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Shears, Vortices, and Mixing During Twist Extrusion

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ABSTRACT: We present an experimental study of the kinematics of Twist Extrusion (TE) and show that TE has the following properties. As in ECAP, the mode of deformation in twist extrusion is simple shear. Unlike in ECAP, there are two shear planes; one of them is perpendicular and the other is parallel to the specimen axis. The following processes are present during twist extrusion: vortex-like flow with large strain gradient, stretching and mixing of metal particles. Twist extrusion opens new technological possibilities, e.g., decreased metal waster compared to ECAP, obtaining profile hollow specimens.

Key words: Twist Extrusion, Severe plastic deformation, Ultrafine grains materials

1 INTRODUCTION

Severe Plastic Deformation (SPD) is a family of metal forming techniques that use extensive hydrostatic pressure to impose a very high strain on bulk solids, producing exceptional grain refinement without introducing any significant change in the overall dimensions of the sample [1]. Several different SPD processing techniques are now available including High-Pressure Torsion (HPT), Equal-Channel Angular Pressing (ECAP), Multi-Directional Forging (MDF), Accumulative Roll-Bonding (ARB), Repetitive Corrugation and Strengthening (RCS) and Twist Extrusion (TE).

Each process has unique properties determining its use in research and practice. This paper presents several properties of Twist Extrusion, which open possibilities for investigating and forming new structures.

□ BASICS OF TWIST EXTRUSION

Twist extrusion was proposed by the first author in [□]. TE is based on pressing out a prism specimen through a die with a profile consisting of two prismatic regions separated by a twist part [□, 3] (see figure 1). As the specimen is processed, it undergoes severe deformation while maintaining its original cross-section. This property allows the specimen to be extruded repeatedly in order to accumulate the value of deformation, which changes the specimen structure and properties.

TE is performed under high hydrostatic pressure in the center of deformation. The pressure is created by applying backpressure to the specimen when it exits the die.

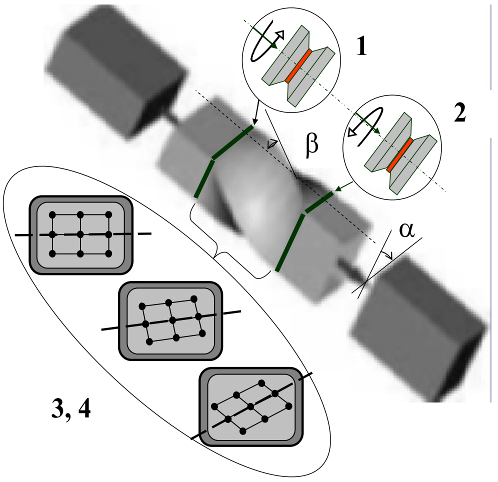

Fig. 1. Twist Extrusion scheme. Show the four main deformation zones, inclination angle of the twist line β and rotation angle α between initial and final cross-sections of the die. The markers in cross-sections are placed on a grid to better illustrate the shift occurring in zone 3.

3 EXPERIMENTAL INVESTIGATION OF TE KINEMATICS

To study the kinematics of metal flow during TE experimentally, we use a specimen with nine fibers embedded along its main axis. The specimen was pressed through a built-up twist die until the stationary flow was reached. It was then removed from the die and cut perpendicularly to its main axis with an interval of 0.5mm, starting from its end. The nine markers in the obtained cross-sections are used to reconstruct the corresponding experimental lines of flow, which are then used to fit a theoretical model of the velocity field [3, 4]. The model incorporates two physical constraints: (1) metal flow is limited by the surface of the die, and (□) metal volume remains constant. The parameters of this model are determined from fitting the observed experimental streamlines. The obtained velocity field is then used to find the strain state of the metal using the continuum mechanics relations.

We performed the experiments on Al, Cu, Ti, and their alloys. All of them have common, characteristic deformation properties described next.

Two shear planes and four deformation zones in TE

There are four sufficiently well separated deformation zones observed when processing different materials with twist extrusion.

