Contents lists available at ScienceDirect

# Journal of Alloys and Compounds

journal homepage: http://www.elsevier.com/locate/jalcom

# Pressure-induced polyamorphism by quantitative structure factor and pair distribution function analysis in two Ce-based metallic glasses

Linji Zhang <sup>a, b</sup>, Fei Sun <sup>b</sup>, Xinguo Hong <sup>b</sup>, Junlong Wang <sup>c</sup>, Gang Liu <sup>b</sup>, Lingping Kong <sup>b</sup>, Hongwang Yang <sup>d</sup>, Xiuru Liu <sup>a, c, \*</sup>, Yong Zhao <sup>a, c</sup>, Wenge Yang <sup>b, e, \*\*</sup>

<sup>a</sup> School of Materials Science and Engineering, Key Laboratory of Advanced Technologies of Materials, Ministry of Education of China, Southwest Jiaotong University, Chengdu, 610031, China

<sup>b</sup> Center for High Pressure Science and Technology Advanced Research (HPSTAR), Shanghai, 201203, China

<sup>c</sup> School of Physical Science and Technology, Southwest Jiaotong University, Chengdu, 610031, China

<sup>d</sup> School of Material Science and Engineering, Shenyang University of Technology, Shenyang, 110870, China

<sup>e</sup> High Pressure Synergetic Consortium (HPSynC), Geophysical Laboratory, Carnegie Institution of Washington, Argonne, IL, 60439, USA

#### ARTICLE INFO

Article history: Received 21 July 2016 Received in revised form 26 September 2016 Accepted 16 October 2016 Available online 27 October 2016

*Keywords:* Metallic glasses Pair distribution function Polyamorphism High pressure

### ABSTRACT

We utilized the pair distribution function method to characterize the pressure-induced polyamorphic transition in  $Ce_{60}Al_{20}Cu_{20}$  and  $Ce_{55}Al_{45}$  metallic glass at room temperature. Using synchrotron highenergy x-ray diffraction we collected scattering information from a large Q-space coverage, which in turn gave a high resolution g(r) that provided accurate local structure information. We observed a sudden change in compressibility and the nearest neighbor distance at 3.50-6.32 GPa for  $Ce_{60}Al_{20}Cu_{20}$  and 2.20-6.89 GPa for  $Ce_{55}Al_{45}$ . The origin of the volume collapse seemed to be pressure-induced qualitative changes in bond shortening that corresponded to different coordination spheres. The poly-amorphic transitions in these two systems from low-density glass (LDG) to high-density glass (HDG) are associated with local atomic rearrangements.

© 2016 Elsevier B.V. All rights reserved.

## 1. Introduction

Metallic glasses (MGs) as new amorphous phase materials have attracted widespread research interest due to their exceptional physical properties compared to other intermetallic alloys [1–4], but they lack long-range translational periodicity, and only have a short-range order (SRO) and medium-range order (MRO) [5,6]. Many researchers suggest that the SRO of MGs is attributed by solute-centered clusters, where a solute atom is surrounded by a large number of solvent atoms, while the MRO originates from high correlation among clusters [5,6]. In addition, MGs are distinctly different from traditional network-forming glasses because they have metallic bonds that are non-directional in nature [6]. Highpressure studies of MGs have fundamental significance for deepening our understanding of numerous macroscopic physical

\*\* Corresponding author. Center for High Pressure Science and Technology Advanced Research (HPSTAR), Shanghai, 201203, China. properties (such as electrical resistivity [7], compressibility [8–10] and high-pressure annealing [11,12]) and comprehending glass behavior by providing new model systems [13] and phase transitions [14,15].

