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TWIST EXTRUSION

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The work presents the results of research and development on Twist Extrusion (TE) process. It was shown the two main deformation zones of TE are located at the two ends of the twist part of the die. The mode of deformation in these zones is simple shear in the transversal layers, as in high pressure torsion (HPT). In terms of strain, at the first approximation, the billet during TE like passes through two "transparent" HPT anvils. TE has a significant commercial potential due to the following physical effects: intensive grain refinement; homogenization and mixing; intensive powders consolidation. There are three main areas in TE application for the present: formation the submicron and nanostructures in the bulk metals samples; processing of the recycled non-ferrous metals and alloys for the improvement of the mechanical properties; production the bulk samples through powders consolidation. Donetsk Institute for Physics and Engineering created a TE Center to showcase the process and educate investors. Our experience with the center has shown that the most prospective directions are producing ultrafine-grained alloys for medical and aircraft applications.

Keywords: twist extrusion, severe plastic deformation, ultrafine-grained materials

Представлено результати досліджень процесу гвинтової екструзії (ГЕ) та розробок з його здійснення. Показано, що основна деформація матеріалів при ГЕ відбувається у двох зонах простого зсуву, розташованих на границях гвинтової ділянки матриці. ГЕ має значний комерційний потенціал завдяки швидкому подрібненню зерен та інтенсивному масопереносу, що призводить до гомогенізації та перемішування матеріалів. На цей час намітилися три основних напрями в застосуванні ГЕ: формування субмікронних і наноструктур в металах і сплавах; обробка вторинних кольорових металів і сплавів для поліпшення їхніх механічних властивостей; виробництво об'ємних зразків шляхом консолідації порошків. Донецький фізико-технічний інститут створив дослідну ділянку ГЕ, щоб продемонструвати процес і залучити інвесторів. Досвід роботи цієї ділянки показав, що найбільш перспективним напрямом застосування ГЕ є виробництво сплавів для медицини та авіації.

Ключові слова: гвинтова екструзія, інтенсивна пластична деформація, субмікрокристалічні матеріали

Introduction

Severe plastic deformation (SPD) processes are defined as methods of metal forming under extensive hydrostatic pressure that may be used to impose very high strain on a bulk solid without introduction of any significant change in the overall dimensions of the sample. SPD is able to produce exceptional grain refinement [1]. Several different SPD techniques are now available; these include High-Pressure Torsion (HPT) [2], ECAP [3], Multi-Directional Forging (MDF) [4], Accumulative Roll-Bonding (ARB) [5], Repetitive Corrugation and Strengthening (RCS) [6] and TE [7].

HPT involves order of magnitude higher pressures than any other SPD process. This provides attainment of uniquely high strains and formation of UFG structures. However, application of HPT is limited to laboratory conditions due to small size of the samples. Other processes, such as ECAP, ARB, RCS and TE, permit processing of substantially larger samples and, therefore, they are of practical interest [1].

Being promising in the commercial sense [1], TE enjoyed some interest, which is reflected in continuous research on the subject [1,8–10] as well as in the emergence of new SPD methods inspired by the concept of TE [11–15].

In [16], strained state of the billet during TE was investigated by experimental and computational method. In the present paper, the finite element method was applied for this purpose. By using the software Deform-3D, the computational experiment was carried out and the regression's relations were obtained for calculation of the basic characteristics of TE.

In recent years, TE has achieved a significant progress in terms of practical use. Donetsk Institute for Physics and Engineering created TE Center to showcase the process and educate investors. This paper gives an overview of the main equipment of TE Center and presents some results of its work.

Basics of Twist Extrusion

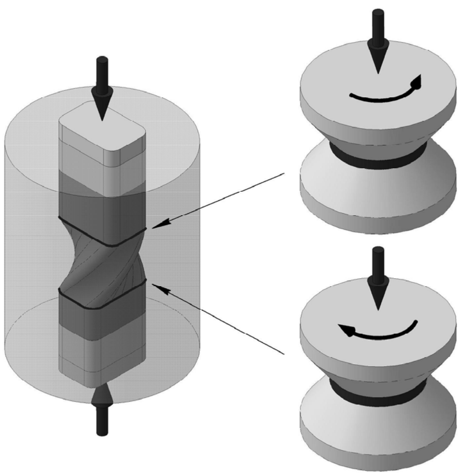


Fig. 1. TE scheme. The analogy of TE with HPT process was shown on the insertions

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 [17,18] (see Fig. 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 deformation zone. The pressure is created by applying backpressure to the specimen when it exits the die.

