FRACTURE SURFACE MORPHOLOGY OF Pd$_{40}$Cu$_{30}$Ni$_{10}$P$_{20}$ AMORPHOUS ALLOY

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Abstract
The fracture surface morphologies of Pd$_{40}$Cu$_{30}$Ni$_{10}$P$_{20}$ bulk amorphous alloy loaded under compression at the temperatures of 77 and 300 K were studied using fractographic analysis. It was found that the failure is localized into narrow shear bands at both the temperatures. The fracture surface can be divided along the shear fracture propagation into three zones according to their typical morphology: (A) slip zone, (B) propagation zone and (C) unstable fracture zone. The morphology of a vein pattern depends on the fracture mode in the final failure stage of the slip bands. The vein pattern is commonly observed on the major crack surface. The chevron pattern morphology was observed at the temperature of 77 K only.

Keywords: bulk amorphous alloy, fracture, vein morphology, chevron pattern

1 Introduction
The intensive study of the structure and properties of amorphous metallic materials started with a development of the rapid quenching technique and after the discovery of the method of their preparation. The motivation was the remarkable combination of mechanical, magnetic and corrosion resistance properties. At the beginning the advanced materials were prepared in the form of thin layers or ribbons [1]. Since multi component metallic alloys with an excellent glass forming ability have been found (the temperature interval between the glass transition and the crystallization temperature is relatively wide in the bulk amorphous alloy, the cooling rate of about 10$^2$ K/s is sufficient to prepare an amorphous structure) the bulk samples of metallic glasses can be prepared and studied [2–4]. Bulk metallic glasses are promising materials not only as functional materials with excellent physical and chemical properties but also as strength ones because of their excellent mechanical properties. The development of the bulk amorphous alloys enabled a wider range of mechanical tests including compression, fracture toughness and fatigue testing as compared with thin ribbons [5].

Inhomogeneous plastic deformation of amorphous metals is localized into a narrow shear band. The catastrophic failure process occurs then in this adiabatic shear band [5]. The study of the micromechanisms of the failure plays a key role in the development of engineering metallic alloys, in manufacturing, and in the assessment of the mechanical integrity of structures.

In the present work we studied the fracture surface morphologies of Pd$_{40}$Cu$_{30}$Ni$_{10}$P$_{20}$ bulk amorphous alloy loaded under the compression at the temperatures of 77 and 300 K. The goal of the detailed observation of fracture surfaces formed at both the experimental temperatures was not only to determine all the present fracture micromechanisms but also to detect a sequence during the formation of the fracture surface.
2 Experimental
Samples of a bulk amorphous alloy with the nominal composition Pd$_{40}$Cu$_{30}$Ni$_{10}$P$_{20}$ (at.%) were prepared by melt casting into a mould. The achieved cooling rate allows the preparation of cylindrical amorphous samples with diameter of 3 mm. The amorphous structure of all the samples was confirmed by X-ray diffraction. The samples of 5 mm long were tested in the uniaxial compression at temperatures of 300 K and 77 K up to a failure with the strain rate of $2.8 \times 10^{-4}$ s$^{-1}$. The morphology of fracture surfaces was analyzed using a scanning electron microscope TESLA BS340 at the accelerating voltage of 20 kV in secondary electrons.

3 Results and Discussion
The deformation is localized into a catastrophic shear band as usual observed for others metallic glasses [6, 7]. From the fracture stress point of view the fracture at the temperature of 77 K may be referred to the premature fracture. The macroscopic plastic deformation was not observed. The measured fracture stresses were 1.65 GPa and 1.52 GPa at the temperatures of 300 K and 77 K, respectively, with a standard deviation of 0.12 GPa.

