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Featured Letter

Instabilities of interfaces between dissimilar metals induced by high pressure torsion

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ABSTRACT

We observed that high pressure torsion (HPT) of a bi-metallic laminate can induce vortex-like folding instabilities of layers. Thus, HPT leads to multiscale swirls which are perpendicular to the anvil axis. These instabilities are similar to folding of metallic surfaces during sliding and to co-axial swirls by HPT. The HPT induced vortex-like instabilities look very similar to the Kelvin-Helmholtz-type flow instabilities in fluids. We demonstrate in this work that this similarity is only apparent, and physical reasons for HPT-induced instabilituies are principally different from those in liquids. We show using finite element simulations that the folding and vortices of metallic layers are driven by plastic instabilities due to local blocking of shear deformation. Thus, HPT of layered samples leads to the multiscale movement of vortices in the material during deformation. These movements resemble turbulent flow of liquids and gases, but they have a completely different physical nature.

1. Introduction

Severe plastic deformation (SPD) is a novel technique permitting to tailor the microstructure of a material in such a way that it contains extremely small crystallites of the constituent phases [1]. The most important modes of SPD are equal channel angular pressing (ECAP), high pressure torsion (HPT) and accumulative roll bonding (ARB) [2]. SPD permits to deform a material up to very high strains without failure. If the material contains alternating thick layers of dissimilar phases prior to SPD, the microstructure changes to a uniform mixture of almost nanograined equiaxed crystallites after SPD. Thus, during SPD the original thick layers of dissimilar phases loose their stability and are gradually fragmented into nanometer sized structures. In the literature vortex-like folding instabilities of interphase boundaries have been reported at the beginning of the HPT process [3,4]. Large swirls with the axis parallel to that of HPT machine were observed in the duplex stainless steel, the Zn–22%Al eutectoid alloy, and high purity (99.99%) aluminum [5,6]. Recently, a similar folding of metallic surfaces was observed during sliding [7–9]. In the present work we studied such instabilities induced by HPT for interfaces between dissimilar metals i.e. when vortices are perpendicular to the HPT rotating axis. We determined the underlying processes using finite element (FE) simulation, scanning electron microscopy (SEM) and transmission electron microscopy (TEM).

2. Experimental

In Fig. 1 a schematic of the HPT Bridgman anvil type unit is shown together with a photograph of our custom-built machine (W. Klement GmbH, Lang, Austria). In the experiments, multilayers consisting of stacked Al/Cu and Al/Ni were used. Each sample consisted of a pile of 25 alternating foils with a thickness of 0.025 mm each. Thus, the total thickness of the sample prior to HPT deformation was 0.625 mm. The pile was placed between the anvils of the HPT machine, pressed up to 5 GPa with simultaneous rotation at a speed of 1 rpm at 20 °C. The anvils with a depression with a diameter of $2R = 10$ mm and a depth of $H = 0.4$ mm were used (see Fig. 1b) for the so-called constrained HPT.

3. Results and discussion

The low magnification optical and SEM images of the Al/Cu and Al/Ni samples crosssections after HPT is shown in Fig. 2. During HPT simple shear takes place with a strain γ defined as:

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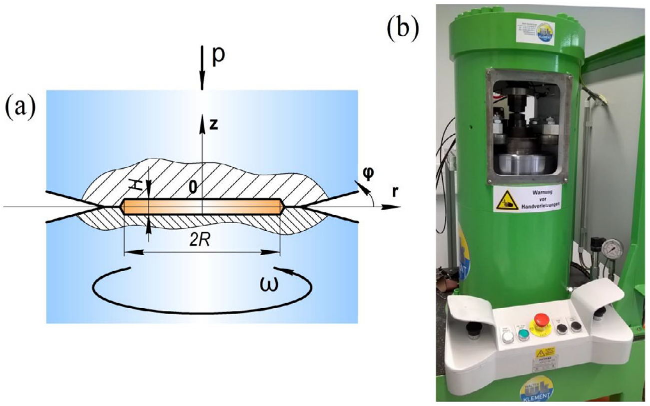

Fig. 1. (a) Scheme of HPT Bridgman anvil type unit; (b) photograph of the custom built device (W. Klement GmbH, Lang, Austria).

$$\gamma = \frac{r\phi}{H} \tag{1}$$

where r is the distance from the rotation axis of the two anvils (center of the sample), H is the sample thickness and φ is the rotation angle. According to Eq. (1), the shear strain is proportional to the radius r being the distance measured from the sample center. In view of this fact, Fig. 2a–c show the changes of the microstructure of multilayered Al/Cu sample changes with increasing r and, therefore, with increasing strain γ. Using Eq. (1) the following values of strain for the respective sections can be determined: (Fig. 2a) $\gamma = 47$, (Fig. 2b) $\gamma = 118$, (Fig. 2c) $\gamma = 212$.

