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Dimensional Changes of Amorphous Alloys Under Swift Ar Ion Irradiation

Liu Changlong, Hou Mingdong, Wang Zhiguang, Cheng Song, Sun Youmei, Zhu Zhiyong, Jin Yunfan, Li Changlin, Wang Yinshu, and Meng Qinghua

(Institute of Modern Physics, The Chinese Academy of Sciences, Lanzhou, China)

Small strips of amorphous alloys $Fe_{77.2}Mn_{0.8}Si_9B_{13}$, $Fe_{39}Ni_{39}V_2Si_{12}B_8$, $Fe_{47}Ni_{29}V_2Si_6B_{16}$, and $Fe_{40}Ni_{40}Si_{12}B_8$ were irradiated below 50°K with 2.79 MeV/u Ar ions delivered from Heavy Ion Research Facility in Lanzhou (HIRFL). The macroscopic dimensions of the samples were measured at room temperature before and after irradiation by means of optical microscopy. The observed dimensional changes of all the samples are very small for the low fluency of 1.5×10^{14}Ar/cm^2. Upon the increase of ion fluency to 1.6×10^{15}Ar/cm^2, dramatic and irreversible dimensional changes are observed and the measured relative changes in width, $\Delta b/b_0$, are in the range of 4.3–12.0%. The results are qualitatively discussed.

Key words: amorphous alloy, Ar ion irradiation, dimensional change.

1. INTRODUCTION

When an energetic ion penetrates into a solid, it loses its energy mainly via two nearly independent processes: i) nuclear energy loss S_n which dominates at low energy and is due to a direct transfer of kinetic energy to the target nuclei (elastic collisions); ii) electronic energy loss S_e, dominant at high energy and due to electronic excitation and/or ionization of the target atoms (inelastic

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collisions). Before the 1980s, the ion radiation damage in metallic targets was commonly attributed to the energy deposited in elastic collisions with target atoms. The energy transferred to the electron (S_e) was supposed to spread out very rapidly without creating noticeable damage. At the beginning of the 1980s, the advent of a new generation of swift heavy ion accelerators (GSI-Darmstadt, GANIL-Caen) has allowed to use high-energy (GeV) heavy ions, and thus to investigate the effects of huge electronic energy loss on the structure and physical properties of solids. In the last decade, an increasing number of surprising experimental results has been reported. It has been demonstrated that electronic energy loss induced either a decrease or an enhancement of radiation damage efficiency in pure metal [1]. A more dramatic effect has been seen in crystalline metallic alloys [2]: amorphization and latent track creation. In amorphous materials, a new effect induced by S_e has been discovered [3]: a huge plastic deformation at constant volume occurs exactly as if the ion beam acted as a hammer.

The ion-induced plastic deformation of amorphous alloys was first reported by S. Klaumünzer *et al.* [3]: the sample dimension perpendicular to the ion beam direction increases with ion fluency, without any saturation, whereas the dimension parallel to it shrinks. The occurrence of this effect depends on many factors, including electronic energy loss S_e, irradiation temperature, and material properties. It has been shown that the deformation rate of amorphous alloy increases almost linearly above an apparent S_e threshold, and it decreases with increasing temperature. For a long time, it was thought that structure changes in a metallic target could not be released by electronic excitations as a result of their rapid de-excitation and delocalization among the continuum states in the conduction electrons. Obviously, the experimental finding of ion-beam-induced plastic deformation of amorphous alloys is inconsistent with this view. Therefore, the radiation-induced dimensional instability of amorphous alloys provides a new access to the question concerning the way in which an intense electronic excitation can provoke atomic rearrangements in solids.

Although many works have been undertaken to investigate this growth effect, to date, only a limited number of papers is published concerning the plastic deformation induced by lighter ions such as Ar ions. In this paper, we report on the experimental results of four kinds of amorphous alloys which have been exposed at temperatures below 50°K to a beam of 2.79 MeV/u Ar ions.

