FRACTURE OF Zr$_{56}$Ni$_{24}$Al$_{20}$ AMORPHOUS ALLOYS AT ULTRALOW TEMPERATURES

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Received: 21.10.2012
Accepted: 05.03.2013

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Abstract
We observed the failure surface of Zr$_{56}$Ni$_{24}$Al$_{20}$ amorphous ribbon samples tested in uniaxial tension in low temperature interval up to 0.5 K. Shear ductile failure manifestations were obviously present. Metallic glasses are usually deformed by the shear fracture with obvious shear bands and show little plasticity before the final fracture. At low temperatures the chevron pattern morphology is rarely present too. The occurrence of chevrons is connected with decreasing of the fracture stress. Analysis of fracture morphology revealed that dominantly chevron morphology is present and that the failure of this amorphous material initiates at low temperatures at geometrical imperfections of ribbons. These failures are often presented as a premature failure.

Keywords: amorphous alloy, failure, chevron pattern, low temperature

1 Introduction
In the past three decades, the deformation and fracture behavior of metallic glasses were widely investigated [1 - 3]. In general, the plastic deformation of metallic glasses is localized in the narrow shear bands, followed by the rapid propagation of these bands and the sudden fracture. ZrNiAl-based amorphous system is important for future development as high-strength type engineering materials useful as a new type of high-elevated temperature strength material. The significant property of the system is wide temperature interval between glass transition and crystalization temperatures. This relatively wide temperature interval of the existence of undercooled liquid state is helpful for exploring the superplasticity for nanomechanotronic device production.

Low temperature mechanical behaviour of metallic glasses has attracted growing attention due to potential such as space exploration, liquified gas storage and cooling type of experimental thermonuclear reactor [4]. Metallic glasses are assumed as a macroscopic brittle materials and show little plasticity before the fracture. The plastic deformation occurs via catastrophic shear band creation and macroscopic shear along these bands. The adiabatic conditions in the shear transformation zone cause the failure by meniscus instability mechanism with vein pattern [5,6].

2 Experimental
Samples made from a bulk amorphous alloy with the nominal composition Zr$_{56}$Ni$_{24}$Al$_{20}$ (at.%) were used in experiments. The 33 µm thick and 3–5 mm wide amorphous metallic ribbons were...
prepared by rapid melt quenching on a spinning metallic disc [7]. The amorphous structure of all samples was confirmed by X-ray diffraction. Ribbons were fractured by a tensile test on the machine with stiffness of 10 kN/mm using the deformation rate of 2.6×10⁻⁴ s⁻¹ in the temperature interval of 0.5–4.2 K and at 300 K. The testing temperatures of tensile tests (0.5; 2.0; 2.1; 3.1; 4.2 K) were obtained by pumping of ³He vapour in cryostat [8]. A scanning electron microscope was used for fractographic observations.

3 Results and discussion
The measured fracture stress $\sigma_f$ in the low temperature region of 0.5–4.2 K as well as in the interval up to the room temperature are introduced to the Fig. 1. The used symbols are connected with dominant micromechanisms of failure. The shear failure manifestations, mainly vein morphology, are assigned by the closed symbols. The minimal value of $\sigma_f$ (697 MPa) at 4.2 K is connected with only chevron patterns with several initiation or reinitiation sites on the fracture surface.

In whole temperature interval the fracture stress remains its values about 1500–1950 MPa without significant influence on the temperature [1, 9]. At low temperatures some samples failed at significantly lower stress. This is probably the case of the premature fracture depicted in Fig.1 by opened symbols.

Fractographic observations reveal the shear failure manifestations. The morphologies of fracture surface are shown in Fig. 2. The fracture surface consists of altered planes in two shear variants in the direction 45° to the ribbon surface on the both orientations. The segments of shear fracture surface variants are mutually perpendicular and their length is more or less equal to 80 µm as Fig. 2 left shows.

![Fig. 1](image1.png)

**Fig.1** The measured dependence of the fracture stress on the temperature below the room temperature (left). An enlarged temperature interval from 0.5 to 4.2 K (right).