Deformation Zones 1 and □ are located at the two ends of the twist part of the die (see figure 1). The mode of deformation in these zones is simple shear in the transversal plane (TP), as in High Pressure Torsion. The shears in the two zones have opposite direction. Each of them gives a von Mises equivalent stress from e ~ 0.0 (in the center) to e ~ 0.5÷0.7 (on the periphery). The zones appear as steps in figure □, which shows how the equivalent strain depends on the coordinate along the extrusion axis.

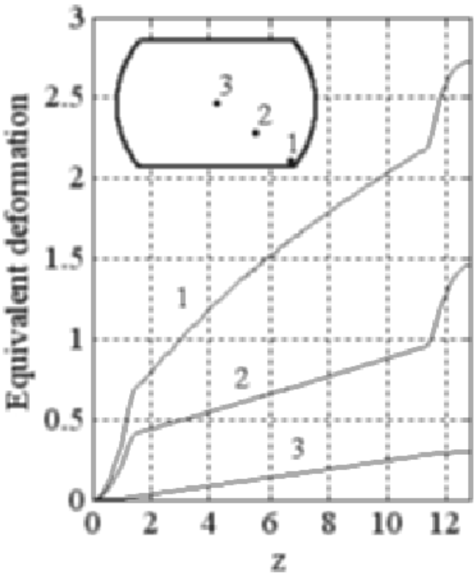

Fig. □ Equivalent strain versus coordinate along the extrusion axis (Z) for representative points of the specimen cross-section, $\beta=55^o$, $\alpha=70^o$.

Deformation Zone 3 (shown in light gray in the cross-sections in figure 1) is located in the twist part of the die between Zones 1 and □. The mode of deformation in Zone 3 is simple shear in the rotating longitudinal plane (LP), which is indicated by the position of the markers in the three relevant cross-sections. The value of equivalent strain accumulated in this zone is in the range 0.□÷0.5. It is this zone that provides the deformation along the extrusion axis, where the equivalent strain in Zones 1 and □is zero (see figure □).

Deformation Zone 4 is located in the twist part of the die in the peripheral layer (1÷□mm thick) of the specimen between Zones 1 and □. Figure 1 depicts this zone as a dark border along the cross-sectional periphery of the specimen. The mode of deformation in this zone is severe simple shear with an equivalent strain of e ~ □(see figure □). Figures 3 shows the distribution of accumulated strain in a perpendicular cross-section.

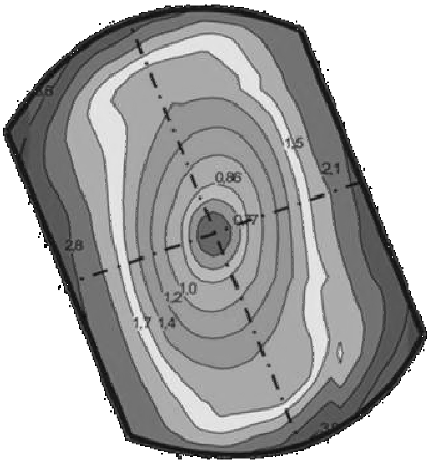

Fig. 3. The distribution of accumulated strain in a perpendicular cross-section

4 TWO MAIN ROUTES OF TE

There are two types of twist dies: clockwise (CD) and counter-clockwise (CCD). When transitioning from CD to CCD, the shears in each of the four deformation zones reverse its sign. This gives us two main routes of TE:

Route I: CD+CD (or CCD+CCD),

Route II: CD+CCD (or CCD+CD).

It is easy to see that in the transversal plane, route 1 gives a cyclic deformation with some amplitude A, while route II gives a cyclic deformation with amplitude □A. In longitudinal plane, route I gives a monotone deformation while route II gives a cyclic deformation. Different loading paths can lead to different structures and properties.

5 STRUCTURE AND PROPERTIES DURING MULTI-PASS TE

Papers [4-11] present experimental results with TE for different materials (Al, Cu, Ti, and their alloys; powders of different composition). Using optical microscopy, it is shown that cross-sections typically exhibit a characteristic macrostructure with structural elements elongated along the direction of a vortex centered at the extrusion axis. In the longitudinal cross-section, this macrostructure resembles a turbulent flow [4, 8]. The underlying microstructure, after multiple TE passes, is characterized by submicron sizes and high angular boundaries [6-10].

