Наносистеми, наноматеріали, нанотехнології
Nanosistemi, Nanomateriali, Nanotehnologii
2016, т. 14, № 4, сс. 553–560

PACS numbers: 62.20.F-, 62.23.St, 62.25.Mn, 81.07.Bc, 81.20.Hy, 81.40.-z, 83.50.Uv

Vortex Formation Under Twist Extrusion

Yu. Beygelzimer[1], R. Kulagin[2], and O. Davydenko[1]

[1]*Donetsk Institute for Physics and Engineering named after O. O. Galkin,*
National Academy of Sciences of Ukraine,
Nauky Ave., 46,
03142 Kyiv, Ukraine
[2]*Institute of Nanotechnology,*
Karlsruhe Institute of Technology,
76021 Karlsruhe, Germany

Twist extrusion (TE) is a technique for simple shear treatment of long metal products. This allows obtaining microstructure and texture in a work piece radically different from those obtained by conventional extrusion. This study aims to investigate the vortex flow during TE, which has not received sufficient attention in the literature. In particular, we study the mechanism of a vortex flow and its influence on the microstructure at different levels.

Ґвинтова екструзія (ҐЕ) — спосіб деформування металів для оброблення довгомірних металевих виробів за допомогою простого зсуву — уможливлює одержувати мікроструктури і текстури в заготовках, кардинально відмінні від тих, що одержані за допомогою звичайної екструзії. Представлене дослідження направлене на вивчення вихрового плину при ҐЕ, якому раніше не приділялося достатньої уваги в літературі. Зокрема, розглядається механізм вихрового плину та його вплив на мікроструктуру на різних рівнях. Також запропоновано перспективи застосування вихрового плину в ҐЕ.

Винтовая экструзия (ВЭ) — способ деформирования металлов для обработки длинномерных металлических изделий с помощью простого сдвига — позволяет получать микроструктуры и текстуры в заготовках, радикально отличающиеся от тех, которые получены с помощью обычной экструзии. Данное исследование направлено на изучение вихревого течения при ВЭ, которому ранее не уделялось достаточного внимания в литературе. В частности, рассматривается механизм вихревого течения и его влияние на микроструктуру на различных уровнях. Также предложены перспективы применения вихревого течения в ВЭ.

Keywords: twist extrusion, simple shear, vortex flow, mixing.

Ключові слова: гвинтова екструзія, простий зсув, вихровий плин, змішування.

Ключевые слова: винтовая экструзия, простой сдвиг, вихревое течение, смешивание.

(Received 1 December, 2016)

1. INTRODUCTION

Twist extrusion is one of the most popular techniques of severe plastic deformation (SPD) whose main aim is to produce ultrafine grained (UFG), *i.e.*, submicron scale, structures in the bulk of metals and alloys.

A burgeoning development of SPD processing over the last two decades and undisputable successes of this research direction [1, 2] have promoted the emergence of some forty various SPD techniques. The taxonomy introduced in [2] distinguishes between the 'principal processing schemes' and the 'derivative' SPD processes. According to the authors, the first group includes the following methods: equal-channel angular pressing, high-pressure torsion (HPT), accumulative roll bonding (ARB), multi-directional forging (MDF), and twist extrusion (TE).

Recently, there has been a tendency to use the SPD processes not only to generate a UFG structure, but also to create hybrid materials with a complex inner architecture furnishing them with a range of improved properties [3]. Of special significance in this regard, there are processes with propensity for profuse material flow in the deformation zones, which allow creating various macro scale structures and textures [4]. Examples include vortex flows, which are characterized by rotation of elementary units of the material. Such processes are used for mixing liquids or particulate materials and for producing textures in polymers during processing in a viscous state [5].

