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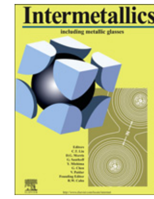

Ductility and toughness of cold-rolled metallic glasses

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ABSTRACT

Cold rolling of $Al_{87}Ni_7La_6$ amorphous ribbons was performed on ribbons embedded in pure Al foils and ribbons alone, in order to study their deformation under constraint. A change in behaviour was observed for the two series of samples due to a different load distribution, so that ribbons alone was deformed up to $\varepsilon = 0.029$ without formation of cracks while, for composite samples, small fragments were always formed. In ribbons rolled alone, along with a macroscopic strain, a plastic deformation was observed at a finer scale, in the cavities present on the ribbon surface. The locally induced strain was quantified by taking into account the size change of cavities in samples rolled to different extents. The formation of shear bands and fracture occurring during cold rolling was studied for composite samples: the shear offset, interband spacing and distribution of fracture angles were determined. A $Zr_{55}Al_{20}Ni_{12}Cu_8Ti_5$ amorphous ribbon was rolled with Al foils and the toughness value was estimated from the shear band offsets finding good agreement with literature data. Therefore, the toughness was estimated also for the Al-based samples obtaining the value of $K_c = 28$ MPa m$^{1/2}$.

1. Introduction

The mechanical properties of amorphous alloys have been the subject of intensive research in recent years [1]. These materials are generally brittle and their ductilisation has proved to be difficult. At temperatures far below the glass transition, deformation is inhomogeneous and takes place via shear softening along bands. In absence of constraints, the shear band activity proceeds unperturbed and the sample fails along a dominant band before detectable plastic deformation can occur. According to the state of the art [2], the most effective way of achieving large deformation of metallic glasses is processing them under constraint. In these conditions, deformation takes place via the activity of shear bands within the glass which finds an obstacle to their propagation in the constraining medium. Evidences of this are frequent: from the extensive formation of shear bands underneath an indenter tip [3] to elongation of amorphous alloys well beyond the elastic limit during rolling [4].

Because of their high strength metallic glasses have been considered as candidate reinforcements in metal matrix composites. Early examples include aligned ribbons in various matrixes: $Fe_{42}Ni_{42}B_{16}$ in Ni [5], $Ni_{78}Si_{10}B_{12}$ in Cu [6], and $Ni_{91}Si_7B_2$ (wt%) in Cu–30Zn brass [7,8]. Tensile tests of the composites showed that the glassy reinforcement could be deformed to a substantial extent while constrained inside the ductile matrix. The strength of the composites followed the rule of mixtures. More recently, a composite made of warm pressed Al and $Al_{85}Y_8Ni_5Co_2$ powders displayed improved plastic properties according to the iso-stress model [9].

In a previous work [10] the repeated co-rolling of stacked layers of an $Al_{87}Ni_7La_6$ amorphous ribbon embedded in a pure Al matrix was studied with emphasis on the constrained deformation of the amorphous component at room temperature. The ductile Al adapted to the surface roughness of the ribbon with stress concentration at weak points, where fracture occurred. A large amount of shear bands was found both parallel and perpendicular to the deformation direction. Larger shear offsets were found near the fracture surface and were attributed to the effect of the stress concentration at weak points after the constraints hindered the slip of previously formed shear bands. SEM studies of ribbon fragments evidenced mostly the occurrence of brittle fracture surfaces with limited number of vein patterns indicating that mostly cold shear bands were operative [11,12].

This paper extends the previous findings by first comparing the deformation of a ribbon alone and an Al/metallic glass composite in terms of rolling fundamentals, then the extent and type of deformation is quantified by observing the reduction in size and the final disappearance of surface imperfections in ribbons not embedded in

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a matrix. Finally, the shear band offset and length in the composites are used to estimate the toughness of the $Al_{87}Ni_7La_6$ metallic glass by applying the model successfully developed for $Ni_{91}Si_7B_2$ [13]. The result for the Al-based glass is validated by performing an analogous estimate for a $Zr_{55}Al_{20}Ni_{12}Cu_8Ti_5$ amorphous alloy of known toughness.

2. Experimental

$Al_{87}Ni_7La_6$ amorphous ribbons in between 30 and 40 μm thick were produced by melt spinning [14,15]. Two series of samples were then prepared for cold rolling tests: ribbons embedded in pure Al foils and ribbons alone. Because of the low sample thickness, in both cases the cold rolling was performed by inserting samples in a stainless steel envelope, that was pre-hardened by rolling in order to favour the transmission of strength from rolls to samples.

Ribbons were cold-rolled alone for 6, 12 and 30 rolling passes in order to achieve different amounts of plastic deformation. The elongation was determined by measuring the ribbon length before (l_0) and after (l) cold rolling. Plane strain conditions were assumed during rolling so that the strain (ε) can be calculated as $\varepsilon = \ln(l/l_0)$. Scanning Electron Microscopy (SEM) was performed on samples before and after cold rolling in order to determine changes in the surface morphology during deformation. The cavity dimensions, length and width, were determined from the SEM images measuring between 75 and 275 cavities depending on the sample.