![Fig. 2](image2.png)

**Fig.2** Alternation of shear plane variants (left). The vein pattern morphology on the shear plane segment (middle) and typical chevron pattern on the normal fracture surface (right)
The segments are covered by short shear slip followed by veins produced by meniscus instability process. The veins are relatively rough as it is typically observed for the shear failure at room temperature for alloys with high glass forming ability [10,11]. Rarely, the chevron pattern morphology as can be seen in Fig. 2 right was observed. This morphology is present on the fracture in the plane of maximal normal stresses, i.e. perpendicular to the tensile axis. The premature fracture is often connected with an initiation on the imperfections of amorphous ribbons as geometric defects at ribbon surface or the presence of small crystallites. Generally, the deformation of amorphous alloys is localized into the creation of the narrow shear bands [12]. Following fracture is catastrophic due to the softening of the shear band regions. The ductile shear failure by the process of meniscus instability inside catastrophic shear band occurs in the plane of the maximal shear stress. The fracture surface generally follows the maximal shear stress plane. The veins are produced by meniscus instability process as it is observed at shear failure at room temperature on the amorphous metallic glasses [10, 12]. The main difference in morphology is the presence of more rough fracture surface with coarse veins as Fig. 3 demonstrates. The possible reason can be the facts that the thermal conductivity and mobility of defects decrease at low temperatures; therefore the failure surface follows energetically more favourable path, although this path is not the ideal plane.

Fig. 3 Vein pattern morphology on the fracture surface at the temperature of 0.5 K (left). Reinitiation in meniscus instability process produces more complicated veins (right).

Fig. 4 Rough veins observed on the shear fracture at the temperature of 2.0 K. A complicated pattern produced in low viscosity shear band area with closed cellular structure and elongated “needles” from the contraction at the final stage of the fracture.
Fig. 5  Ductile fracture surface morphology at 0.5 K, shear failure with shear band near fracture surface (left). Detailed ductile fracture surface morphology at 0.5 K (right). The chevron walls are covered by small cells.

The heat generated in the shear band is sufficient to heating relatively wide volume of material, therefore veins produced by meniscus instability are relatively rough with elongated pendles [11, 13]. This morphology is shown in Fig. 4. According to direct temperature increase measurements [12] it is confirmed that the heating of material inside the shear plane is up to the temperature above the glass transition temperature, and probably up to the melting temperature. For the samples failed at low temperatures, chevron patterns are frequently observed (Fig. 2 right). The chevron patterns are the manifestation of the failure in the plane of maximal tensile stress. Detailed study of chevrons reveals that the failure in plane of maximal normal stresses also consists of small inclined areas of the shear plastic deformation micromorphology as it can be seen in Fig. 5.

By decreasing the testing temperature, the critical size of the initiation centres of chevron-like failure decreases [14, 15]. The smaller imperfections of amorphous structure become active and modify the initiation of the failure at the stress below the yield stress of the material.

4 Conclusion
Fracture analysis of amorphous alloys Zr$_{56}$Ni$_{24}$Al$_{20}$ failed in the temperature interval 0.5–300 K has shown that the main fracture morphology is the ductile shear failure type. Fracture stress does not decrease with the temperature lowering. Shear ductile failure manifestations were observed at low temperatures up to 0.5 K. Below the temperatures 4.2 K, the chevron pattern morphology is present too. Severe initiation centres for chevron-like fracture were observed. The presence of chevrons initiated by defects is connected with decreasing of fracture stress. Therefore this is the case of premature fracture and measured fracture stress not represented yield stress of intrinsic material.

References

Acknowledgement
This work was supported by the implementation of the projects Nos. 26220120021 and 26220120033 provided by the European Regional Development Fund. The authors are also grateful to the Slovak Academy of Sciences –VEGA No. 2/0185/11 and the Centre of Excellence "Nanofluid" and Slovak Research and Development Agency – contract No. APVV-0171-10.