In general, the first sharp diffraction peak (FSDP) of x-ray diffraction patterns is associated with medium range ordering [16]. Therefore, it provides direct structural information at the atomic level and statistical information of average inter-atomic spacing (d) according to the well-known Ehrenfest relationship i.e.  $d \propto (1/Q_1)$ [16]. A non-cubic power law scale,  $\rho/\rho_0 = (Q_1/Q_{10})^{\bar{D}}$  with D = 5/2, was proposed recently to describe the fractional structure in a macroscopic isotropic disordered system [16,17]. Based on these relationships, the easily measurable FSDP position Q<sub>1</sub> has been broadly employed to characterize density change and volume change in various MGs [14,18-24]. Previous high-pressure experiments revealed that an interesting consequence of MGs is that amorphous-amorphous transitions (AAT) occur under higher pressures [14,18–24]. Polyamorphism was first observed in Ce<sub>55</sub>Al<sub>45</sub> MG [14], then a series of lanthanides-based MG such as Ce75Al25, Ce70Al10Ni10Cu10, Gd40Y16Al24Co20, Pr60Cu20Al10Ni10, Yb<sub>60</sub>Ca<sub>2.5</sub>Zn<sub>20</sub>Mg<sub>17.5</sub>, Pr<sub>75</sub>Al<sub>25</sub>, (La<sub>0.5</sub>Ce<sub>0.5</sub>)<sub>64</sub>Al<sub>16</sub>Ni<sub>5</sub>Cu<sub>15</sub>, were found





CrossMark



<sup>\*</sup> Corresponding author. School of Physical Science and Technology, Southwest Jiaotong University, Chengdu, 610031, China

E-mail addresses: xrliu@swjtu.edu.cn (X. Liu), yangwg@hpstar.ac.cn (W. Yang).

to display the discontinuous change of  $2\pi/Q_1$  under high pressure, which is attributed to a pressure-induced low density state (LDS) to high density state (HDS) transition [19-25]. Recently, polyamorphic transitions were reported in binary Ca-Al MGs, and discontinuous changes in compressibility were detected at ~18 GPa, 15.5 GPa, and 7.5 GPa in Ca<sub>80</sub>Al<sub>20</sub>, Ca<sub>72.7</sub>Al<sub>27.3</sub>, and Ca<sub>66.4</sub>Al<sub>33.6</sub> MGs, respectively [18]. The most widespread hypothesis about the mechanism of polyamorphism in MGs is electronic structural inheritance from the solvent elements [4,18,25]. For example, x-ray absorption spectroscopy analysis ascribes the polyamorphic transition in Ce75Al25 MG to pressure-induced 4f electron delocalization of the Ce atoms [25]. However, this usually ignored the anomalous behavior of the average atomic distance between a center atom and atoms in the first shell during the MG polyamorphic transitions. Instead, here, we focus on systematically evaluating this anomalous behavior by applying state-of-the-art advanced synchrotron-based high-energy x-ray diffraction analysis. The large coverage in Qspace provides accurate structural information from the pair distribution functions (g(r)), which motivated us to study the local structural anomalous changes during the polyamorphic transitions in the Ce<sub>60</sub>Al<sub>20</sub>Cu<sub>20</sub> and Ce<sub>55</sub>Al<sub>45</sub> MGs under high pressure.

#### 2. Experiments methods

Ce<sub>60</sub>Al<sub>20</sub>Cu<sub>20</sub> and Ce<sub>55</sub>Al<sub>45</sub> MG ingots were prepared by arcmelting a mixture of pure elements whose purities ranged from 99.8 to 99.9% in an argon atmosphere. The ingots were remelted five times to ensure composition homogeneity. Our Ce<sub>60</sub>Al<sub>20</sub>Cu<sub>20</sub> and Ce<sub>55</sub>Al<sub>45</sub> MGs ribbon samples were ~30  $\mu$ m thick and ~3 mm wide and prepared using the single-roller melt-spinning method. Our lab x-ray diffractometer verified the glass nature of Ce-based metallic glass. We conducted in situ high-energy x-ray diffraction experiments (HEXRD) with a symmetrical diamond anvil cell (DAC) on the X17B2 beamline at the National Synchrotron Light Source (NSLS), Brookhaven National Laboratory (BNL). HEXRD studies on Ce<sub>60</sub>Al<sub>20</sub>Cu<sub>20</sub> and Ce<sub>55</sub>Al<sub>45</sub> MGs were performed with a wavelength of 0.188 Å and 0.1529 Å, respectively. The focused beam size was about 30  $\mu$ m  $\times$  5  $\mu$ m in full width at half maximum. A Pelkin Elmer area detector was used for collecting the diffraction patterns. To gain the best statistics, 800 diffraction patterns were collected for each pressure point by alternating the beam on and off for the best background subtraction and average. The two samples were first cut into small chips, around  $170 \times 170 \times 30 \text{ }\text{um}^3$  and  $80 \times 80 \times 30 \ \mu\text{m}^3$  respectively, then loaded into symmetrical DACs along with small ruby balls around the sample as pressure calibrants. The sample chamber was a 250 µm diameter hole drilled in a Re gasket with a pre-indented thickness of around 60 µm and we used silicone oil as the pressure-transmitting medium. The background profile was taken from the same sample chamber before sample loading. To calibrate the detector to sample distance and detector tilting angles, we collected the diffraction image of a standard CeO<sub>2</sub> for fitting a standard pattern.