To date, the potential of vortex flows in forming structures and textures in solids has not been tapped into, and research in this area is undoubtedly very worthwhile and promising. Among the mentioned five 'principal' SPD processing schemes, TE is the only extrusion process involving a vortex flux. In this process, the material elements are engaged in translational movement and, at the same time, are rotated about an axis parallel to the extrusion axis. As will be shown below, such a vortex flow can be used to form a spiral-shaped architecture within the billet. Furthermore, it can be applied to produce internal folds of the kind of damascene steel patterns [6] and can also be used for mixing various substances that constitute the billet.

2. THE PRINCIPLE OF TWIST EXTRUSION

The principle of TE is to extrude a billet through a die that has a so-called twist zone between straight inlet and outlet channels (Fig. 1).

The surface of the twist zone is formed by the die profile 'swept' along a helix line. Such geometry of the die channels allows the workpiece to well preserve its initial shape well.

When a workpiece is extruded through a TE die sketched in Fig. 1, the metal is subject to plastic deformation. During the TE process, the main deformation mode is simple shear that takes place at the transients between the twist and straight channels [7]. The strain rate, accumulative von Mises strain, and its distribution in the processed bar is determined by the geometry of the TE die: height of the twist zone, pitch of the twist surface, and dimensions of the transverse profile. The von Mises strain accumulated during one TE pass is approximately 1.0 [8].

Owing to the little change in the shape of the workpiece during TE, the process can be repeated for accumulation of large strains. At relatively low homologous temperatures, TE leads to intensive grain refinement accompanied by formation of deformation-induced high-angle grain boundaries. As a result, TE can be used to form ultrafine grained structures, which are characterized by physical and mechanical properties significantly different from those in coarse grained structures.

Kinematics of flow during TE was analysed in the paper that introduced the TE process [9]. It was shown that the total metal flow during TE can be considered as a sum of two components: so-called helical flow and deviations from helical flow. Herein, helical flow denotes ideal tool-controlled motion of a virtual rigid plane (remaining plane during TE) normal to the extrusion direction. As a result of such ideal helical flow, material points of each virtual plane preserve their relative locations and move together in the extrusion

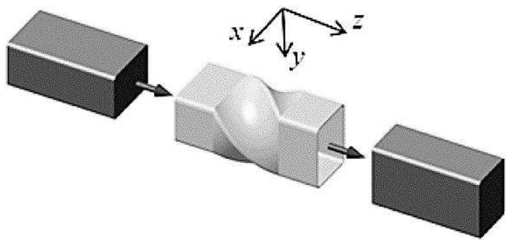


Fig. 1. Schematic of the TE process.

direction. Deviations from ideal helical flow are termed as cross flow; these deviations result in planar flow within the virtual planes of the sample. In contrast to helical flow, cross flow leads to displacement of the material points from their relative locations within the planes normal to the extrusion direction.

Mathematically the decomposition of the total metal flow into the two components can be shown by considering velocity fields. The velocity field of total metal flow **V** [9] is decomposed as

$$\mathbf{V} = \mathbf{V}_1 + \mathbf{V}_2, \tag{1}$$

where $\mathbf{V}_1$, $\mathbf{V}_2$ denote velocity fields of helical flow and cross flow, respectively.

Below the velocity field in Eq. (1) is shown to lead to vortex flow of metallic materials at different scales, which opens new routes to tailored microstructures.

3. RESULTS AND DISCUSSION

3.1. Helical Flow and Vortex Flow at the Microscale

Let us consider a Cartesian coordinate system xyz whose z axis is arranged along the symmetry axis of a rectangular TE die, while x and y axes are parallel to the sides the die profile. The velocity field of helical flow is then defined by the components [9]

$$V_{1x} = -\frac{yV_0 \tan\beta}{R}, \; V_{1y} = \frac{xV_0 \tan\beta}{R}, \; V_{1z} = -V_0, \tag{2}$$

where β is the slope angle of the twist line, V_0 is the speed of the billet along z-axis, and R is the radius of the circle circumscribing the rectangle of the die profile.

