Journal of Applied Mechanics and Technical Physics, Vol. 45, No. 3, pp. 449–452, 2004

SHEAR BAND FORMATION IN Fe–Cr–Mo–V–B–Si AMORPHOUS ALLOY UNDER NANOINDENTATION

M. N. Vereshchagin,[1] S. N. Dub,[2]
V. G. Shepelevich,[3] and O. M. Ostrikov[1]

UDC 548.24

The formation of shear bands in Fe–Cr–Mo–V–B–Si *amorphous alloy under nanoindentation Is studied. The indentation process is considered against the background of shear band formation in the amorphous material.*

Key words: *hardness, nanoindenter, amorphous alloy, shear band.*

The formation of an indentation has received much attention owing to the wide popularity of tools used to study material microhardness [1]. At present, interest [2–4] in the indentation method has considerably increased in connection with the successful activities of companies such as "Nano Instrument Inc." (USA), which produce measurement equipment that is in great demand and enables a new high level of research. It has become possible to determine the dependence of the indentation depth h on the load P with higher accuracy.

In most cases, the dependence $P(h)$ is continuous and is adequately described by a function of form type $P = \alpha h^m$. However, when twins, cracks, or shear bands occur near stress concentrators [5–7], the dependence $P(h)$ has discontinuities, whose number usually corresponds to the number of two-dimensional defects formed near the indenter.

It is unclear which hardness of the material is true: the hardness measured before or after the formation of a twin, crack, or shear band. This question arises because the behavior of the dependence $P(h)$ after formation of a two-dimensional defect differs from that in the absence of such defects [4]. It is therefore obvious that the modern concepts of material microhardness are far from perfect require a comprehensive study of the effect of two-dimensional defects on the formation of an indentation on a surface using Vickers, Knoop, and Berkowicz diamond pyramids or other indenters.

The goal of this paper is to study the mechanisms of indentation formation on iron based amorphous alloys using Vickers and Berkowicz pyramids under conditions of shear band formation.

Experimental Procedure. We studied Fe–Cr–Mo–V–B–Si amorphous alloy produced by melt spinning on the outer surface of a disk-shaped copper crystallizer [8]. The alloy was melted in a quartz tube with a slot opening 0.25–0.30 mm wide at an excess argon pressure of 0.2–0.5 MPa. The cooling rate of the band was $8 \cdot 10^5$ °C/sec.

X-ray structural and phase analyses of the amorphous band were performed on a DRON-3 diffractometer using monochromatic $\mathrm{Cu}_{K\alpha}$ radiation for a voltage of 30 kV, a current of 20 mA, and a counter rate of 2 deg/min.

Shear bands near the stress concentrator were studied by scanning electron microscopy using a CamScan-4 setup.

The dependences $P(h)$ and $p(h)$ were obtained with the aid of a NANO INDENTER II hardness tester ("Nano Instrument Inc.).

[1]Sukhoi Gomel' State Technical University, Gomel' 246746, Belarus'. [2]Institute of Superhard Materials, National Academy of Sciences, Kiev 04074, Ukraine. [3]Belarus' State University, Minsk 220050, Belarus'. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, Vol. 45, No. 3, pp. 172–175, May–June, 2004. Original article submitted May 26, 2003; revision submitted September 17, 2003.