#### 3. Results and discussion

High-energy diffraction patterns of  $Ce_{60}Al_{20}Cu_{20}$  and  $Ce_{55}Al_{45}$ MGs are shown in Fig. 1(a) and (b), respectively. We observed no crystalline diffraction peaks after carefully inspecting the twodimensional XRD patterns recorded on the area detector. Upon compression, the broad diffusive amorphous peak shifts to a higher Q direction due to compression. The I(Q) data of  $Ce_{60}Al_{20}Cu_{20}$  at various pressures up to 17.52 GPa are displayed in Fig. 1(a). Surprisingly, the shape of the diffraction pattern changed above 3.50 GPa. The third peak began to appear at around 4.5 Å<sup>-1</sup> accompanied by the second peak's diffraction intensity diminishing, while the third peak intensified. The final XRD features at 17.52 GPa are obviously different from those at low pressures e.g. 0.92 GPa. In Fig. 1(b), a similar change of diffraction pattern shape can be found above 6.89 GPa for  $Ce_{55}Al_{45}$ . This is a clear sign that the interatomic distance distribution changes under high pressure,



**Fig. 1.** High-energy x-ray diffraction patterns of  $Ce_{60}Al_{20}Cu_{20}$  and  $Ce_{55}Al_{45}$  MGs at various pressures. Intensity profiles of I(Q) of  $Ce_{60}Al_{20}Cu_{20}$  up to 17.52 GPa (a) and  $Ce_{55}Al_{45}$  MG up to 14.33 GPa (b) in a DAC. Inverse FSDP position  $2\pi/Q_1$  of  $Ce_{60}Al_{20}Cu_{20}$  MG (c) and  $Ce_{55}Al_{45}$  MG (d), as a function of pressure.

and properly different amorphous phases occur in  $Ce_{60}Al_{20}Cu_{20}$  and  $Ce_{55}Al_{45}$  MGs under high pressure.

The position of the first diffraction maximum Q<sub>1</sub> is determined by the Gaussian function fit after subtracting the baseline. Since the  $2\pi/Q_1$  correlates with the volume of glass with a power law function, it has been widely used to estimate the relative volume change under high pressures [16]. The pressure dependence of  $2\pi/Q_1$  value is plotted in Fig. 1(c) and (d) for Ce<sub>60</sub>Al<sub>20</sub>Cu<sub>20</sub> and Ce<sub>55</sub>Al<sub>45</sub> MGs, respectively. In Fig. 1(c), the  $2\pi/Q_1$  decreases with increasing pressure and begins to deviate from the fitting curve above 3.50 GPa. The  $2\pi/Q_1$  as a function of pressure coincides with the other fitting line above 6.32 GPa. It is remarkable that two glassy states that are distinctly separated by a transition region exist between 3.50 and 6.32 GPa, with a volume reduction of about 1.7% (i.e.  $2\pi/Q_1 \sim 0.86\%$ ) at 6.32 GPa. The anomalous change of  $2\pi/Q_1$  over the pressure range of 3.50-6.32 GPa clearly reveals an amorphousamorphous transition (AAT) from a low-density glass to a highdensity glass. In Fig. 1(d), a similar anomalous change of  $2\pi/Q_1$ over the pressure range of 2.20-6.89 GPa is also observed for Ce<sub>55</sub>Al<sub>45</sub> MG. It demonstrates an AAT from a low-density glass at low pressure to a high-density glass at high pressure with a volume reduction of about 3.92% (i.e.  $2\pi/Q_1 \sim 2.05\%$ ) at 6.89 GPa.

