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Features of Twist Extrusion: Method, Structures & Material Properties

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Abstract. During the last decade it has been shown that severe plastic deformation (SPD) is a very effective for obtaining ultra-fine grained (UFG) and nanostructured materials. The basic SPD methods are High Pressure Torsion (HPT) and Equal Channel Angular Extrusion (ECAE). Recently several new methods have been developed: 3D deformation, Accumulative Roll Bonding, Constrained Groove Pressing, Repetitive Corrugation and Straightening, Twist Extrusion (TE), etc. In this paper the twist extrusion method is analyzed in terms of SPD processing and the essential features from the "scientific" and "technological" viewpoint are compared with other SPD techniques. Results for commercial, 99.9 wt.% purity, copper processed by TE are reported to show the effectiveness of the method. UFG structure with an average grain size of ~0.3 μm was produced in Cu billets by TE processing. The mechanical properties in copper billets are near their saturation after two TE passes through a 60° die. Subsequent processing improves homogeneity and eliminates anisotropy. The homogeneity of strength for Cu after TE is lower than after ECAE by route B_C, but higher than after ECAE by route C. The homogeneity in ductility characteristics was of almost of inverse character. The comparison of mechanical properties inhomogeneity in Cu after TE and ECAE suggests that alternate processing by ECAE and TE should give the most uniform properties.

Introduction

Recently, it has been shown that severe plastic deformation (SPD) is very effective for obtaining nano/ultra fine-grained materials from initially coarse grained material and by powders/amorphous material consolidation. The obtained materials have outstanding mechanical properties [1-4]. The most developed SPD techniques are High Pressure Torsion (HPT) and Equal Channel Angular Extrusion (ECAE). Recently several new techniques have been developed: 3D Deformation, Accumulative Roll Bonding, Constrained Groove Pressing, Twist Extrusion (TE), etc.

The principle of TE is shown at fig. 1 [5, 6]. Under TE, a billet is extruded through a "twist die". Each billet's cross-section is deformed as follows: at first, it becomes twisted to some angle in one direction, and then – re-twisted to the same angle in the opposite direction. After each pass of the TE processing the billet's form and dimensions are maintained. This achieves severe values of strain to accumulate in a billet with no form changes. In [5, 6] it was shown that each physical cross-section of a billet is deformed in the same way as a thin disk during HPT processing, in the first approximation. Initially torsion to some angle in one direction is achieved, and then re-torsion to the same angle in the opposite direction, i.e. the deformation is cyclic with an amplitude of a quasi-monotone part equal to half the full strain. For the dies normally used, the accumulated strain per pass is about 1.2 [5]. As the billet's form does not change during the processing, it is possible to deform it repeatedly in order to accumulate strain, as in ECAE processing.

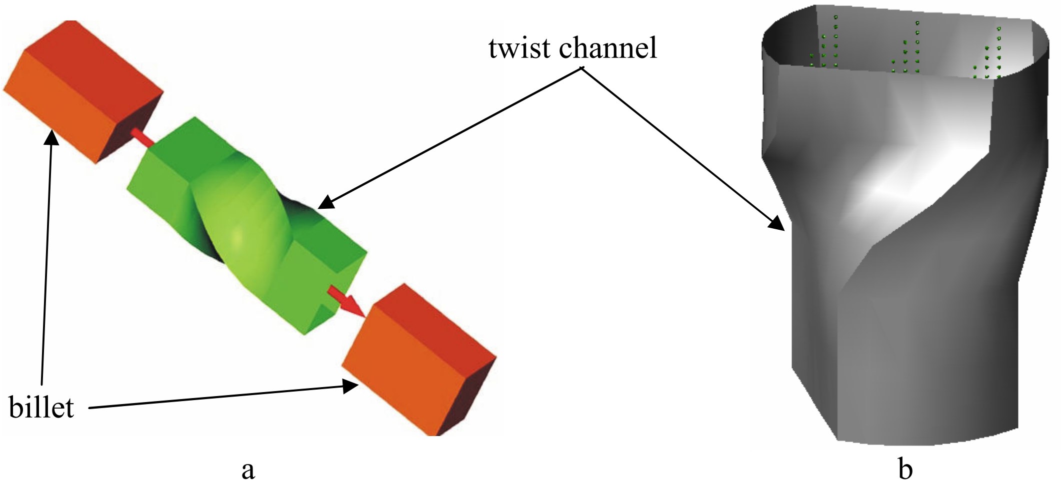

Fig. 1. Schemes of twist extrusion processing (a) and twist channel in a die (b)

