Structure of deformed Al-based amorphous alloys

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Abstract. The structure of deformed Al-based amorphous alloys was studied by X-ray diffraction, scanning, transmission and probe electron microscopy. It has been found that the material in the shear bands has lower values of Young's modulus and density. The shear band width is about 50 nm. In the band, no redistribution of the alloy components typical for phase separation is observed. The size of the regions with reduced Young’s modulus around the shear band is in the range from several tenths of a micron to 1 µm.

1. Introduction

Today metal amorphous and partially crystalline alloys are objects under extensive study. The size of samples varies depending on the material composition and the cooling rate. These materials have an unusual structure and demonstrate high physical and chemical properties. Fe-based partially crystalline alloys (FINEMET) have splendid hysteresis properties. Zr-based amorphous alloys in the form of rods and plates (BMG) show good mechanical properties. The value of elastic deformation in them can reach a few per cent [1]. Al-based amorphous-nanocrystalline alloys with rare-earth metals have superior strength properties with a low specific weight [2,3]. These materials can be formed under crystallization as a result of heating or deformation. Deformation of amorphous alloys usually occurs by the formation of shear bands (deformation bands). The amorphous phase in the shear band has characteristics different from those of the surrounding amorphous matrix. In the shear band, the amorphous phase is less ordered and has reduced density [4,5]. The value of differences in the density of the amorphous phase in deformation bands can range from a few to tens of per cent [6, 7]. In the deformation band, the processes of mass transfer are simplified, and the diffusion coefficient at room temperature can exceed that in the surrounding matrix by 5-6 orders of magnitude [8]. This significant change in the kinetic characteristics in these distinguished regions leads to the simplified formation of nanocrystals in them [9,10]. Nanocrystals are not always formed in shear bands [11,12], and the question remains open, what conditions are necessary for their formation. Deformation bands come out to the surface of the sample, and steps are formed. The thickness of the shear bands ranges from several tens to hundreds of nanometers [13]. There are several models which describe the processes resulting in the formation of shear bands. They use the concept of free volume and its evolution. Thus, according to the model described in [4,13], both the production of free volume and its annihilation occur under the development of the flow in the shear band. In principle, the composition of the amorphous phase in the shear bands can differ from that of the surrounding matrix. Then phase separation will be observed, which is found in these materials under deformation [14-16]. Shear bands determine largely the mechanical properties of amorphous materials, being their “weak point”. The
amorphous phase around the shear band is weakened [17,18]. Microhardness decreases in the shear band and in the matrix surrounding the bands. The size of the region where the microhardness decreases significantly exceeds the thickness of the shear band and can reach 150 µm [19, 20]. Such a size of the reduced microhardness region was observed in a Zr-based alloy under compression. The question arises to what extent this size of the region with reduced strength properties around the band is typical of other deformation methods, as well as if the composition of the band differs from that of the matrix.

The present paper is devoted to clarification of these questions. Al-based alloys with transition and rare-earth metals were chosen as the research objects. The present work aims at determining the local distribution of regions with different Young’s moduli in the samples containing numerous deformation bands. The samples of the Al_{87}Ni_{8}La_{5} amorphous alloy were selected as the objects; this alloy is deformed at room temperature with the formation of shear bands.

2. Experimental
Al_{87}Ni_{8}La_{5} and Al_{90}Y_{10} amorphous alloys were obtained by rapid melt quenching. The ribbons had a thickness of about 40 µm and a width of 10 mm. The obtained samples were subjected to deformation by multiple rolling and high-pressure torsion (HPT). The structure and composition were investigated by X-ray diffraction methods using Co Kα and Cu Kα radiation and by transmission, scanning and scanning transmission electron microscopy. Deformation of the Al_{87}Ni_{8}La_{5} alloy was carried out by multiple rolling (at room temperature); the decrease in thickness was 90%. The Al_{90}Y_{10} alloy was deformed by high-pressure torsion (5GPa). Maps of the distribution of mechanical properties were plotted by probe microscopy methods (PeakForceQNM). To plot the maps, the samples were preliminarily polished so that no steps remained on the surface, which arise when deformation bands come out to the surface.