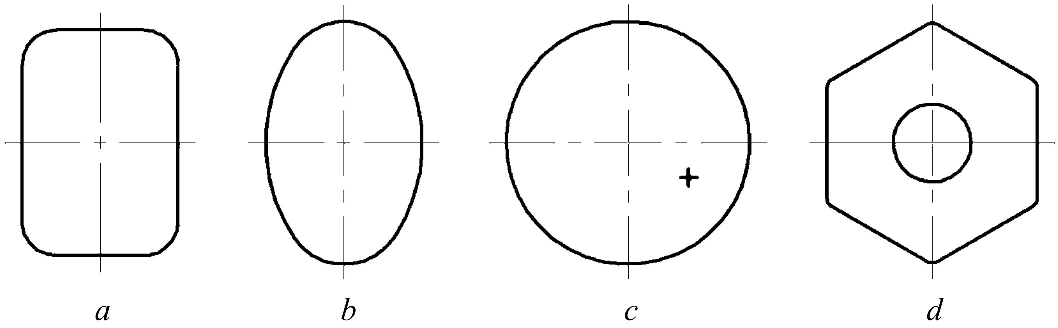


Fig. 2. A few examples of cross-sections of dies for twist extrusion: *a* – rectangular; *b* – elliptical; *c* – circular, '+' denotes the position of extrusion axis; *d* – hexagonal with a hollow centre

The profile of TE die cross-section can be arbitrary. A few examples of possible profiles are shown in Fig. 2.

Let us emphasise here a principal ability of TE to process bars having circular cross-section profile. This can be achieved when the axis of extrusion is shifted away from the axis of symmetry of the channel. It is illustrated in Fig. 2,*c* where extrusion axis indicated by '+' is located aside from the centre of symmetry of the channel in the middle of the cross-section. Tubular billets with a hollow centre can also be processed by TE when extrusion on a barrel is used, Fig. 2,*d*.

In [16], it was shown by means of experimentally-computational method that the two main deformation zones of TE were located at the two ends of the twist part of the die (see Fig. 1). The mode of deformation in these zones is simple shear in the transversal layers, as in HPT. In terms of strain, at the first approximation, the TE of a billet is similar to passes through two «transparent» Bridgman anvils (see insertions in Fig. 1). The presence of two zones of intensive simple shear we confirmed by simulation of TE with finite element method. In addition, numerical experiments allowed employment of different values of die parameters and materials in order to obtain the engineering relations for design of the technology and equipment for TE.

Finite element method simulations of deformation during TE were conducted with the aid of Deform-3D software permitting three-dimensional analysis[1]. Design model of the TE die is shown in Fig. 3.

The die and punches were modeled with rigid elements, while 50000 tetrahedral elements were employed for the samples. The adaptive meshing was used to accommodate large strains during simulations. Reduced integration and hourglass control were applied in the analysis. Von Mises plastic model was employed. The backpressure was varied. Friction between the samples and the matrix walls was expressed according to Zibel's law: $\tau = \mu\sigma_y$, where σ_y was the yield stress, μ was the friction coefficient ($\mu = 0.1$).

[1] The calculations were performed by R. Kulagin.

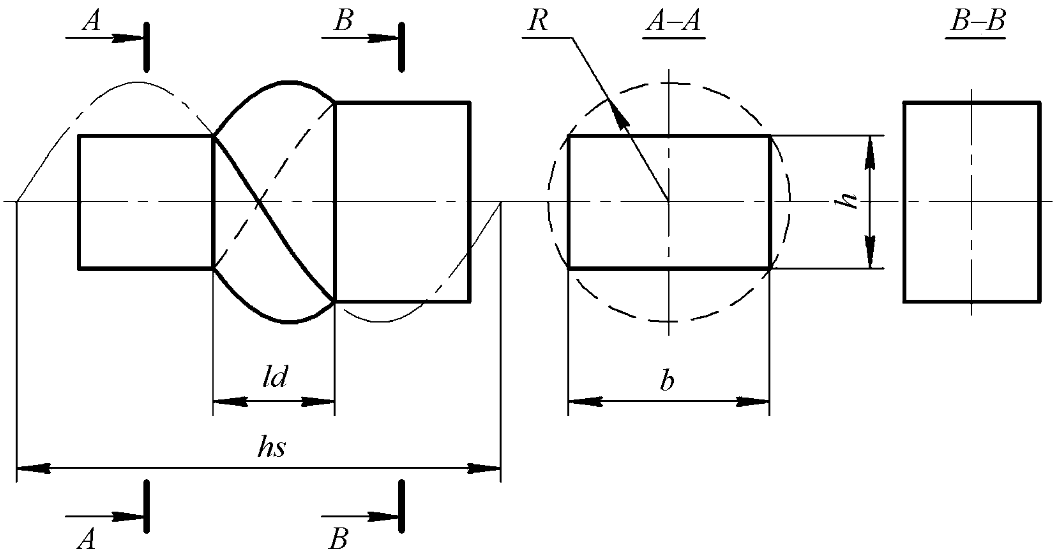
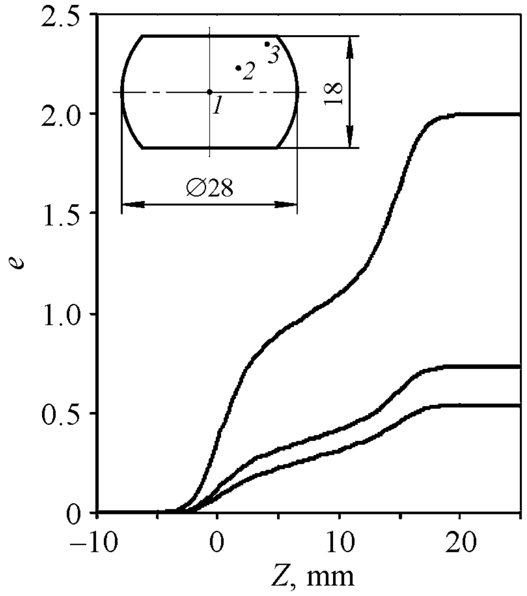