2. EXPERIMENTAL PROCEDURE

The starting materials were melt-spun ribbons (approximately 30 μm thick, 1 cm wide), which have different nominal compositions, as shown in Table 1. These ribbons were thinned to a final thickness, t_0, of 8.0 to 10.5 μm by means of electrolysis. Small strips of a rectangular shape (approximately 3 × 1 mm^2) were cut from the thinned amorphous alloys. Several samples, differing in glass composition, were clamped side by side between two small copper plates so that a portion (approximately 1 × 1 mm^2) of each sample stood out and was thus available for exposure to the ion beam. An indium layer was placed between the two plates to improve good thermal contact between the specimens and the sample holder. Several of these sample holders could be tightly screwed to a cold finger which could be contacted to a cryostat. An indium layer was again used between the sample holders and the cold finger. The cryostat was inserted into a special vacuum chamber mounted at the beam line of HIRFL. The cryostat could by turned by ± 180° around a vertical axis manually. Only one irradiation geometry was used in this work, i.e., the normal surface of the sample was aligned parallel to the ion beam. Several specimens were irradiated simultaneously by sweeping the beam spot. The irradiation of the samples was performed using flux of 1.4×10^{10}Ar/cm^2 · s. Each irradiation run was subdivided into a small fluency of $\Phi t = 6.0 \times 10^{13}$Ar/cm^2, with a 180° turn of the samples.

During the irradiations, the temperature was measured by a calibrated Rh-Fe thermocouple which was fixed on the cold finger and was kept below 50°K. The dimensional changes of the samples were measured by means of optical microscopy before and after irradiations.

For 2.79 MeV/u Ar ions, the projected ranges, R_p, the range stragglings, ΔR_p, the thickness averaged electronic energy loss, $\langle S_e \rangle$, the nuclear energy loss, $\langle S_n \rangle$, and the total displacement cross

Table 1

The relative changes in width, $\Delta b/b_0$, of four kinds of amorphous alloys obtained after 2.79 MeV/u Ar ion irradiation for different fluences and the corresponding parameters.

Sample	t_0 (μm)	$R_p \pm \Delta R_p$ (μm)	$\langle S_e \rangle$ (keV/Å)	$\langle S_n \rangle$ (eV/Å)	$\langle P \rangle$ (10^{-17}cm^2)	ρt ($\times 10^{15}$Ar/cm^2)	$\Delta b/b_0$ (%)
$Fe_{47}Ni_{29}V_2Si_6B_{16}$	8.0	11.7 ± 0.5	1.09	2.18	1.75	1.15	0.4
						1.6	7.6
$Fe_{77.2}Mno_{0.8}Si_{19}B_{13}$	8.5	11.9 ± 0.5	1.06	2.31	1.85	0.15	0.7
						1.6	12.0
$Fe_{39}N1_{39}V_2Si_{12}B_8$	10.0	11.4 ± 0.5	0.96	5.62	4.43	0.15	0.5
						1.6	6.0
$Fe_{40}Ni_{40}Si_{12}B_8$	10.5	11.3 ± 0.5	0.83	10.00	7.84	0.15	0.3
						1.6	4.3
$Pd_{80}Si_{20}$[a]	8.5	16.7 ± 0.7	1.00	1.40	0.83	2.68	1.1

(a) Cited from Ref. [4].

section, $\langle P \rangle$, which takes only into account nuclear collisions, are summarized in Table 1 for the amorphous alloys used. These data are calculated using the Monte Carlo code TRIM-91. Therefore, in all cases, the final thickness t_0 of any sample is less than R_p, i.e., projectile implantation can be negligible.

The turning can improve the uniformity of energy deposition via S_n and S_e. The effect of turning on the depth dependence of the deposited energy is illustrated in Fig. 1 for amorphous alloy $Fe_{77.2}Mn_{0.8}Si_9B_{13}$. It can be seen from Fig. 1 that S_e is more than two orders of magnitude larger than S_n, i.e., the energy deposited into the electronic system of the targets exceeds by far the kinetic energy which is directly transferred to target atoms by nuclear collisions.