It follows that TE can be considered as a "three-dimensional option of HPT". However, per se TE is "equal channel" extrusion (i.e. similar to ECAE) from a technological aspect. Very reasonable questions are: "what can this process give that is and why should one be concerned with it?"; TE has a number of peculiarities in both the stress-strain state and technological implementation so the process is attractive for both investigation and application.

Features of the Twist Extrusion: Method

From the viewpoint of the stress-strain state of a specimen, there are four important properties:

1) The simple shear plane in TE is perpendicular to the longitudinal axis of a specimen, instead of being at 45-60 degrees as in ECAE which allows new structures and textures to be obtained. Moreover, deformation by ECAE and TE in various combinations and regimes increases the number of possible deformation paths: besides those achievable by ECAE only, different combinations with paths achievable by TE (deformation through the same die and pipelined deformation through dies with oppositely twisted channels) can be obtained.

2) TE has a deformation gradient is quite steep in the cross-section, making it similar to HPT. There are still very few results on the effects of the deformation gradient on structure and properties, but there is enough evidence to show that increasing the gradient one can intensify grain refinement in metals and increase their ductility [7]. Note that experiments on Al alloys showed a quite homogeneous distribution of grain size and microhardness on a billet cross-section [8].

3) TE (unlike ECAE) is characterized by intense flows of material being deformed within the cross-sections of a billet. This homogenizes structure and properties of the material which is very important for deforming powder materials since it intensifies the consolidation processes.

4) TE is also characterized by a significant nonmonotone change of specimen surface when it goes through the die: on entering the twisted region, a billet's surface expands (by 70-80%), and it returns to the original size on exiting the region. Such changes affect the metal's structure and could allow the insertion of various alloying elements into surface layers of the billet.

From the technological viewpoint, TE has the following properties:

1) The size of the terminating distorted areas of the specimen, that is the head and rear parts, of the billet, is much smaller under TE than under ECAE [6], which is especially important when doing repeated runs.

2) TE can handle profile billets including those with an axial channel [5].

3) TE can easily be installed on any standard extrusion equipment by replacing a standard reduction die with a twist die.

4) TE (unlike ECAE) does not change the direction of a billet's movement, which allows TE to be easily embedded into existing industrial lines.

We thank Dr. Rack who pointed out the last two properties and for valuable comments about TE.

Due to the these features, TE appears very promising for obtaining UFG materials, via both bulk billets' grain refinement and powder consolidation. Experiments on miscellaneous metals [5-13], shown the effectiveness of TE in grain refinement, improving mechanical properties [8, 11] and prove TE to be an effective SPD technique.

Features of Twist Extrusion: Structures

The response of the copper structure on twist extrusion processing. To study the development of copper's structure during deformation, annealed Cu specimens (*T*=500°C, 4 hours, *e*=0) were used. Several deformation cycles were applied and the deformed specimens were examined by TEM which showed that after two passes a cellular structure was formed. A considerable number of shear band sections (fig. 2[1]) were observed with 0.3…0.5 μm distance between high-angular dislocation walls. Normally, the high-angular dislocation walls were paired, while sometimes two types of paired high-angular dislocation walls were observed. After three TE passes, the deformation structure became more uniform but single cells were still observed. Overall, the structure consisted of shear bands oriented in two planes of the subgrains. There were also well-shaped grains. The average size of the structural element was 0.3 μm.