Fig. 3. Design model of the TE die (*hs*, *R*, *ld*, *h*, *b* are the geometric parameters of the die)

Accumulation of von Mises strain at three different locations of the sample cross-section in the TE is shown in Fig. 4. The calculation were performed for the following parameters: *hs* = 150 mm, *ld* = 25 mm, *h* = 25 mm, *b* = 40 mm. *Z* axis was directed along the extrusion axis, the *X* and *Y* axis were oriented, respectively, along smaller and larger part of the initial cross-section of the die.

Fig. 4 shows two zones of intense deformation at the entrance and exit from the twist part of the die. The analysis of the strain rate tensor components (see Fig. 5)



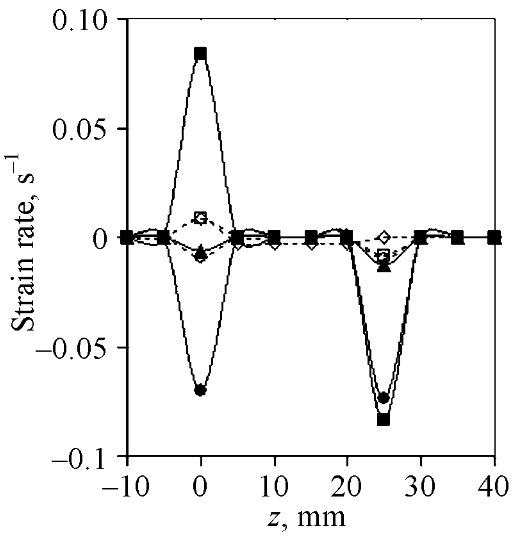


Fig. 4. Accumulation of von Mises strain for three typical points of the cross section (see insertions) during TE

Fig 5. The values of the strain rate tensor components along trajectories of the three typical points. (Note: locations of the three points in the sample cross-section are the same as Fig. 4). □ – e_{xx}, ◊ – e_{yy}, ○ – e_{zz}, ▲ – e_{xy}, ■ – e_{yz}, ● – e_{zx}

shows that really simple shear takes place within the layers perpendicular to the extrusion axis. It is evidenced by the fact that the moduli of components e_{zx}, e_{zy} in the mentioned areas are much higher than the absolute values of all other components of the strain rate tensor.

Von Mises strain distribution for a final cross-section for TE die is shown in Fig. 6. The isostrain contours form closed loops around the centre of the cross-section.