At low γ (Fig. 2a) the macrostructure contains alternating Cu and Al layers and looks very similar to the initial layered structure. With increasing γ (Fig. 2b) the microstructure transforms to a so-called boudinage one [10–12] with typical clamping of the copper layers. The increased fragmentation seen in Fig. 2b demonstrates that in the section perpendicular to the radius the boudinage structure forms due to the movement of vortices. These vortices have an axis perpendicular to that of HPT machine. Such microscopic vortices differ from that point of view from the (almost macroscopic) swirls observed in duplex steel [5,6]. Such swirls have an axis parallel to the torsion axis (the can be even co-axial with HPT machine).

The copper fragments rotate and protract between them the separating aluminum layers. During further increase of γ, the layered structure forms again (Fig. 2c). However, in this stage the layers became much thinner than in the original sample prior to HPT. Such a microstructure appears due to the kinematics of simple shear. The fibers, which are perpendicular to the velocity vector incline and stretch along the shear direction. The diametric sections of Al/Ni sample (Fig. 2d and e) show the formation of folding instabilities of originally flat Al and Ni layers. If the shear strain increases, the primary vortices (visible in the middle of the micrographs Fig. 2d and e) gradually disappear in the chaotic (turbulent) structure of refined grains visible in the left and right periphery parts of the micrographs. With increasing strain the chaotic (turbulent) zone becomes broader (compare Fig. 2d and e). Such behaviour is similar to that of co-axial swirls during HPT of duplex steel [5,6]. Those swirls also merge and then disappear with increasing strain.

In the following possible reasons for the formation of vortices as observed during HPT are analysed [3]. These vortices are similar in appearance to those observed in turbulent flow of liquids and gases [1]. Previously, similar vortices or folding instabilities were observed in other processes of plastic shear of solids like friction [13] or shear of indented bodies [7]. Large swirls with the axis parallel to that of HPT anvils were observed in the duplex stainless steel, the Zn–22%Al eutectoid alloy, and high purity (99.99%) aluminum [5,6]. The authors of Refs. [3,13] explain the formation of vortices-like folding instabilities with Kelvin-Helmholtz instability, which can appear at the interface between two dissimilar liquids moving with different velocity. In [7,8] it is shown that vortices-like folding is driven by grain-induced plastic instability. Here, an alternative explanation of the striking phenomena observed in different media is presented.

Let us first underline that Kelvin-Helmholtz instabilities appear due to the pressure increase in a moving medium in the location where the flux expands. This circumstance leads to the stability loss of an interface between two dissimilar liquids and following vortices formation [14]. For this effect to occur, the stresses in the medium driven by the inertial forces need to be in the same order of magnitude as stresses driven by the internal forces. The inertial forces have the order of magnitude of ρv^2 [14], where ρ and v are density and velocity of a medium, respectively. Internal stresses in a plastically deforming body have an order of