Next, we analyzed the structure factors S(Q) to further demonstrate that the two amorphous phases are structurally different. Applying the usual corrections and normalization procedure, the structure factor S(Q) is calculated from the measured intensities I(Q) to determine the coherent scattered intensity in the absolute electron units:

$$S(Q) = \frac{I_{e.u.}^{coh} - \left(\langle f^2 \rangle - \langle f \rangle^2\right)}{\langle f \rangle^2}$$
(1)

with  $\langle f \rangle^2 = (\sum c_i f_i)^2$  and  $\langle f^2 \rangle = \sum c_i \cdot f_i^2$ , where  $f_i$  is the atom form factor of the element i and  $c_i$  is the concentration [26–28]. Fig. 2(a)

and (b) show the S(Q) plots for Ce<sub>60</sub>Al<sub>20</sub>Cu<sub>20</sub> and Ce<sub>55</sub>Al<sub>45</sub> MGs as a function of pressure, respectively. In Fig. 2(a), the distinct difference between the HDG and LDG is the appearance of a small peak at around 4.5  $Å^{-1}$  (hereafter called the third peak), which indicates a new atomic packing mode in the short-range order. The appearance of the third scattering peak at a higher Q value in the HDG phase gives better ordering in the short range, thus polyamorphism appears at this pressure. We discovered similar behavior in Ce<sub>55</sub>Al<sub>45</sub> MG, as shown in Fig. 2(b). The second peak splits and the third peak starts to appear from 2.2 GPa, which means that new diversification of the atom packing modes emerges at high pressure and the structure of the HDG becomes more ordered like Ce<sub>60</sub>Al<sub>20</sub>Cu<sub>20</sub>. In addition, the first halo in the S(Q) curves referring to the first sharp diffraction peak (FSDP) reveals the structural information of the medium-range length scale in MGs [19]. In order to see the difference induced by pressure, we introduced a differential structure factor  $\Delta S(Q) = S_p(Q)-S_1(Q)$  [19]; where  $S_p(Q)$  is the structure factor S(Q) measured at the applied pressures and  $S_1(Q)$  is the first pressure point, which is 0.92 GPa and 0.17 GPa for Ce<sub>60</sub>Al<sub>20</sub>Cu<sub>20</sub> and Ce<sub>55</sub>Al<sub>45</sub> MGs respectively. In Fig. 2(c) and (d),  $\Delta S(Q)$  near the FSDP are plotted to focus on the medium-range length scale during polyamorphism. In Fig. 2(c), the  $\Delta S(Q)$  shifts to a higher momentum transfer (Q) under high pressure due to compression and begins to exhibit a change over the slope (as the arrow shows) at around 6.32 GPa. In Fig. 2(d), a similar discontinuous change of slope (as the arrow shows) is found at around 5.63 GPa in Ce<sub>55</sub>Al<sub>45</sub> MG. These changes indicate that two different glass phases exist in the applied pressure range: LDG and HDG, in line with the results defined solely from the data of the inverse FSDP positions  $2\pi/Q_1$  of the two metallic glasses.

To reveal the atomic packing distribution, we investigated the structure evolution in real space. The pair distribution function g(r) is a powerful tool to characterize the local atomic packing, especially for the disordered and amorphous systems that do not have distinguished sharp diffraction patterns from the crystalline



Fig. 2. Structure factor S(Q) of  $Ce_{60}Al_{20}Cu_{20}$  MG up to 17.52 GPa (a) and  $Ce_{55}Al_{45}$  MG up to 14.33 GPa (b). The  $\Delta S(Q)$  vs. Q curves around the FSDP of  $Ce_{60}Al_{20}Cu_{20}$  MG (c) and  $Ce_{55}Al_{45}$  MG (d) under applied pressures.



Fig. 3. Pair distribution function g(r) of (a)  $Ce_{60}Al_{20}Cu_{20}$  MG up to 17.52 GPa and (b)  $Ce_{55}Al_{45}$  MG up to 14.33 GPa.