When the components are known, the velocity field of helical flow V_1 reduces to the following velocity gradient tensor

$$\frac{d\mathbf{V}_1}{d\mathbf{r}} = \begin{pmatrix} 0 & 0 & -\dfrac{yV_0}{R\cos^2\beta}\dfrac{d\beta}{dz} \\ 0 & 0 & \dfrac{xV_0}{R\cos^2\beta}\dfrac{d\beta}{dz} \\ 0 & 0 & 0 \end{pmatrix} + \begin{pmatrix} 0 & -\dfrac{V_0\tan\beta}{R} & 0 \\ \dfrac{V_0\tan\beta}{R} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}. \tag{3}$$

The first term in Eq. (3) shows the presence of simple shear at the transient planes between the twist zone and the straight channels

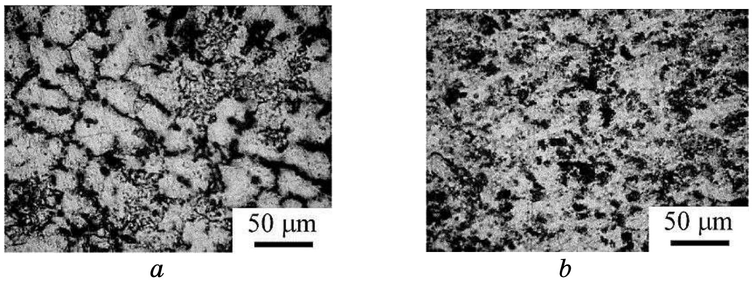


Fig. 2. Microstructures of aluminium alloy AV87 before (*a*) and after (*b*) one passes of twist extrusion (extrusion temperature 100°C, backpressure 100 MPa).

because only at the transient zones $d\beta/dz \neq 0$. The second term in Eq. (3) describes rigid body rotation around z-axis.

According to the previous works [10], in metallic materials, large simple shear strains cause vortex flow at a scale with a characteristic dimension of 10 μm. This vortex flow is similar to the turbulent flow in fluids. Vortex flow at this scale leads to intensive mass transport and mixing of phases in the material (Fig. 2).

3.2. Cross Flow and Vortex Flow at the Macroscale

Cross flow is defined as deviations from the ideal tool-controlled flow. The main features of cross flow were analysed for titanium by using a flow visualization technique and numerical simulations. Samples of commercially pure titanium were twist-extruded through a die of a rectangular profile at 350°C with back pressure of 200 MPa. For visualization of metal flow during TE, copper fibres were embedded into the titanium samples as shown in Fig. 3.

Metallurgical sectioning and optical analysis of the sample cross sections allowed tracking marker coordinates. For the titanium sample shown in Fig. 3, *b*, coordinates of initial (x, y) and deformed (x', y') markers were defined in terms of the Cartesian coordinate system (Fig. 1).

The cross flow during TE can be considered as a mapping that carries material points before TE into points after TE within the planes normal to the extrusion direction. The mapping can be represented in a form of the following equations:

$$x' = f(x, y)\,,\ \ y' = g(x, y)\,, \tag{4}$$

where functions $f(x, y)$ and $g(x, y)$ are found from the experimental data.

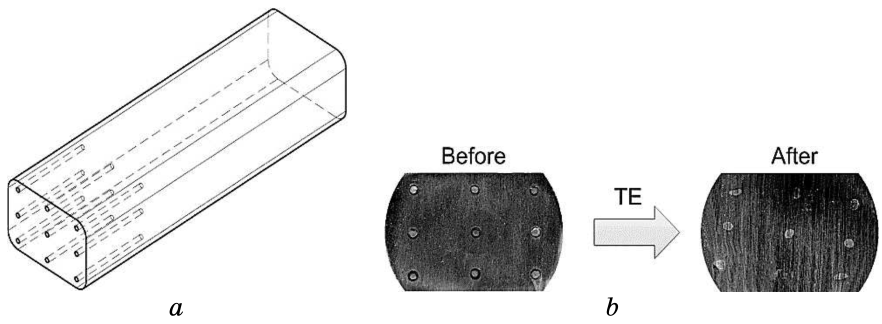


Fig. 3. Visualization of metal flow during TE: *a*) a sketch of the sample with embedded copper markers before TE; *b*) photographs of the sample cross sections with markers before and after TE.