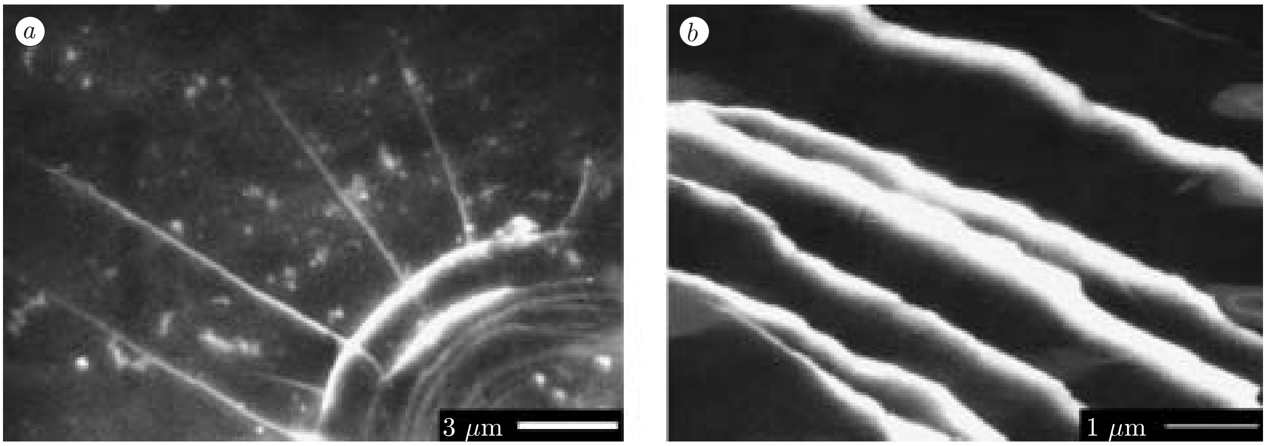

Fig. 1. Typical deformation pattern near a stress concentrator on the surface of Fe–Cr–Mo–V–B–Si amorphous alloy: a) shear bands in the form of semirings and radials; b) shear bands in the form of semirings.

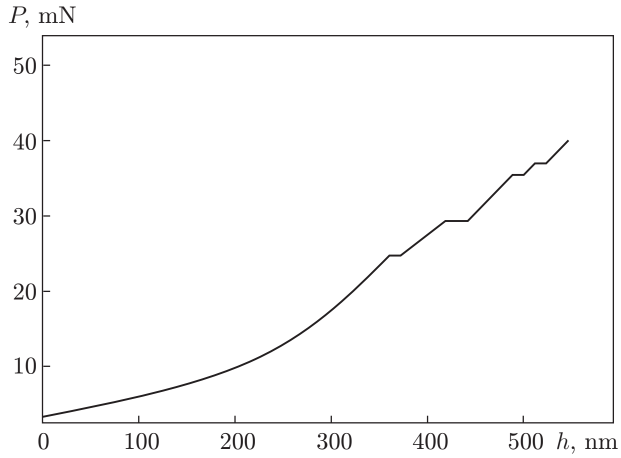

Fig. 2

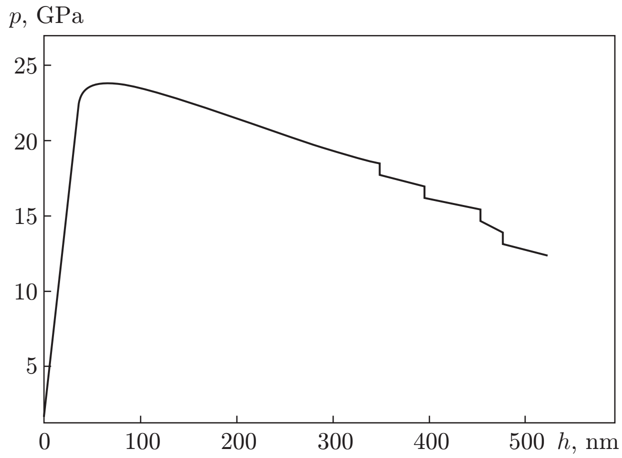

Fig. 3

Fig. 2. Dependence $P(h)$ for indentation of Fe–Cr–Mo–V–B–Si alloy using NANO INDENTER II.

Fig. 3. Average indentation contact pressure p versus penetration depth h.

Experimental Results and Discussion. X-ray structural analysis shows that the materials studied are x-ray amorphous materials. This is manifested in a typical smearing of the peak corresponding to the (110) α-Fe plane. No other peaks were revealed in the x-ray pattern.

The main distinguishing feature of the local plastic deformation of the amorphous alloy surface is the intense development of shear bands [8, 9], which have a significant effect on the nature of indentation formation. The formation of shear bands is responsible for discontinuities in the function $P(h)$, leads to removal of elastic energy from the indenter, and facilitates short-term acceleration of indenter penetration into the material studied. Under nanoindentation, shear bands in the form of radials do not occur. They are formed under indenter forces of 1–1.5 N [8, 9] (Fig. 1a). In the nanoindentation process, an indentation is formed against the background of development of shear bands in the form of semirings surrounding the indenter (Fig. 1b).

Figures 2 and 3 show the results of nanoindentation of amorphous materials. The dependence $P(h)$ (Fig. 2) can be approximated by the function [4] $P = Hh^2/k$. It should be noted that this formula is generally insufficiently adequate to describe the dependence $P(h)$. The reason is that the curve has discontinuities. Therefore, the approximation $P = Hh^2/k$ is valid only for separate parts of the curve. The refined expression for $P(h)$ has the form

$$P = \begin{cases} \gamma\beta_1 Hh^2/k, & 0 < h < h_1, \\ \gamma\beta_2 Hh^2/k, & h_1 < h < h_2, \\ \gamma\beta_3 Hh^2/k, & h_2 < h < h_3, \\ \quad\ldots\ldots\ldots\ldots\ldots\ldots & \\ \gamma\beta_n Hh^2/k, & h_{n-1} < h < h_n. \end{cases} \tag{1}$$

Here γ is a certain nondimensional factor which depends on loading rate [4], β_j is a factor that takes into account deviation of the function $P(h)$ from the dependence $P = Hh^2/k$ caused by the formation of the jth shear band, $h_j$is the indenter displacement that determines the continuity range of the function $P(h)$ between the moments at which shear bands occur, and n is the number of shear bands.