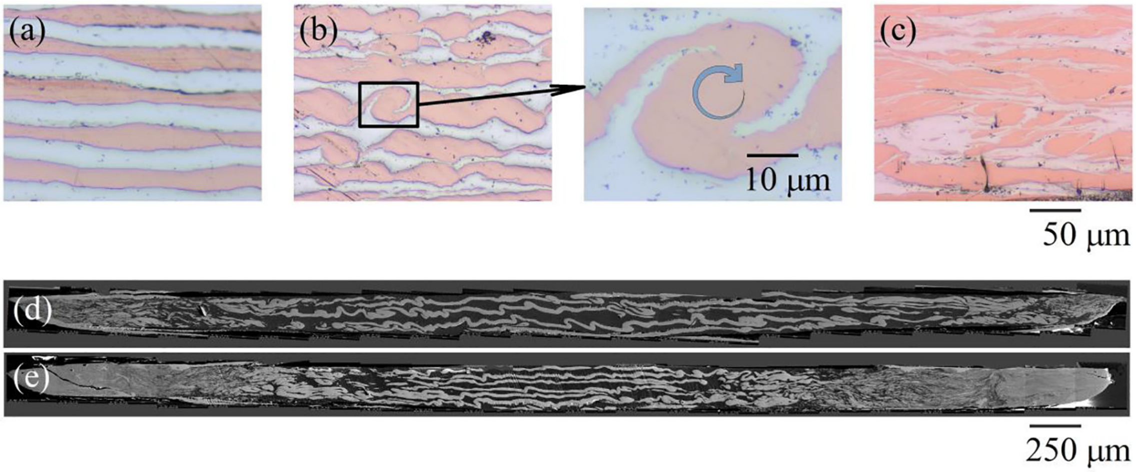

Fig. 2. Low-magnification optical (a–c) and SEM (d and e) images of the macrostructure of the samples after HPT. (a–c) Al/Cu sample after 3 rotations of the anvil. The sections shown are perpendicular to the radius at a distance from the center of: (a) 1.0 mm, (b) 2.5 mm, and (c) 4.5 mm. Profound fragmentation is observed in (b). Insert shows enlarged image of two vortices more clearly is indicative for the vortices in the deformed multilayers. (d and e) Al/Ni sample after 2 (d) and 5 (e) rotations of the anvil. Sections are diametric, i.e., they are parallel to the radius and intersect the center of the sample. This allows to observe the changes of the layered structure from the center to the outer edge of the sample.

magnitude of its yield stress σ_s. In this case the ratio between inertial and internal stresses in a plastically deforming body have an order of magnitude of $\kappa = \rho v^2/\sigma_s$. For the case of copper $\rho = 8900\ \mathrm{kg/m^3}$, $\sigma_s = 300$ MPa. With a flux velocity of $v \sim 10^{-3}$ m/s for a typical HPT deformation we obtain $\kappa \sim 10^{-11}$, in other words the inertial forces during HPT can be neglected. That means that the physical mechanism leading to Kelvin-Helmholtz instabilities at the interfaces between two dissimilar liquids does not take place for slowly deforming metals. Despite the apparent similarities in the observed structure, it is concluded from the above considerations that the nature of vortex-like folding instabilities in solids and liquids is different.

In Ref. [15], the formation of vortices in the material during plastic deformation by simple shear is attributed to local blocking of shear deformation. Let us explain this with a simple model. We assume that a layer of the material with a higher strength is located in a plastically deformable medium experiencing simple shear in the horizontal direction (see Fig. 3a). Since the yield strength of this layer is higher than the plastic flow stress of the medium, plastic shear within the layer does not take place, i.e. the layer blocks shear deformation. In the case of simple shear, there is a velocity gradient across the medium in the shear direction. It means that at the upper boundary of the stronger layer the velocity of the medium is greater than at the lower boundary. For this reason, in the moving coordinate system associated with the layer, the velocities of the medium from the upper and lower sides of the layer have opposite directions. According to L. Prandtl [14], the layer causing the velocity discontinuity can be considered as a system of distributed vortex fibers (Fig. 3b). Under certain conditions, the system loses its stability and breaks up into separate vortices that cause bending of the layer and its destruction to unfolding fragments [14].

In this paper, we do not aim to obtain a criterion for the loss of stability of stronger layer, but we illustrate the above qualitative assumptions by numerical simulation using finite element model implemented in DEFORM-2D/3D-v11.0 package [16]. Fig. 3 shows a schematic of the sample geometry used for the FE model and the resulting structures during deformation. Medium 1 as a plastically deforming material is placed between two anvils moving in the opposite directions. The distance between the anvils is kept constant. Medium 1 contains a layer 2 of a material with a higher yield strength (Fig. 3a). The yield stress of the layer 2 is assumed to be ten times larger than that of medium 1.

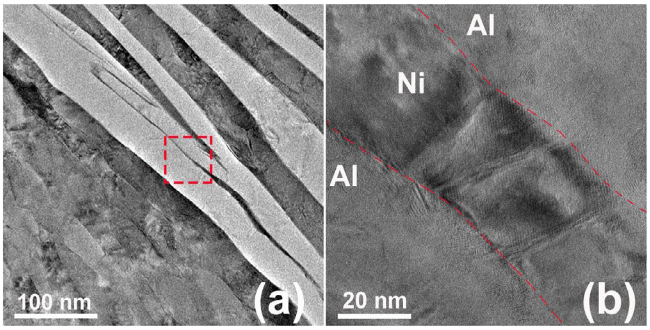

Fig. 4. (a) Bright field TEM image of the Ni/Al specimen obtained at the middle of the radius; dark and bright areas correspond to Ni and Al, respectively; the red square marks the area for HRTEM in (b); (b) HRTEM image of the Ni layer embedded in the Al phase; the Ni layer contains several subgrains divided by low angle boundaries.