The composite samples were prepared by placing $Al_{87}Ni_7La_6$ ribbons about 2 cm long between two foils of pure Al 100 μm thick and 2 cm long. The amount of glassy ribbons was chosen so that their volume fraction with respect to Al was 20%. This ratio was chosen by considering the hypothetical strength of an Al-based composite containing aligned fibres. At this ratio, the effect of fibres should start prevailing over that of the matrix. During processing, the fibres did not remain homogeneously distributed, however, no relevant difference in deformation and fracture mode could be detected.

Samples were rolled in the stainless steel envelope. Folding the Al-ribbon composite was necessary when its length became comparable to that of the steel container and when the thickness of the rolled composite became too thin. With this setting it was found that all ribbon samples fractured inside the Al foils irrespective of the number of foldings and passes [10]. These samples were studied in cross section by SEM in order to reveal the presence of shear bands and to highlight their fracture behaviour.

$Zr_{55}Al_{20}Ni_{12}Cu_8Ti_5$ amorphous ribbons produced by melt spinning were also cold-rolled inside Al foils, with the same experimental conditions used for the Al-based samples. Also in this case, samples fractured inside the Al foils and were analysed as detailed above.

3. Results

3.1. Ductility during cold rolling

All glassy samples display manifest permanent deformation which can be quantified for the ribbons rolled alone. The elongation (ε) is 0.011, 0.013, and 0.029 after 6, 12, and 30 rolling passes, respectively. There was no evident formation of cracks during rolling up to 30 rolling passes. Further rolling causes crack initiation.

As well known, ribbons produced by melt spinning have a typical roughness on the surface, i.e. the side solidified in contact with the copper wheel (wheel side) presents lines due to the wheel roughness and cavities due to gas bubbles that remains entrapped between the melt and the quenching wheel. In Fig. 1a, an example of the wheel side of the as quenched $Al_{87}Ni_7La_6$ ribbon is reported, in which cavities appear homogeneously distributed on the ribbon surface.

During rolling, besides the already mentioned macroscopic plastic deformation measured by the increase in sample length, plastic deformation is seen also at a finer scale in ribbon cavities. In Fig. 1b, a SEM image of the sample rolled 30 times is reported showing evident reduction of the cavity dimensions with respect to

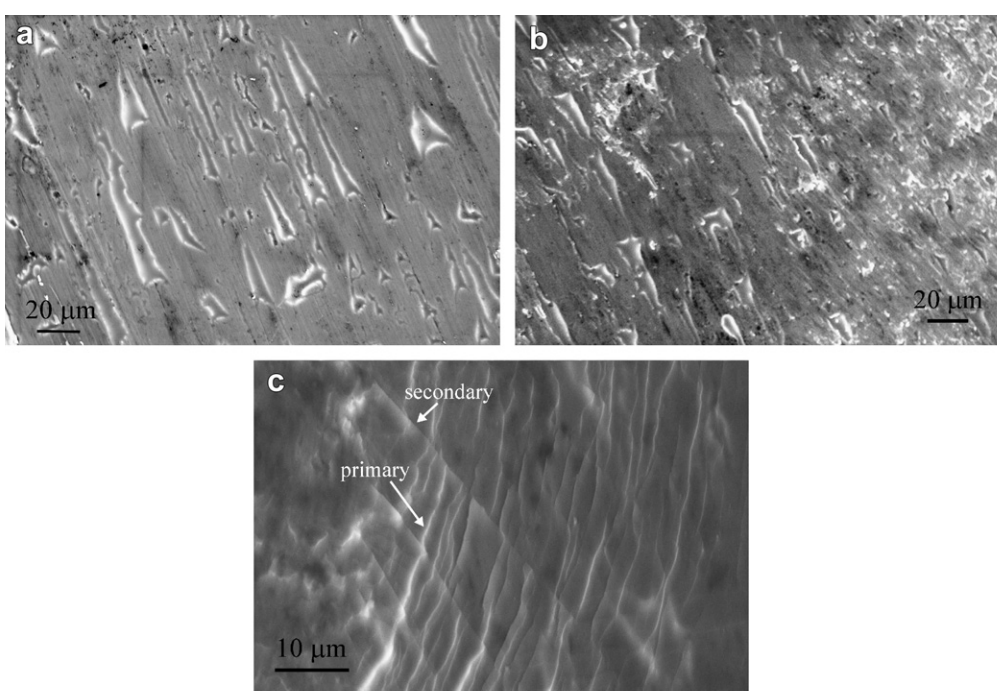

Fig. 1. Secondary electrons SEM image of the wheel side surface of the as quenched ribbon (a) and after 30 rolling passes (b), showing the decrease of the cavities size with strain. Deformation occurs through activation of primary and secondary shear bands (c).