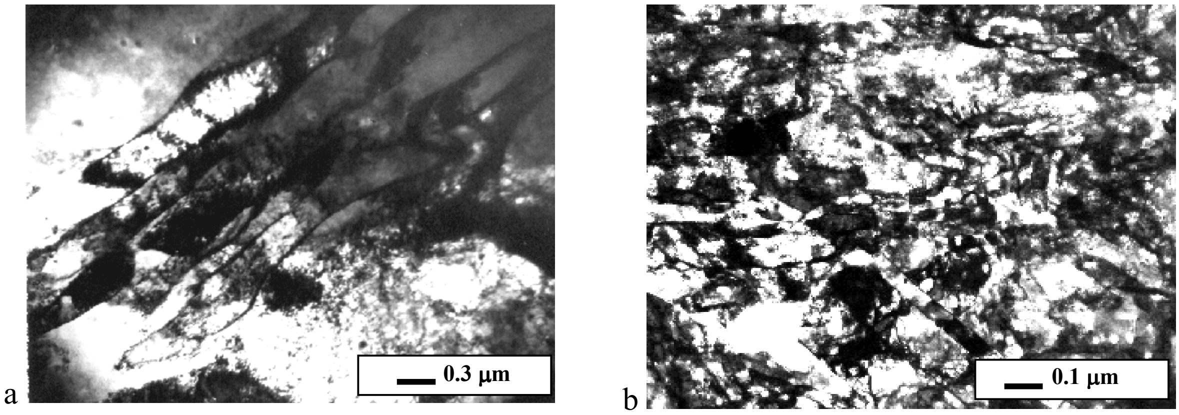

Fig. 2. Microstructure of copper after two (a) and three (b) TE passes

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[1] Measurements and electronic microscopy were performed by Prof. S. Dobatkin, Moscow Institute of Steels and Alloys, Russia.

Features of Twist Extrusion: Properties

The effect of twist extrusion on the mechanical properties of copper. Usually, the mechanical properties are determined with only one or two standard specimens are because of dimensions of such specimens are comparable with dimensions of SPD processed billets. These undoubtedly important data make it possible to estimate the efficiency of the SPD processing, but do not show the distribution of mechanical properties across the billets.

Recently a few reports on the properties and structural distribution in ECAE processed billets were published [15-18]. The uniformity of TE processing is an even more important question to be addressed as the process seems to give a non-uniform strain distribution. [5, 6] showed considerable, but not dramatic, theoretical heterogeneity of strain distribution in a billet, which should primarily manifest itself in heterogeneity of mechanical properties; but hardness measurements on the cross section of Ti and Al-alloys billets showed a quite uniform distribution. The TE processed Al alloys also revealed a quite uniform grain size distribution on the cross-section of the billets. The results of experimental study (in tensile tests of micro-specimens) of mechanical properties homogeneity and anisotropy in commercially pure copper billets after twist extrusion processing are given below.

The as-received 30 mm diameter hot extruded rods of 99.9 wt.% purity commercial copper were machined to a diameter 28 mm and extruded through a conventional conical die at 250ºC to the profile shown at Fig. 3. Twist extrusion of the Cu billets was done at room temperature through a counterclockwise twisted die with angle of twist line slope 60º. Billet (a) was extruded with 2 TE passes (accumulated strain e~2.4) while billet (b) was subjected to 4 TE passes (accumulated strain e~4.8). All the processing was done with s backpressure of about 200 MPa.