This structure provides good strength and ductility properties in the specimens processed with TE. In some cases, the properties are strongly anisotropic [4, 8], but the anisotropy can be obviated by changing the form of the die cross-section, increasing the operating temperature, subsequent recrystallizing thermal processing or such postprocessing deformations as drawing or direct extrusion. With that, the microstructure still remains submicrocrystalline [4, 8].

Despite the inhomogeneity of deformation, the structure and properties of materials tend to even out with subsequent TE passes. This is due to two factors: (1) mixing (see below), and (□) stabilization of structure and saturation of properties, once strain exceeds some saturation level e_S [5, 11]. Such stabilization and saturation are not unique to TE. They are typically present in any deformation method based on simple shear; for example, saturation happens in torsion [1□]. A possible mechanism explaining this effect in SPD is analyzed in [13]. With the number of passes, the zone where strain exceeds the saturation threshold, gradually fills up the entire cross-section. This tends to level out the structure and properties across the cross-section [5].

6 NEW POSSIBILITIES COMING FROM TE

The main routes of TE can be combined with any SPD or metal forming processes (e.g., ECAP, rolling, extrusion) to broaden the space of possible loading paths. The field of equivalent strain under TE has a large gradient. This is of interest for investigating the effects of strain gradient on the evolution of material structure, as well as obtaining gradient structures.

Strain distribution and deformation zones boundaries strongly depend on the geometry of die's cross-section, inclination angle β and rotation angle α. By varying these parameters, one can change strain intensity in different zones. In particular, profiles with a rectangular cross-section increase strain in zones 1 and □ while decreasing it in zones 3 and 4. If the profile contour contains circular arcs about the direction of extrusion, this leads to the opposite effect---it decreases strain in zones 1 and □ while increasing it in zones 3 and 4.

The presence of two new planes of controllable shear, different from those in ECAP, provides additional means for forming material structure and properties. For example, one can create equiaxial fragments using TE as well as using a combination of TE with ECAP. Intensifying the shear in zones 1 and □, creates a structure with pronounced anisotropic properties.

Deformation Zones 3 and 4 form a vortex-like flow, which stretches metal particles. The stretching increases with subsequent TE passes as long as the dies have the same direction (all clockwise or all counter-clockwise). Passes with alternating directions create folds (figure 4). Alternating stretching and folding leads to mixing, as in Smale's horseshoe [14]. The capability for severe mixing is a distinguishing characteristic of TE, which can be used for homogenization of composite materials, intensification of mechanochemical reactions, etc.

Zone 4 allows one to obtain very interesting mixing-related effects, due to the following factors: First, this is the zone of the most severe shear leading to formation of folds not only on the macro but also on the microlevel. As mentioned before, this leads to mixing according to the Smale's horseshoe mechanism. Also, since the surface area of the specimen first increases by 50% and then returns to its original size as the specimen goes through the die, the material in the core and on the surface mix. This can be used for mechanical impurity doping of the surface layers of the specimen.

TE opens new technological options due to the position of its shear planes. For example, TE decreases metal waste, compared to ECAP, and allow manufacturing profile hollow specimens.

7 CONCLUSION

As in HPT and ECAP, deformation in TE is performed through simple shear. There are multiple shear planes, unlike in HPT and ECAP. These planes are perpendicular and parallel to the central axis of the specimen.

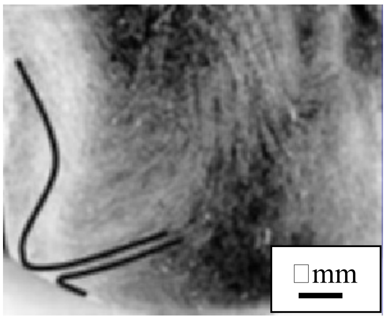

Fig. 4. Cross-section of the specimen. Folds after □pass TE, route II.

Other effects of TE include formation of vortexes with stretching, and mixing of metal particles. We identified and described four well-defined deformation zones with different properties of metal flow.