The samples failed by uniaxial compression at room temperature have shown distinguished zones on their fracture surfaces in accordance with the morphological scheme of the ductile failure of metallic glasses that can be seen in Fig. 1 left. The right side of Fig. 1 shows an intensively deformed part near to the edge of the fracture surface after a catastrophic slip in the plane of maximal shear stress. This part represents the zone „A” of the schematic picture of the fracture surface of the bulk amorphous sample fractured by uniaxial compression [8]. This zone is equivalent to the flat surface in amorphous ribbons in the first stage of the localized shear.

Figure 2 demonstrates the vein pattern typical for the zone „B” of the scheme in Fig. 1 left. The right side of Fig. 2 shows the strongly elongated shear failure dimples that are oriented in the direction of the shear displacement. These cavities do not exhibit any presence of the inhomogeneous nucleation on extraneous particles.

The final stage of the fracture by compression is characterized by the presence of the complex vein morphology on the relatively rough fracture surface as can be seen in Fig. 3 representing the zone „C” of the fracture. The fracture surface is formed through the meniscus instability process inside a thin shear band. A detailed picture in Fig. 3 right shows the vein alignment from small valleys to the top of ridge parts. More complex relief in the zone „C” is a consequence of spreading of heat generated in the catastrophic shear band.

![Fig. 1](image1.png)

**Fig. 1** Left – the scheme of the total view of the ductile fracture surface. The arrows indicate the valley parts in the zone „C”. Right – intensively deformed part of the first stage „A” of the fracture.
Fig. 2  The cell pattern morphology of a central part („B“) of the fracture surface at room temperature. Right – the cells elongated in the shear direction.

Fig. 3  The vein pattern morphology on a relief („C“) of the fracture surface at room temperature. The coalescence of veins into a central vein at ridge parts of the relief surface (right).

The zone „C“ is formed at last stages of failure, therefore this volume undergoes thermal treatment for relatively longer time in comparison with the condition in the zone „B“ [5, 9]. The roughness of the fracture surface as well as the complex vein alignment is influenced by more complex stress distribution at last stages of fracture too and it is controlled by a local failure mode inside the shear band (e.g. traction, shear, tearing) or their combination [11].

The samples failed at the temperature of 77 K have shown the failure initiation in the plane of maximum tensile stress with the formation of chevron morphology. Subsequently the crack propagates through the shear mechanism. This fracture mode (fracture mode I. – opening mode) is usually present on samples after their partial embrittlement due to the low temperature or due to the structural relaxation of the amorphous structure [9]. A lower value of the fracture stress is the consequence of the premature failure.

A crack propagation at the temperature of 77 K occurs via the formation of chevrons followed by a shear failure. Characteristic features of the chevron morphology can be seen in Fig. 4 left and their details are shown on the right side of Fig. 4. This part of the fracture surface is macroscopically perpendicular to the axis of the compression stress.

**Figure 5** demonstrates the characteristic dimples of the ductile fracture oriented significantly in the direction of the initial shear displacement. The combined and grooved vein morphology on the ridge parts of the fracture surface can be seen in Fig. 5 right.
Fig. 4 The chevron fracture morphology formed at initial stages of the failure in the plane of the maximum tensile stress at the temperature of 77 K.

Fig. 5 Characteristic ductile failure veins (left) and the combined morphology of veins (right) failed at the temperature of 77 K.

Numbers of remelted drops were observed on the fracture surface after the failure at both temperatures which support a hypothesis of the adiabatic heating during the fracture inside the shear band [7, 11]. Due to the high crack velocity, short time of the fracture and a high amount of elastic energy released during the shear band formation, the overheated phase is formed and its relicts are observed on the fracture surface [8, 12–14].

4 Conclusion
The catastrophic inhomogenous deformation was observed in Pd–Cu–Ni–P amorphous metallic alloy at the room temperature as well as at the liquid nitrogen one. The shear band initiation and propagation are main mechanisms of the ductile shear failure at the temperature of 300 K. The fracture at the temperature of 77 K is initiated through the chevron micromechanism and the meniscus instability process inside the catastrophic shear band forms the final fracture surface.

References
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