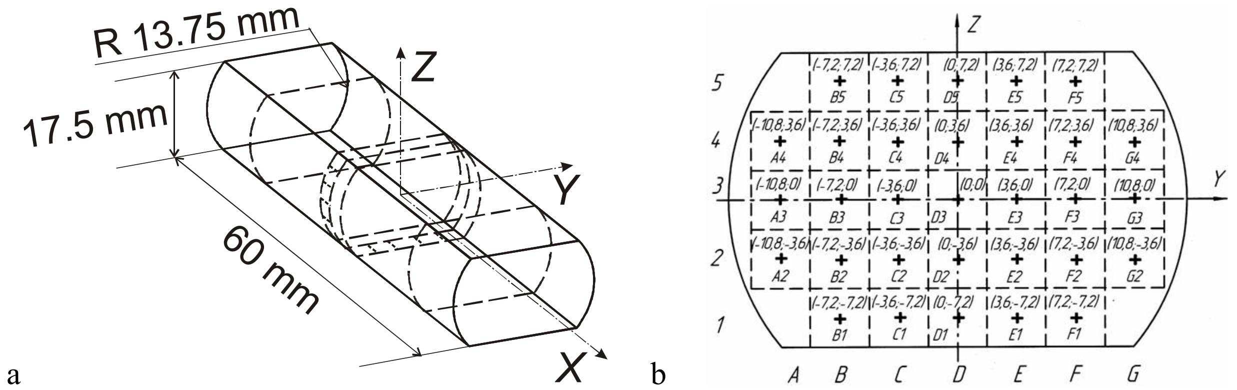


Fig. 3. (a) Scheme and coordinate system of a billet for twist extrusion; *X* is direction of extrusion; dashed lines show cutting lines for tensile test specimens. (b) Plan of billet cutting on a cross-section and map of tensile specimens.

To study the homogeneity of mechanical properties across the billets' cross-sections, two sections were cut from each billet up and down from the stated origin of coordinates as shown at Fig. 3 a. 31 small-size tensile test specimens having a nominal diameter of 1.5 mm and a gage length of 7.5 mm were cut out from each the sections parallel to the extrusion axis *X* as shown in Fig. 3 b.

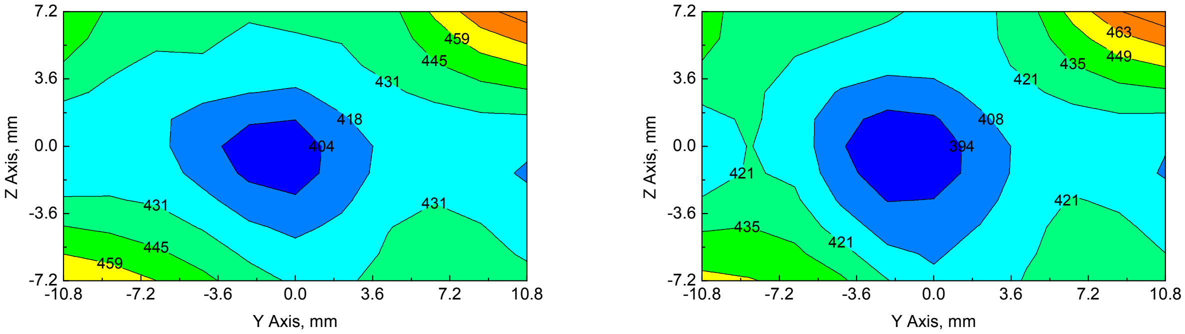
In [10, 11] anisotropy in mechanical properties observed in commercially pure titanium billets after twist extrusion processing was reported.

In order to study the same effect on the mechanical properties of copper, specimens for mechanical tests were also in the transverse direction, parallel to *Y* and *Z* axes according to scheme shown in Fig. 3a.

All tests were carried out at room temperature at a strain rate ~ 10^{-3} s^{-1}. The following mechanical properties were determined in the tests: ultimate tensile strength (UTS), yield strength (YS), elongation to failure and reduction in area. As a measure of the mechanical properties heterogeneity, an index of variation *V* expressed as a ratio of standard deviation *SD* to a parameter average value $\bar{x}$ was used:

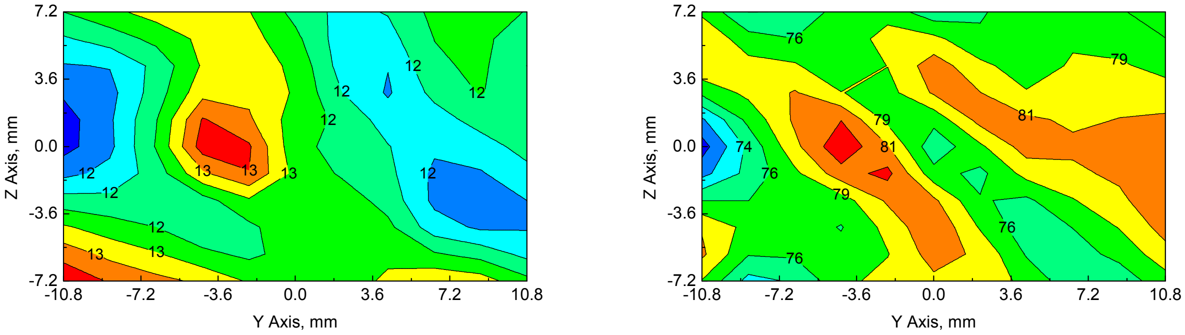
$$V = \frac{SD}{\bar{x}} \cdot 100\%. \tag{1}$$

The tensile tests data of samples cut along the extrusion axis are summarized at figures 4 and 5.



Mean 430.4 MPa; Range 73 MPa
(a)

Mean 419.3 MPa; Range 77 MPa
(b)



Mean 12.5 %; Range 2.4 %
(c)

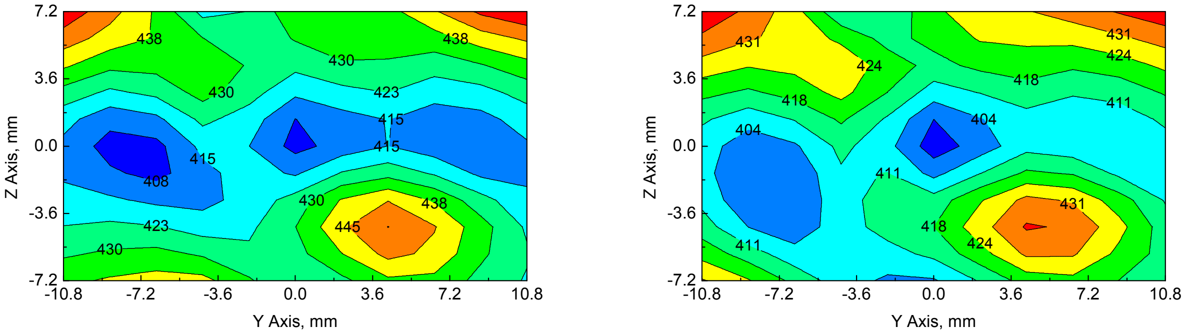
Mean 78.1 %; Range 18.0 %
(d)

Fig. 4. Tensile test data on the variation of mechanical properties on the Cu billet cross-section after 2 TE passes: (a) – Ultimate Tensile Strength, MPa; (b) – Yield Strength, MPa; (c) – Elongation to Failure, %; (d) – Reduction in area, %;

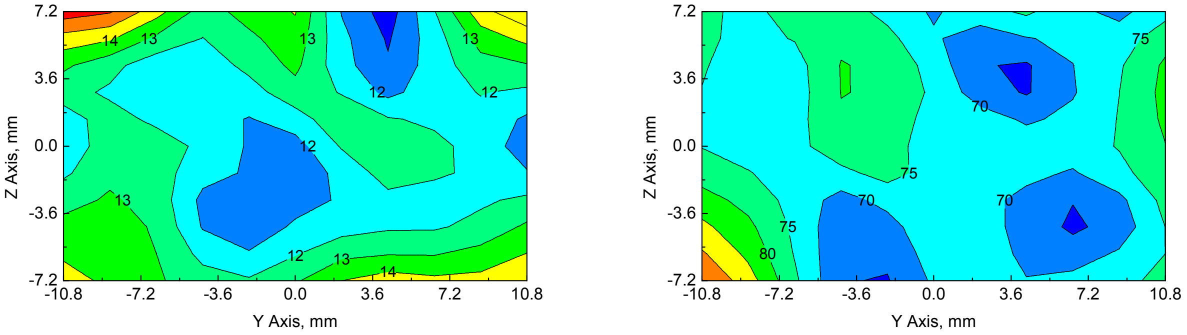
Fig. 4 shows that on the billet cross-section after two TE passes location of the maximum ductility strictly corresponds to the location of the minimum strength. Note that these areas are located near the billet’s vertical axis.