TE has already been successfully used to obtain UFG structure with good properties in Al, Cu and Ti alloys, but most importantly, TE opens new possibilities for investigating and forming new structures with new properties.

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REFERENCES

1. R.Z. Valiev, Y. Estrin, Z. Horita, T.G. Langdon, M.J. Zehetbauer and Y.T. Zhu, Producing Bulk Ultrafine-Grained Materials by Severe Plastic Deformation. JOM 58(4) (□006) 33-39
□ Y.E. Beygelzimer, V.N. Varyukhin, S.G. Synkov, A.N. Sapronov, V.G. Synkov, New Schemes of Accumulation of Large Plastic Deformation. Fiz. Tekh. Vys. Dav. Vol. 14, 3 (1999) 109-111 [in russian].
3. Y. Beygelzimer, D. Orlov, and V. Varyukhin, New Severe Plastic Deformation Method: Twist Extrusion. In: Proc. Second Int. Symp. on Ultrafine Grained Materials, The Minerals, Metals, and Materials Society, eds. Y.T. Zhu et al., Warrendale, PA (□00□) □97-301.
4. Y. Beygelzimer, V. Varyukhin, D. Orlov and S. Synkov: Twist extrusion process for strain accumulation, TEAN, Donetsk (□003) [in russian].
5. Y. Beygelzimer, D. Orlov, A. Korshunov, S.Synkov, V. Varyukhin, I.Vedernikova, A. Reshetov, A.Synkov, L.Polyakov and I.Korotchenkova, Features of Twist Extrusion: Method, Structures and Material Properties. Solid State Phenomena, 114 (□006) 69-78
6. A.P. Shpak, V.N. Varyukhin, V.I. Tkatch V.V. Maslov, Y.Y. Beygelzimer,S.G. Synkov, V.K. Nosenko and S.G. Rassolov, Nanostructured Al86Gd6Ni6Co□ bulk alloy produced by twist extrusion of amorphous melt-spun ribbons. Materials Science and Engineering A 4□5 (□006) 17□–177
7. V. Varyukhin, Y. Beygelzimer, S. Synkov and D. Orlov, Application of Twist Extrusion. Materials Science Forum 503-504 (□006) 335-339
8. V.V.Stolyarov, Y.E. Beigel'zimer, D.V.Orlov and R.Z. Valiev, Refinement of Microstructure and Mechanical Properties of Titanium Processed by Twist Extrusion and Subsequent Rolling. The Physics of Metals and Metallography, 99, □(□005 □04-□11.
9. D. Orlov, A. Reshetov, A. Synkov, V. Varyukhin, D.Lotsko, O. Sirko, N. Zakharova, A. Sharovsky, V. Voropaiev, Yu. Milman and S. Synkov, Twist Extrusion as a Tool for Grain Refinement in Al-Mg-Sc-Zr Alloys. In: Nanostructured Materials by Severe Plastic Deformation, eds. Y. T.Zhu and V.Varyukhin. Springer, (□006) 77-81
10. M.Berta, D.Orlov and P.Prangnell, Grain refinement response during twist extrusion of an Al-0.13 % Mg alloy. International Journal of Materials Research (Zeitschrift fur Metallkunde), 98, 3 (□007) □00-□04.
11. S. V. Dobatkin, A.A.Kuznetsov, G.A.Salishchev, Y.Y.Beygelzimer and D.V.Orlov, Submicrocrystalline structure of oxygen-free copper after different methods of severe plastic deformation. Metalurgija, 45, 3 (□006) □45-□51.
1□ P. W. Bridgman, Studies in Large Plastic Flow and Fracture, with Special Emphasis on the Effects of Hydrostatic Pressure, Harvard (195□)
13. Y. Beygelzimer: Grain refinement versus voids accumulation during severe plastic deformations of polycrystals: mathematical simulation. Mechanics of Materials 37 (□005) 753–767
14. J. M. Ottino, The Kinematics of Mixing: Stretching, Chaos, and Transport, Cambridge and New York, Cambridge University Press (1989)