Figure 3 shows the dependence $p(h)$ (p is the average indentation contact pressure). This dependence is also nonmonotonic in the region of plastic deformation of the surface by the indenter. One can see sudden drops in the curve, accompanied by discontinuities.

From the results shown in Figs. 2 and 3, one can draw the following conclusions on the nature of the indentation formation:

1) the deformation of an amorphous material by the indenter includes an elastic stage (the initial segment of the curve in Fig. 3);

2) the initial stage of plastic deformation has an interval in which shear bands are not formed;

3) when a shear band occurs, the indentation contact pressure is low, but it decreases abruptly (see Fig. 3); this is accompanied by an increase in the rate of indenter penetration into the amorphous material, which is manifested in a shift of the segment of the curve $P(h)$ (see Fig. 2).

Thus, it can be assumed that shear bands facilitate the removal of elastic energy from the indentation, resulting in a momentary decrease in the indentation resistance of the amorphous matrix. In this case, the depth h is slightly greater than in the absence of shear band. According to relation (1), this is accompanied by a decrease in the microhardness H.

Since the material hardness before and after shear band formation has different values, the question arises as to which of the two values is true. In other words, can one assume, within the framework of the definition of material hardness [1], that in the initial stage of plastic deformation, the material hardness before shear band formation is higher than that after shear bands occur?

Conclusions. From an analysis of the development of semiring-shaped shear bands in an iron based amorphous alloy under nanoindentation and the formation of an indentation under conditions of intense formation of shear bands, it was established that the discontinuities in the curves $P(h)$ and $p(h)$ are related to the formation of shear bands. The behavior of these curves after the discontinuities shows that The shear bands lead to stress relaxation near the indenter and facilitate Indenter penetration into the amorphous material.

REFERENCES

1. V. K. Grigorovich, *Metal Hardness and Microhardness of* [in Russian], Nauka, Moscow (1976).
2. U. D. Hangen, "A comparison of nano-hardness and scratch-resistance on mohs minerals," *Z. Metallkd.*, No. 9, 1074–1077 (2001).
3. O. Kraft, D. Saxa, M. Haag, and A. Wanner, "The effect of temperature and strain rate on the hardness of Al and Al-based foams as measured by nanoindentation," *Z. Metallkd.*, No. 9, 1068–1073 (2001).
4. O. M. Ostrikov and S. N. Dub, "Effect of loading rate on the mechanism of plastic deformation in bismuth," *Zh. Tekh. Fiz.*, **71**, No. 5, 44–46 (2001).
5. M. N. Vereshchagin, V. G. Shepelevich, O. M. Ostrikov, and S. N. Tsybrankova, "Effect of isochronous and isothermal annealing on the plastic deformation of Fe–Cr–Mo–V–B–Si amorphous alloy under local loading," in: *Structure and Properties of Metallic and Slag Melts*, Proc. X Russ. Conf., Vol. IV: *Relationship between the Structure and Properties of Different States* (*Crystalline, Quasicrystalline, Amorphous, and Liquid*) [in Russian], Izd. Yuzh.-Ural'sk. Univ., Ekaterinburg–Chelyabinsk (2001), pp. 3–6.

6. O. M. Ostrikov, "Special features of the shape of wedge twins in bismuth single crystals deformed by a point load," *Fiz. Metal. Metalloved.*, **90**, No. 1, 91–95 (2000).
7. O. M. Ostrikov, "Express method for determining the contribution of twinning and slip to the plastic deformation of indented single crystals," *Fiz. Metal. Metalloved.*, **89**, No. 5, 106–109 (2000).
8. M. N. Vereshchagin, V. G. Shepelevich, O. M. Ostrikov, and S. N. Tsybrankova, "Analysis of the plastic deformation of Fe–Cr–Mo–V–B–Si amorphous alloy using the local deformation method," *Kristallografiya*, **47**, No. 4, 691–696 (2002).
9. M. N. Vereshchagin, V. G. Shepelevich, O. M. Ostrikov, and S. N. Tsybrankova, "Plastic deformation of Fe–Cr–Mo–V–B–Si amorphous alloy under indentation by a Vickers pyramid," *Fiz. Metal. Metalloved.*, **93**, No. 5, 101–104 (2002).