Indeed, Fig. 3c shows that the local shear blocking leads to bending of the layer 2. The layers with higher strength can serve as layer 2 during HPT of layered materials. Bending of the layers, their fragmentation and rotation of resulting sections of the layers can evolve gradually to a chain of vortices (Fig. 3d). This is illustrated in Fig. 2b, which shows the fragmentation of copper layers. The spiral shape of these fragments (see the insert) indicates that their appearance is associated with the vortex motion. Subsequent shear deformation stretches these vortices into layers of a much smaller thickness compared to the thickness of the original layers (see Fig. 2c).

One can hypothesize that the described process of fragmentation periodically repeats, thereby leading to further decrease of the layer thickness. The microstructure of the multilayered Al/Ni sample after HPT deformation ($\gamma \sim 150$) (Fig. 4) supports this suggestion. It clearly shows the alternating nanoscale layers of Al and Ni. The layer of Ni is elongated parallel to the shear direction and divided into fragments by small-angle boundaries (Fig. 4b). It looks like a lamellar structure of Ni formed at large plastic deformations [17]. We assume that Ni grains in the sample under investigation play the role of the strengthened layers considered above. Under the action of shear stresses, they lose stability and are divided into sub-grains.

We have considered above the vortices associated with stronger layers blocking plastic shear. Other cases of shear blocking are also

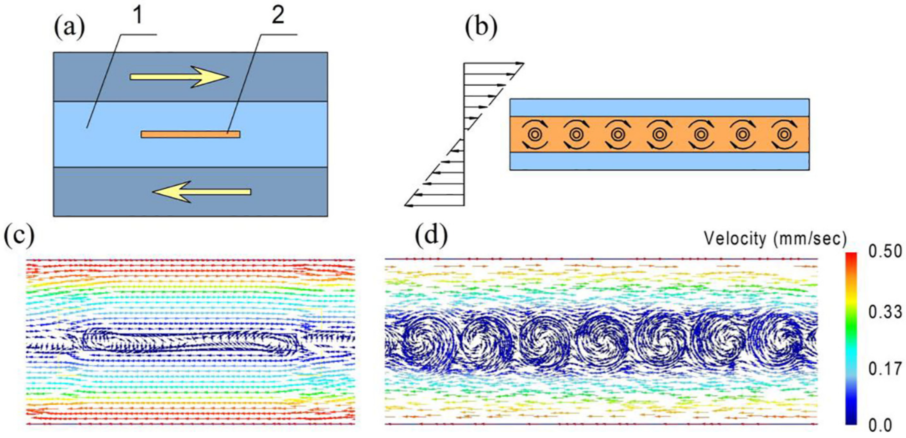

Fig. 3. Model of simple shear with local blocking of shear deformation: (a) – plastically deformed medium, (1), subjected to simple shear in the horizontal direction, and a layer of a stronger material (2); (b) – velocity profile of the medium outside of a stronger layer and representation of the layer that contains the velocity discontinuity in the form of a chain of vortices (the vortex axes are perpendicular to the plane of the figure); (c) – velocity field showing bending of the stronger layer in the plastic medium under simple shear (the geometric model for the calculation corresponds to Fig. 2a, flow stress of the stronger layer is 10 times higher than that of the medium); (d) – velocity field showing the rotations of the fragments of the layer formed as a result of its fragmentation (the materials of the medium and the layer are the same as in Fig. 2c). Simulations in (c) and (d) were conducted using DEFORM software.

possible. They cause turbulent motion in the deformed medium. In particular, such blockers can be fine precipitates of hard intermetallic phases or local solid-solution hardened areas at interfaces, which are formed as a result of mutual diffusion-like mass transfer. The mass transfer is accelerated by the extremely high steady-state density of point defects during HPT [18–21]. Each shear-blocker causes the formation of vortices at its scale level. As a result, HPT of layered samples leads to the multiscale movement of vortices in the deforming material. This movement resembles turbulent flows of liquids and gases, but it has a completely different physical nature.

4. Conclusions

High pressure torsion (HPT) of a bi-metallic laminate can induce vortex-like folding instabilities of layers. The instabilities are remarkably similar to the Kelvin-Helmholtz-type flow instabilities in fluids and folding of metallic surfaces during sliding. Such folding and vortices of metallic layers are driven by plastic instabilities due to local blocking of shear deformation. HPT of layered samples leads to the multiscale movement of vortices in the material during deformation. These movements resemble turbulent flow of liquids and gases, but they have a completely different physical nature.

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