structure. The  $g(r) = \rho(r)/\rho_0$  was calculated by the Fourier transformation of S(Q), where  $\rho(\mathbf{r})$  is the atomic pair density distribution function,  $\rho_0$  is the mean atomic density [16]. The g(r) curves of Ce<sub>60</sub>Al<sub>20</sub>Cu<sub>20</sub> and Ce<sub>55</sub>Al<sub>45</sub> MG at various pressures are plotted in Fig. 3(a) and (b) respectively. Interpolative pictures contain the g(r)raw data, the g(r) curve after subtracting the baseline, and the six fitting peaks of g(r) curve at the initial pressure. Fig. 4(a) and (b) show the positions of the six fitted peaks at applied pressures. The g(r) consists of all the partial g(r) that are related to the correlations between any two elements in the sample by superposition [14]. Considering that the studied rare earth-based amorphous sample contains 55% Ce atom and 60% Ce atom in the Ce<sub>60</sub>Al<sub>20</sub>Cu<sub>20</sub> and  $Ce_{55}Al_{45}$  MGs, the first peak of partial g(r) related to the Ce-Ce correlation is the strongest among all partial g(r). Therefore, the first peak of g(r) corresponds mainly to the Ce-Ce correlation and can indicate the change of atomic bonds [14]. In Fig. 4(a), the first peak position (nearest neighbor distance) shifts to smaller values with increasing pressure from 0.92 GPa to 17.52 GPa, illustrating that the diameter of the Ce atom decreases with pressure. A discontinuous change of the first peak position, as well as the other five peaks, occurs at 3.50-6.32 GPa, illustrating that a structurally different amorphous phase has resulted under high pressure. Pressure-induced qualitative changes in bond shortening of the six peak positions seem to be the origin of the volume reduction in our experiment. In Fig. 4(b), a similar discontinuous change of the six peak positions is found at 2.20–6.89 GPa. These results suggest that the polyamorphic transition observed in Ce<sub>60</sub>Al<sub>20</sub>Cu<sub>20</sub> and Ce<sub>55</sub>Al<sub>45</sub> MGs accompanies local structural anomalous changes. As reported by a previous spectroscopy study, the sudden volume collapse in Ce<sub>75</sub>Al<sub>25</sub> metallic glass is related to the 4f electron delocalization at a similar pressure range [25]. We believe that the polyamorphic transitions observed at these 55% and 60% Ce-based metallic glasses originate from the same mechanism, but with a slightly higher-pressure range. Due to the Ce 4f electron delocalization, the size of the Ce atom shrinks faster and causes densification with a rearrangement of the neighboring atoms.



Fig. 4. The six peak positions of g(r) for (a)  $Ce_{60}Al_{20}Cu_{20}$  MG and (b)  $Ce_{55}Al_{45}$  MG, as a function of pressure.

#### 4. Conclusions

In summary, with the aid of high-energy synchrotron x-ray diffraction, we successfully observed structural anomalous changes during pressure-induced polyamorphism in Ce<sub>60</sub>Al<sub>20</sub>Cu<sub>20</sub> and Ce<sub>55</sub>Al<sub>45</sub> MGs. A sudden change in compressibility and the nearest neighbor distance was observed at 3.50-6.32 GPa in  $Ce_{60}Al_{20}Cu_{20}$  MG and at 2.20–6.89 GPa in  $Ce_{55}Al_{45}$  MG. There was a distinct difference between the low-density glass and high-density glass in both systems. The volume reduction seems to originate from pressure-induced qualitative changes in bond shortening that correspond to different coordination spheres. The polyamorphic transition from a low-density state into a high-density state is ascribed to the special effects of pressure-induced 4f electron delocalization and local atomic rearrangement.

### Acknowledgments

This work was supported by NSAF (Grant No:U1530402), NSFC (Grant No: 11004163) and Fundamental Research Funds for the Central Universities (Grant No: 2682014ZT31). The experimental work was performed at X17B2 beamline at National Synchrotron Light Source (NSLS), the Brookhaven National Laboratory (BNL).

#### References

- A.L. Greer, Science 267 (1995) 1947.
- W.H. Wang, Nat. Mater. 11 (2012) 275. [2]
- M.F. Ashby, A.L. Greer, Scr. Mater. 54 (2006) 321. [3]
- [4] J. Schroers, W.L. Johnson, Phys. Rev. Lett. 93 (2004) 255506.
- [5] D. Ma, A.D. Stoica, X.L. Wang, Nat. Mater. 8 (2009) 30.
  [6] H.W. Sheng, W.K. Luo, F.M. Alamgir, J.M. Bai, E. Ma, Nature 439 (2006) 419. [7] Q.S. Zeng, V.V. Struzhkin, Y.Z. Fang, C.X. Gao, H.B. Luo, X.D. Wang, C. Lathe,