After four TE passes (Fig. 5), the areas of maximum ductility do not corresponds to the areas of minimum strength as closely as observed after two passes. The areas were shifted from the billet’s vertical axis area, i.e. randomization and homogenization of the mechanical properties occurs on the cross-section.

The mean values of mechanical properties were at about the same level but the range of the variation within the cross-section was about two times lower.



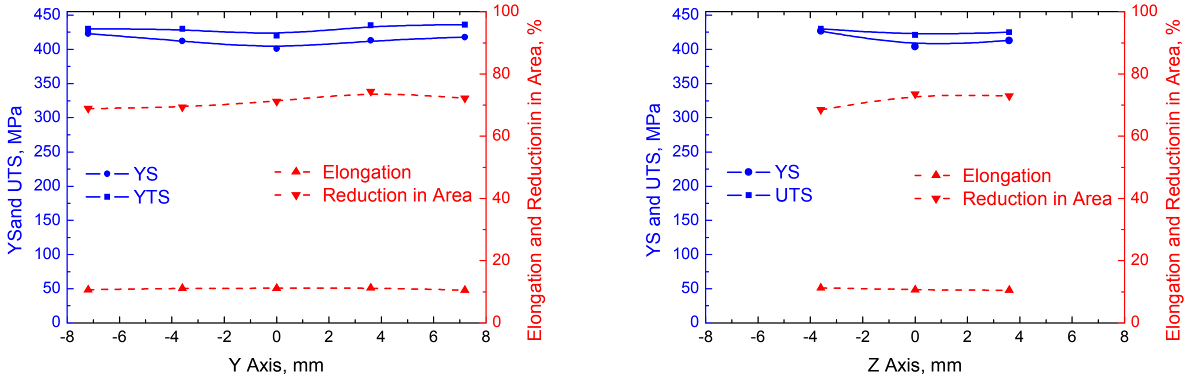
a Mean 426.1 MPa; Range 47 MPa b Mean 415.7 MPa; Range 43 MPa



c Mean 12.4 %; Range 4.3 % d Mean 73.4 %; Range 20.7 %

Fig. 5. Tensile test data on the variation of mechanical properties on the Cu billet cross-section after 4 TE passes: (a) – Ultimate Tensile Strength, MPa; (b) – Yield Strength, MPa; (c) – Elongation to Failure, %; (d) – Reduction in area, %;

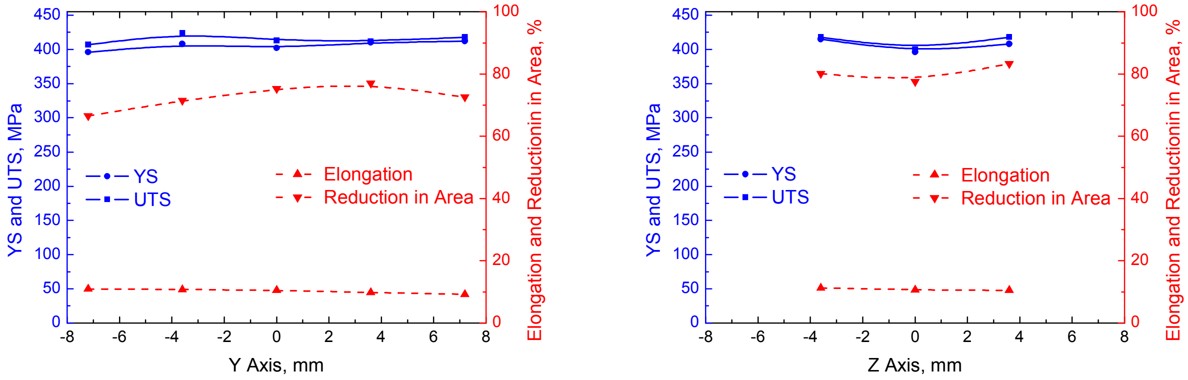
The mechanical properties variation perpendicular to the extrusion axis is shown in Figs 6 and 7.



