ni_9Al_8)Si_{0.5}$ bulk metallic glass alloy. *Journal of Alloys & Compounds*, 495(**1**), 224-228.
8. Chen, B., Shi, T.L., Li, M. et al. (2014) Laser welding of annealed $Zr_{55}Cu_{30}Ni_5Al_{10}$ bulk metallic glass. *Intermetallics*, 46(**3**), 111–117.
9. Siegel, R.W. (1993) Nanostructured materials-mind over matter. *Nanostructured Materials*, 3(**1**), 1–18.
10. Karch, J., Birringer, R., Gleiter, H. (1987) Ceramics ductile at low temperature. *Nature*, **330**(6148), 556–558.

Received 01.07.2019