- W.L. Mao, F.M. Wu, H.K. Mao, J.Z. Jiang, Phys. Rev. B 82 (2010) 054111.
- [8] W.H. Wang, Z.X. Bao, C.X. Liu, D.Q. Zhao, Phys. Rev. B 61 (2010) 3166.
- [9] J. Wang, R. Li, R. Xiao, T. Xu, Y. Li, Z. Liu, L. Huang, N. Hua, G. Li, Y. Li, T. Zhang, Appl. Phys. Lett. 99 (2011) 151911.
- [10] P. Yu, K.C. Chan, W. Chen, L. Xia, J. Alloy. Compd. 509 (2011) 8518.
- [11] Y. Wang, W. Zhao, G. Li, Y. Li, R. Liu, J. Alloy. Compd. 551 (2013) 185.
- [12] D.Q. Zhao, M.X. Pan, W.H. Wang, B.C. Wei, T. Okada, W. Utsumi, J. Phys. Condens. Matter 15 (2003) 749.
- [13] Q.S. Zeng, H.W. Sheng, Y. Ding, L. Wang, W.G. Yang, J.Z. Jiang, W.L. Mao, H.K. Mao, Science 332 (2011) 1404.
- [14] H.W. Sheng, H.Z. Liu, Y.Q. Cheng, J. Wen, P.L. Lee, W.K. Lou, S.D. Shastri, E. Ma, Nat. Mater. 6 (2007) 192.
- [15] X.R. Liu, S.M. Hong, Appl. Phys. Lett. 90 (2007) 251903.
- [16] A. Guinier, X-Ray Diffraction: in Crystals, Imperfect Crystals and Amorphous Bodies, 1994, p. 61. Dover, New York.
- [17] Q.S. Zeng, Y. Kono, Y. Lin, Z.D. Zeng, J.Y. Wang, S.V. Sinogeikin, C.Y. Park, Y. Meng, W.G. Yang, H.K. Mao, W.L. Mao, Phys. Rev. Lett. 112 (2014) 185502. [18] H.B. Lou, Y.K. Fang, Q.S. Zeng, Y.H. Lu, X.D. Wang, Q.P. Cao, K. Yang, X.H. Yu,
- L. Zheng, Y.D. Zhao, W.S. Chu, T.D. Hu, Z.Y. Wu, R. Ahuja, J.Z. Jiang, Sci. Rep. 2 (2012) 376.
- [19] G. Li, Y.Y. Wang, P.K. Wang, P.K. Liaw, Y.C. Li, R.P. Liu, Phys. Rev. Lett. 109 (2012) 125501.
- [20] W. Zhao, Y.Y. Wang, R.P. Liu, G. Li, Appl. Phys. Lett. 102 (2013) 031903.
- [21] M.J. Duarte, P. Bruna, E. Pineda, D. Crespo, G. Garbarino, R. Verbeni, K. Zhao, W.H. Wang, A.H. Rpmero, J. Serrano, Phys. Rev. B 84 (2011) 224116.
- [22] Q.S. Zeng, Y.C. Li, C.M. Feng, P. Liermann, M. Somayazulu, G.Y. Shen, H.K. Mao, R. Yang, J. Liu, T.D. Hu, J.Z. Jiang, Proc. Natl. Acad. Sci. 104 (2007) 13565. [23] C.L. Lin, A.S. Ahmad, H.B. Lou, X.D. Wang, Q.P. Cao, Y.C. Li, J. Liu, T.D. Hu,
- D.X. Zhang, J.Z. Jiang, J. Appl. Phys. 114 (2013) 213516.
   [24] Q.S. Zeng, Y.Z. Fang, H.B. Lou, Y. Gong, X.D. Wang, K. Yang, A.G. Li, S. Yan,
- C. Lathe, F.M. Wu, X.H. Yu, J.Z. Jiang, Low-density to high-density transition in Ce75Al23Si2 metallic glass, J. Phys-Condens. Mater. 22 (2010) 375404.
- [25] Q.S. Zeng, Y. Ding, W.L. Mao, W.G. Yang, S.V. Sinogeikin, J.F. Shu, H.K. Mao, J.Z. Jiang, Phys. Rev. Lett. 104 (2010) 105702.
- [26] Y. Waseda, The Structure of Non Crystalline Materials: Liquids and Amorphous Solids, 1980, p. 41. Mexico, New York.
- [27] G. Shen, V.B. Prakapenka, M.L. Rivers, S.R. Sutton, Rev. Sci. Instrum. 74 (2003) 3021
- [28] N. Mattern, J. Bednarcik, H.-P. Liermann, J. Eckert, Intermetallics 38 (2013) 9.