3. Results and discussion
Figure 1 shows the image of the surface of the Al_{87}Ni_{8}La_{5} alloy after deformation by multiple rolling. One can see numerous steps, which are formed as a result of deformation bands coming out to the surface of the sample. The steps form a net, the distance between the bands varies from several tenths of a micrometer to several micrometers. Nanocrystallization (formation of Al nanocrystals) does not occur; there is only a diffuse halo in the corresponding X-ray diffraction pattern (figure 1b).

![Figure 1](image1.png)

**Figure 1.** Steps of shear bands on the surface of the deformed Al_{87}Ni_{8}La_{5} alloy (a); X-ray diffraction pattern of the deformed Al_{87}Ni_{8}La_{5} alloy (b).

No traces of a change in the properties related to the deformations bands are seen on the initial map of distribution of the Young’s modulus over the surface of this sample (under a load of 0.3 µN). Figure 2 illustrates a map of Young’s modulus distribution obtained under a load of 0.85 µN. One can see that the regions of reduced Young’s modulus appear. These areas appear with increasing load. The width of these regions is tenths of a micrometer, and the location correlates with the width and
location of the steps on the sample surface (figure 1a). Note that the regions of reduced Young’s modulus have a lateral size of less than 1 µm. These sizes of the regions of reduced Young’s modulus do not correspond to the regions of reduced microhardness observed by nanoindentation, the width of which was more than 100 µm [20]. Such a large difference in the size of the region is probably caused by different types of deformation or the other alloy composition.

![Figure 2](image2.png)

**Figure 2.** Maps of distribution of the Young’s modulus in the deformed Al$_{87}$Ni$_{8}$La$_{5}$ alloy (a – PeakForce = 0.85 µN).

The authors of [20] deformed the sample by compression and studied the distribution of microhardness around a separate (single) band, whereas in our samples there were numerous bands formed under multiple rolling. An amorphous-nanocrystalline structure (figure 3a) was observed in the Al$_{80}$Y$_{10}$ sample after deformation by the HPT method at 0.5 revolution. The average size of Al nanocrystals was 8 nm. Typical peaks from nanocrystals are present against the background of the halo in the X-ray diffraction pattern (figure 3b).

![Figure 3](image3.png)

**Figure 3.** TEM image (a) and X-ray diffraction pattern (b) of the Al$_{80}$Y$_{10}$ amorphous sample after deformation by the HPT method (0.5 revolution).

Scanning across the shear bands (as demonstrated in figure 4a) allowed obtaining the distribution of Al and Y concentrations in the sample along the marked scanning line. A significant decrease in the intensity of the signal from the shear band compared to the signal from the surrounding sample is seen in the obtained plot (figure 4b). Most probably, this is related to a reduced material density in the shear band. It is also possible that the thickness of the electron microscopic foil in the region of the shear band was less, as well as the simultaneous influence of several factors on intensity of the signal. The width of the region correlates with that of the shear band (figure 4a) and is about 50 nm. Note that the ratio of the amplitudes of Al and Y signals inside and outside the shear band remains constant.
Consequently, redistribution of the concentrations under deformation and band formation does not occur.

![Figure 4](image)

**Figure 4.** STEM image (a) (the size of the electron beam was about 2 nm) and EDS spectra (b) (along the line in the image) of the Al$_{90}$Y$_{10}$ sample after deformation by HPT method (0.5 revolution).

4. Conclusions
Studies of the structural evolution of Al-based amorphous alloys of Al-Ni-RE (RE = La, Y) systems under deformation have demonstrated the following:
- no redistribution of element concentration occurs in the shear bands, i.e., the composition of the band and the matrix is similar;
- the sizes of regions with reduced Young’s modulus around the shear band are in the range from several tenths of a micron to 1 µm.

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