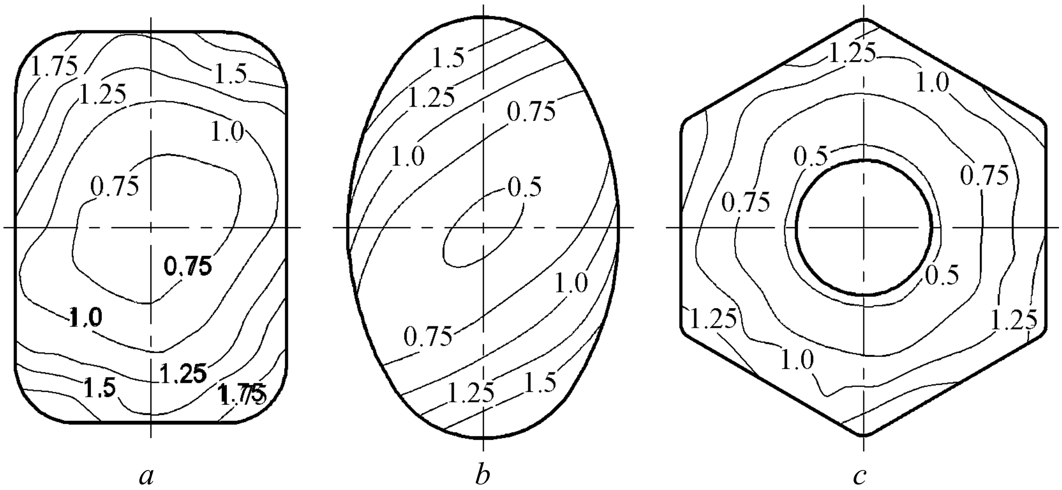


Fig. 6. Distributions of Von Mises equivalent strain in cross-section of billets having rectangular (*a*), oval (*b*) and hexagonal with hollow centre (*c*) profiles

In general, the character of strain distribution and strain accumulation was in agreement with the previously reported results obtain experimentally [16].

Relations for the main Twist Extrusion characteristics calculation

In TE technology development and equipment design, the following main characteristics of the process are of a great importance: TE pressure (p), the minimum ($e_{\min}$) and the average (e_{av}) strain over the cross-section of the billet. In order to obtain relations for calculating these characteristics, a planned numerical experiment was carried out using the Deform-3D software. As variable factors, the dimensionless parameters were chosen that changed in the following ranges: hs/R = 3–11, ld/hs = 0.1–0.2, h/b = 0.5–1.

As a result of regression analysis, the following engineering relations for three major TE characteristics were obtained [19]:

$$e_{\min} = 3.08\left(\frac{hs}{R}\right)^{-0.65}\left(\frac{ld}{hs}\right)^{0.87}\left(\frac{h}{b}\right)^{-1.15},$$

$$e_{\text{av}} = 3.46\left(\frac{hs}{R}\right)^{-0.47}\left(\frac{ld}{hs}\right)^{0.55}\left(\frac{h}{b}\right)^{-0.56},$$

$$p = \sigma_y\left(e_{\text{av}} + \mu\frac{2(h+b)l}{hb}\right) + p_{bp},$$

where l was the billet length, p_{bp} was the backpressure.

These relations can be used for practical implementation of TE.

Applications of Twist Extrusion

Fig. 7. Pilot-plant equipment for TE

TE Center encloses TE equipment (see Fig. 7), metal forming equipments (installation for direct extrusion, rolling mill and facilities for wire-drawing), cutting equipment, heat-treatment facilities.

Pilot-plant equipment for TE has the following characteristics: the maximum pressure of 2000 MPa, the maximum backpressure of 700 MPa; the temperature of the container and the die is up to 400°C, the ram velocity is 3 mm/s, the dimensions of the specimens are 30 × 40 × 140 mm.

There are several technologies based on TE. We have got the UFG billets of Al–Mg alloy[2]. The grain size about 300–500 nm has been reached (see Fig. 8). The mechanical properties of the alloy are given in Table 1. The obtained material has a higher strength-to-weight ratio and fatigue strength. Therefore it has good prospects of application in aircraft and automotive industries, as a load carrying structural units and aircraft covering. Using of this alloy can reduce the specific quantity of metal per structure and specific fuel consumption, and increase the life of the individual units of the machine as well.

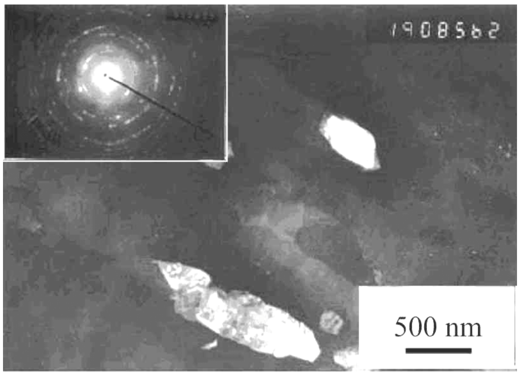
Table 1

Mechanical properties of Al–4.45Mg–0.4Mn–0.3Sc–0.1Zr alloy

State of alloy	YS	UTS	σ_{-1}	El, %
	MPa			
Initial	290	400	180	15
4 pass TE	350	420	330	10

The second promising material for TE commercialization based on the grain refinement effect is commercially pure (CP) titanium for medical application. We have processed billets from the CP titanium by four passes of TE followed by rolling. As a result of TE, the grain refinement to submicron level has occurred (see Fig. 9). Strength properties of the billets increased approximately twofold, while the plasticity of the material remained at an acceptable level (Table 2).