YS: Mean 413.4 MPa; Range 22 MPa;
UTS: Mean 430.2 MPa; Range 16 MPa;
Elongation: Mean 10.9 %; Range 0.8 %;
Reduction in area: Mean 71.2 %; Range 5.4 %;
(a)

YS: Mean 414.7 MPa; Range 23 MPa;
UTS: Mean 425.3 MPa; Range 9 MPa; .
Elongation: Mean 10.8 %; Range 0.8 %;
Reduction in area: Mean 71.7 %; Range 5.1 %;
(b)

Fig. 6. Tensile tests data on mechanical properties in transverse direction in Cu billet after 2 TE passes: (a) – direction parallel to Z axes; (b) – direction parallel to Y axes;



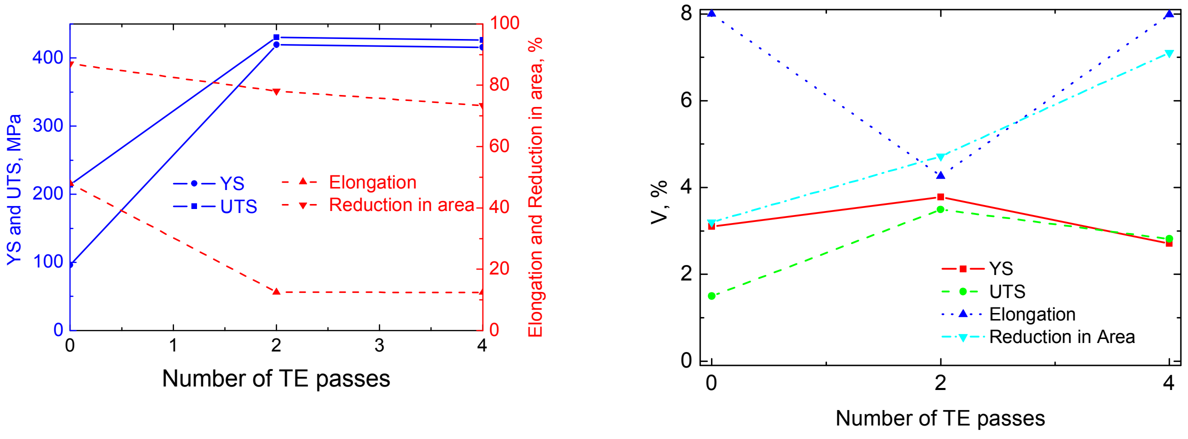
YS: Mean 405.6 MPa; Range 16 MPa;
UTS: Mean 414.8 MPa; Range 17 MPa;
Elongation: Mean 10.2 %; Range 1.7 %;
Reduction in area: Mean 72.6 %; Range 10.4 %.
(a)

YS: Mean 406.3 MPa; Range 19 MPa;
UTS: Mean 412.8 MPa; Range 18 MPa;
Elongation: Mean 10.8 %; Range 0.8 %;
Reduction in area: Mean 80.3 %; Range 5.7 %.
(b)

Fig. 7. Tensile tests data on mechanical properties distribution in transversal direction in Cu billet after 4 TE passes: (a) – direction parallel to Z axes; (b) – direction parallel to Y axes;

From these figures, it can be seen see that the mechanical properties are distributed homogeneously in both directions perpendicular to the extrusion axis and are of similar values to those in the longitudinal direction. This means that anisotropy in mechanical properties was almost absent. The general tendency in the development of mechanical properties with an increasing of number of twist extrusion passes is similar: almost constant mean values with a narrowed range.

The Summary of mean values of mechanical properties with number of TE passes increasing is shown at Fig. 8 a.