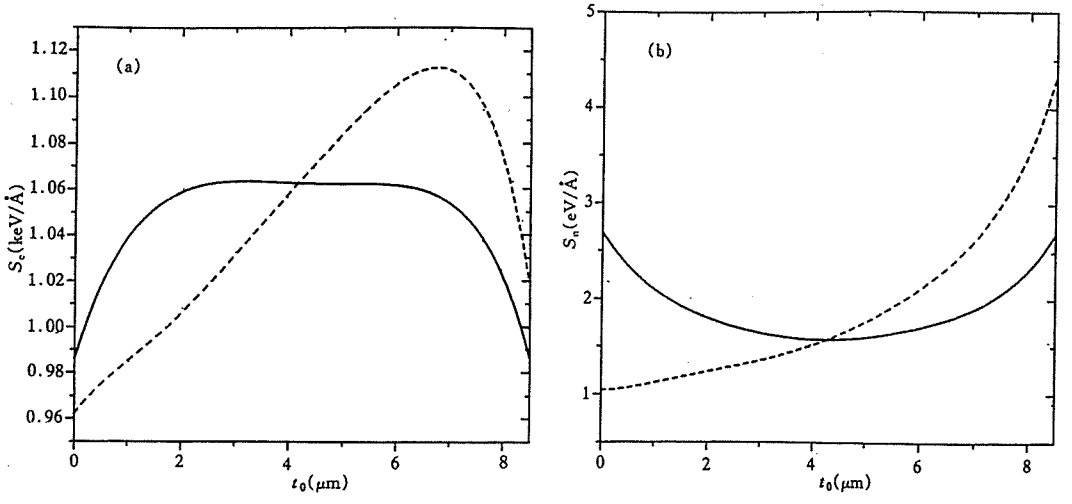

Fig. 1

Energy deposited by 2.79 MeV/u Ar ions in amorphous alloy $Fe_{77.2}Mn_{0.8}Si_9B_{13}$ via electronic excitations (left) and elastic collisions (right) versus target depth, calculated by the TRIM-91 program. The total target thickness is about 8.5 μm. Dashed lines indicate the case without target turning; solid lines indicate the case in which beam entrance and exit to the target are exchanged in small fluency steps.

3. RESULTS

During the irradiation, all the amorphous alloys investigated in this work exhibited dimensional changes above a certain fluency. The measured relative changes in width, $\Delta b/b_0$, of the amorphous samples for two different fluences are represented in Table 1. One can see that the changes of samples are fluency dependent. For the low ion fluency of 1.5×10^{14}Ar/cm^2, the observed deformation is very small (less that 1%). After increasing ion fluency to 1.6×10^{15}Ar/cm^2, all the samples show large growth in dimensions perpendicular to the ion beam. The measured relative changes in width are in the range from 4.3 to 12.0%. Moreover, the observed deformation depends on the composition of the sample.

In Fig. 2, the relative change of the width of amorphous alloys $Fe_{77.2}Mn_{0.8}Si_9B_{13}$ and $Fe_{47}Ni_{29}V_2Si_6B_{16}$ are plotted as a function of ion fluency Φt. This figure demonstrates the linear expansion of these amorphous alloys in the direction perpendicular to the ion beam with the ion fluency. The straight lines in this figure are the results of linear fits to the experimental data. The slopes of the curves give the deformation rates which are the direct measures of the deformation yields per incident ion. In the figure, the deformation result of amorphous alloy $Pd_{80}Si_{20}$ obtained after irradiation with 170 MeV Ar ions at temperatures below 50°K is also given [4]. Compared to this it result, is obvious that much larger growth is observed in our sample under nearly similar irradiation conditions.

The photograph of amorphous alloy $Fe_{77.2}Mn_{0.8}Si_9B_{13}$ after irradiation to the fluency of 1.6×10^{15}Ar/cm^2 is shown in Fig. 3. For the irradiated part, in addition to the large deformation, the formation of wrinkles in the sample is also observed, which is due to the mechanical constraints of the sample holder and the unirradiated part of the sample. However, no change occurs for the unirradiated portion of sample.

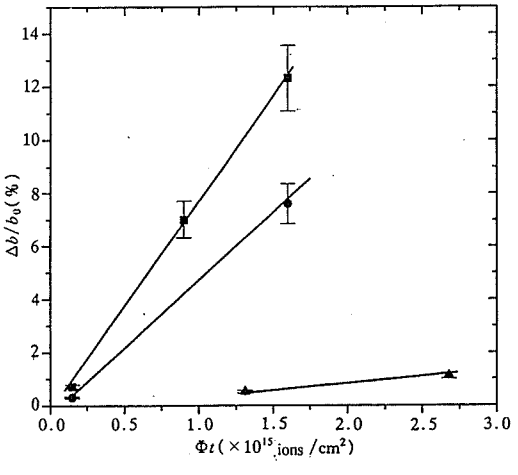

Fig. 2
Relative changes in width versus ion fluency Φt for amorphous alloys $Fe_{77.2}Mn_{0.8}Si_9B_{13}$ (■) and $Fe_{47}Ni_{29}V_2Si_6B_{16}$ (●). Deformation results cited from Ref. [4] are also given (▲).