[2] The work was performed with Dr. Milman's laboratory (Frantsevych Institute for Problems of Materials Science, Kiev, Ukraine).



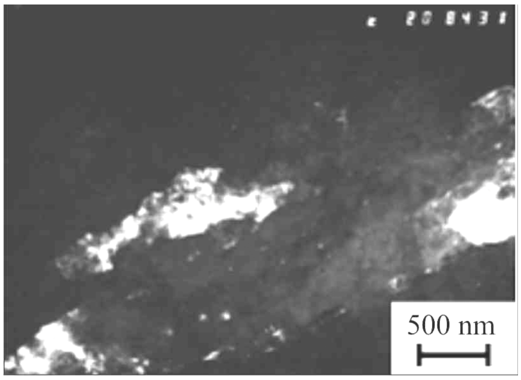


Fig. 8. Structure formed in the Al–Mg alloy processed with TE

Fig. 9. Structure of CP titanium after four TE passes

Table 2

Mechanical properties of CP titanium

State of Ti	YS	UTS	El, %
	MPa		
Initial	350	430	20
4 pass TE + Rol. 70%	800	840	15

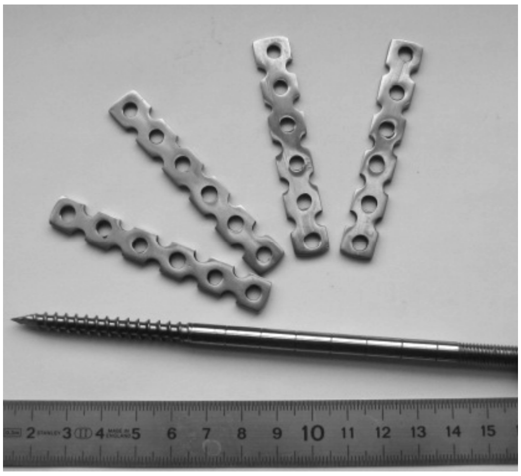


Fig. 10. Products from UFG titanium, obtained by TE for medical application

The obtained UFG titanium has been used for production of implants for use in traumatology and orthopedics (see Fig. 10). Due to improved mechanical properties, such implants can be used instead of similar products from alloyed titanium, for example, Ti–6Al–4V. The advantage of our plates is that due to the absence of impurities and alloying elements, they have a better biocompatibility with human tissues and are not rejected by the body. Besides, due to high strength of nanocrystalline titanium, the assortment of implants can be greatly expanded. In particular, it is possible to reduce the implant cross-section at half or even two-time as less. This fact allows us to increase considerably the number of patients which can be operated in order to insert such implants. Currently, many people can not be operated for implants insertion because of medical reasons associated with relatively large implant size to the bone.

Conclusions

We present a study of the kinematics of Twist Extrusion (TE) and show that the mode of deformation in TE is simple shear. Unlike Equal-Channel Angular

Pressing (ECAP), there are two main shear layers perpendicular to the specimen axis. TE has significant commercial potential due to the following physical effects: intensive grain refinement; homogenization and mixing; intensive powders consolidation. Donetsk Institute for Physics and Engineering created a TE Center to showcase the process and educate investors. Our experience with the center has shown that the most prospective directions are producing UFG alloys for medical and aircraft applications.

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ВИНТОВАЯ ЭКСТРУЗИЯ

Представлены результаты исследований процесса винтовой экструзии (ВЭ) и разработок по его осуществлению. Показано, что основная деформация материалов при ВЭ происходит в двух зонах простого сдвига, расположенных по границам винтового участка матрицы. ВЭ имеет значительный коммерческий потенциал благодаря быстрому измельчению зерен и интенсивному массопереносу, приводящему к гомогенизации и перемешиванию материалов. В настоящее время наметились три основных направления в применении ВЭ: формирование субмикронных и наноструктур в металлах и сплавах; обработка вторичных цветных металлов и сплавов для улучшения их механических свойств; производство объемных образцов путем консолидации порошков. Донецкий физико-технический институт создал опытный участок ВЭ, чтобы продемонстрировать процесс и привлечь инвесторов. Опыт работы этого участка показал, что наиболее перспективным направлением применения ВЭ является производство субмикрокристаллических материалов для медицины и авиации.

Ключевые слова: винтовая экструзия, интенсивная пластическая деформация, субмикрокристаллические материалы