(a) (b)

Fig. 8. Summary of mean values of tensile tests data (a) and heterogeneity indexes (b) for Cu billets after twist extrusion processing;

From this figure, one can see that the mechanical properties in copper billets are almost saturated after two passes of twist extrusion through the 60º die. Subsequent processing does not significantly affect the mean values of the mechanical properties of commercially pure copper, but increases the homogeneity of strength (Fig. 8b). Heterogeneity indexes in strength are very close to one another for both billets' conditions and for YS after four TE passes the index was even lower than for the initial condition. Homogeneity in elongation reduces twice after two TE passes and is close to the initial value after four passes, while for reduction in area it decreases monotonously with the number of TE passes. This is typical for experimental practice. It is interesting to note that the homogeneity in reduction in area after four TE passes became notably higher (~15%) than homogeneity in elongation.

Comparison of twist extrusion and equal channel angular extrusion processing. The comparison is based on data reported in [16], where authors used the same material and tests conditions. As stated earlier the estimated true strain after one TE pass is e≈1.2. In the case of ECAE through a 90º die, true strain is e≈1.15 as reported in [19, 20]. Therefore, the values of true strain imposed by one pass of TE and ECAE are comparable and number of passes in these processes will produce similar true strain values.

After two passes, heterogeneity indexes values for strength properties after TE processing are higher at about 20% than after ECAE processing by route B_C, but about two times lower than after ECAE processing by route C. After four passes, *V* for TE processed copper became about the same as for copper processed by ECAE using route B_C, but still much lower than if processed by ECAE route C. Note that in this condition heterogeneity indexes for TE and ECAE route C processing tend to fall while at ECAE route B_C processing they tend to increase. The *V* value for elongation after two TE passes is lower at about 75% than after two passes of ECAE processing by both routes, but became about 15% higher after four passes. The heterogeneity index after two TE passes for reduction in area is also lower than after both routes of ECAE. After four passes, its value became higher than *V* after ECAE by route C, but lower than ECAE by route B_C.

The mean value of ultimate tensile strength in copper after TE processing is slightly higher than one after ECAE processing by route C, but lower than ECAE by route B_C. Surfaces of strength properties distribution in longitudinal direction after twist extrusion seem to be mostly convex upwards while after ECAE processing they are convex downwards (especially when route B_C is used) [16]. (This refers to the "surface" 3D representation of the properties distribution in a billet cross-section; so "convex upwards" means that a property in the centre is superior to the property on the periphery and "convex downwards" means that a property in the centre is lower than the same property on the periphery). For ductility characteristics, an inverse picture can be observed. Therefore, it could be expected that alternate processing by ECAE and TE should give more uniform properties.

Conclusions

1. The twist extrusion method was analyzed in terms of severe plastic deformation processing. The essential features from both a "scientific" and a "technological" point of view of TE in comparison with other SPD techniques are shown.

2. Some results on commercial, 99.9 wt.% purity, copper processing by TE are reported to demonstrate features obtained by twist extrusion:

a) Ultra fine-grained structure with an average size of the structural element of about 0.3 μm was formed in copper billets by means of twist extrusion processing.

b) The mechanical properties in copper billets are almost saturated after two passes of twist extrusion through a 60° die. Subsequent processing does not significantly influence mean values, but improves the homogeneity of mechanical properties.

c) After four passes of twist extrusion, the mechanical properties are quite homogeneously distributed within the billets' cross-section, and anisotropy was eliminated. Local extremums of mechanical properties are located outside of billets' extrusion axis area in spite of the theoretical distribution.

3. Homogeneity in strength for copper after twist extrusion processing is lower than after ECAE processing by route B_C, but higher than after ECAE processing by route C. Homogeneity in ductility after TE processing was of mostly inverse character: lower than after ECAE processing by route C, but higher than after ECAE processing by route B_C.

4. A comparison of mechanical properties distribution in copper after TE and ECAE processing suggests that alternate processing by ECAE and TE should give more uniform properties throughout a billet's cross-section.

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