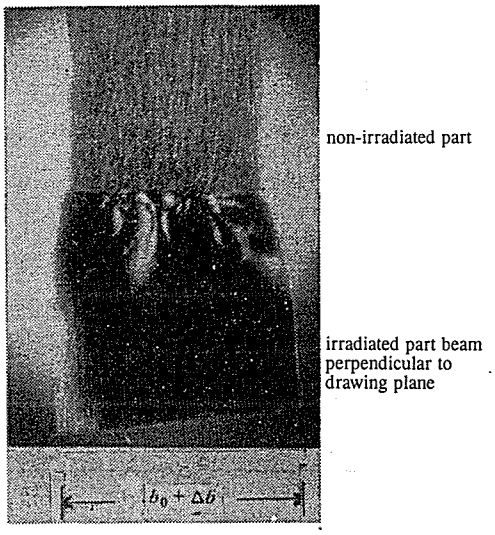

Fig. 3
Photograph of amorphous alloy $Fe_{77.2}Mn_{0.8}Si_9B_{13}$. The upper part is without irradiation, but its lower part has been has been homogeneously irradiated below 50°K with 2.79 MeV/u Ar ions up to 1.6×10^{15} Ar/cm^2.

4. DISCUSSION

It is well known that the deformation rate of amorphous alloys depends on several factors, including electronic energy loss, nuclear energy loss, temperature, and target properties. In our studies, there exist two main factors which may influence the accuracy of our obtained growth results. One is the sample thickness, which has a strong influence on the uniformity of energy depositions via S_e and S_n along the incident direction in the samples, especially for the case that the sample thickness is near the projected range. The inhomogeneous energy deposition may lead to the bending of samples towards to the coming direction of the ion beam. The bending of the sample changes the irradiation geometry between the sample and the ion beam and decrease the deformation rate [8]. The other factor is the target temperature. A temperature gradient may exist in the irradiated sample part along the length direction during irradiations, which could lead to inhomogeneous dimensional changes of the irradiated samples because of the strong dependence of the deformation rate on temperature.

So far, many papers have been published on the deformation effect induced by high S_e (several MeV/μm). In contrast, little work has been done on the deformation effect induced by low S_e ($\leq$ 1.0 MeV/μm). To our knowledge, the only low S_e-induced deformation result was obtained on amorphous alloy $Pd_{80}Si_{20}$ after 170 MeV Ar ion irradiation below 50°K. Comparing this result with reported data, many large dimensional changes are observed for our amorphous alloys under similar irradiation conditions. These differences could be attributed to two main reasons:

(1) The influence of the properties of amorphous alloys, including composition and processing techniques. It is known that the growth rate of amorphous alloys depends on their nominal compositions [5]. Many results have shown that the Pd-based amorphous alloys are less sensitive to the growth than Fe-based amorphous alloys. The resulting difference of growth rates between these two types of amorphous alloys can reach a factor of 5–10.

(2) The influence of the thickness of the sample. The thickness of the sample will influence the energy deposition of ions in solids. The increase of sample thickness will increase the energy deposition via nuclear collisions, and thus increase the amount of defects produced through nuclear collisions. The production of defects in an amorphous alloy can be visualized as the creation of free volume. Then with increasing free volume, the viscosity of amorphous alloy will dramatically decrease, and a small shear stress will produce a large strain. The correlated growth of defects has been demonstrated by A. Audouard [7]. In our case, the thickness of sample is only slightly smaller than the projected range. Therefore, much energy deposited via nuclear collisions can be expected.

The ion-beam-induced plastic deformation of amorphous alloys has been known about for many years. However, the understanding of its physical mechanism is very limited. Many attempts have been made to use some kind of defect reaction kinetics to explain this phenomenon. The growth of amorphous solids under energetic heavy ion bombardment, for instance, has been attributed to the production of "shear units" representing some "mechanical polarization" of material which is assumed to "trigger irreversible shear transformations." This type of defect structure is thought to result from the "Coulomb explosion" induced by electronic excitations and ionization of the atoms in the wake of projectiles [5]. To date, H. Trinkaus [6] has discussed the irradiation growth of amorphous solids in the terms of a visco-elastic model emphasizing the difference in respect to crystalline solids. In this model, the growth of amorphous solids is attributed to the relaxation of shear stress coupled to the thermal expansion in cylindrical thermal spikes induced by intense electronic excitation and to the subsequent freezing-in of the associated strain increase upon cooling down. Simple expressions for pronounced thermal spikes and low temperature are derived, and the key parameters which control the growth effect are also given. Although the theoretical results are in good agreement with the experimental results in most cases, this model is based on the fact that the electronic energy loss S_e is large enough to melt the irradiated regions along the trajectory of a high energy ion. It cannot be used for explanation of growth results induced by a lower electronic energy loss. Therefore, further data

accumulation and theoretical investigations are needed in order to better understand the physical mechanism involved in the ion-beam-induced growth.

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