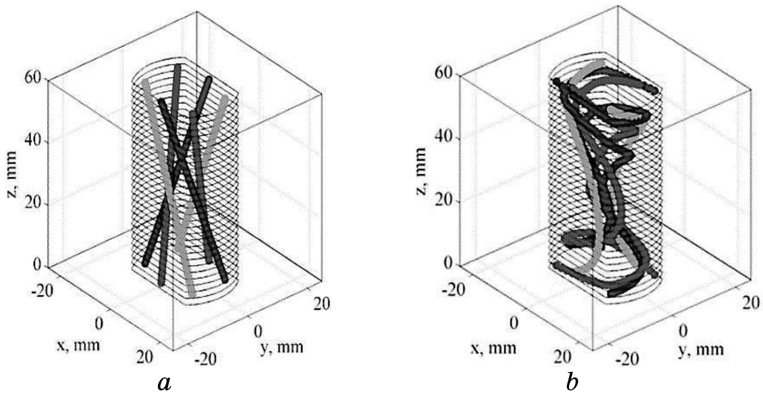
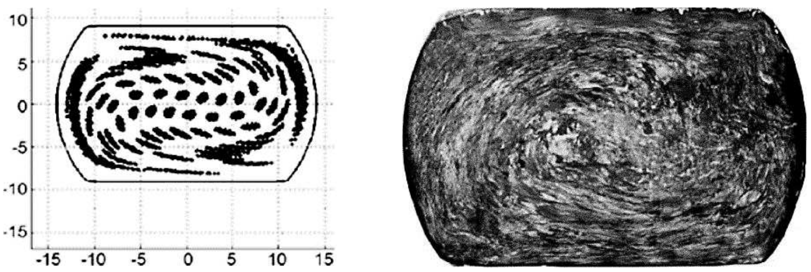


Fig. 4. Shape transformation of an inclined fibres that takes place during multipass TE: *a*—initial arrangement and shape; *b*—after 5 passes.

The mapping described by Eq. (4) makes possible tracking any material points during TE.

The mapping provides a solution for the inverse problem: to find the arrangement and shape of an initial manifold of material points needed for a prescribed final arrangement and shape. It follows that, for example, fibres initially inclined in respect to the extrusion axis can form a helical shape after multipass TE. The orientation of the helical fibres is controlled by the die geometry. The ability to form helical fibres during TE provides a route for producing materials with a chiral structure [11]. Based on the mapping, Fig. 4 exemplifies a shape transformation of inclined fibres because of multipass TE.

Finally, considering TE as a mapping supported by marker techniques makes it possible to predict formation of vortex microstructures, which were observed experimentally in Fig. 5.



a *b*

Fig. 5. Vortex structure formed by TE: a point set after seven transformations described by Eq. (4); (b) microstructural traces of vortex flow in aluminium after 4 TE passes [12].

Formation of vortex structure is accompanied by significant mixing of the material [5]. In TE, mixing can be further intensified by rotating the billet 180° around its axis after every 5–7 passes, which results in periodical change of the vortex direction. Moreover, during TE, the material near surface periodically flows into the billet volume while some inner material emerges. Owing to these counter flows, multipass TE provides prerequisites for mechanical alloying [13]. By the virtue of the mentioned mixing effect, performing TE in surface-active media grants surface treatment of the material for further improvement of its properties (*e.g.*, surface hardening).

4. SUMMARY

In twist extrusion, deformation of metallic materials is accompanied by vortex flow that takes place at different scales. Multiscale vortex flow opens new horizons for tailored microstructure formation and improving properties of materials.

ACKNOWLEDGMENTS

Publications are based on the research provided by the grant supports of the State Fund for Fundamental Research (project F 71/56-2016) and the National Academy of Sciences of Ukraine (project 48/16-H).

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