Applications of Twist extrusion

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Outline

• TE
• Mechanics of the TE
• Two in one
  • Fragmentation
  • Consolidation
• Rolling with shear
• Main result
The idea of TE:

Twist channel
The idea of TE:

The shape and the dimensions of the work-piece do not change!

Equivalent strain $e \sim 1$

Twist channel
The idea of TE:

Equivalent strain e~2

Repeated twist extrusion leads to grain refinement
Peculiarities of the TE
Shear plane

The simple shear plane in TE is perpendicular to the axis of the specimen, instead of being at 45-60 degrees as in ECAE. This allows us to obtain new structures and textures.
TE is characterized by intense flows of material being deformed within cross-sections of the billet. This is very important when deforming powder materials since it intensifies consolidation processes.
Possible cross-sections of final product

- TE can handle profile billets including those with the axial channel.

- TE does not change the direction of the billet moving which allows one to embed TE into already existing industrial lines.
- TE can easily be performed on any standard extrusion equipment by putting a twist die in place of the standard die.
Waste of metal at TE and ECAP

Form of the TE processed billets: amount of waste material
Waste of metal at TE

Form of the TE processed billets (Cp Ti Grade 2)

As-machined for processing

After I TE pass

After IV TE passes

After VI TE passes
Change of specimen surface

TE is characterized by a significant nonmonotone change of specimen surface while the specimen goes through the die. Such changes affect metal structure and could allow one to insert various alloying elements into surface layers of the billet.
Twist extrusion easy to install on the standard installation for direct extrusion
Mechanics of the TE
VELOCITY FIELD

\[ V = V_1 + V_2 \]

Velocity field = Twist flow + Flow within the Specimen cross-section
Experimental investigation of the process's mechanics

Specimen with the fibers
Experimental investigation of the process’s mechanics
Finding of the velocity field from the experimental stream lines

Experimental stream line
Theoretical stream line
Strain distribution

\[ \varepsilon_{i_{\text{max}}} = \tan \beta_{\text{max}}; \]
\[ \Lambda_{\text{max}} = \sqrt{3} \tan \beta_{\text{max}}; \]

\[ \varepsilon_{i_{\text{min}}} = 0.4 + 0.1 \tan \beta_{\text{max}}; \]
\[ \Lambda_{\text{min}} = \sqrt{3}(0.4 + 0.1 \tan \beta_{\text{max}}); \]
Mathematical simulation
# Methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>FEM</td>
<td><em>Physics and technique of high pressure</em> (2003), №4</td>
</tr>
</tbody>
</table>
Simulation of grained refinement. Cellular model

- Initial grain
- Plastic deformation $\Delta \sigma$
- Deformation continues Rotation moments appear
- Moment stresses relax through grain splitting

Process:
1. Outer stress $\Delta \sigma^0$
2. Stress on each element $\sigma^n$
3. Extension $D^n \Delta t$ and rotation $\Omega^n \Delta t$ of each element
4. RVE initial state
5. RVE new state
Simulation of grained refinement. Cellular model

Grain size, \( \mu m \):
Continuum approach

Specific fragment boundary area $S$

Continuum model of material

Porosity $\Theta$
Kinetic equations of the model.

\[
\frac{d\bar{N}}{d\gamma} = (C_1 + C_2 C_5 \bar{N}_b)F(\bar{S}) - (C_3 + C_4)\bar{N} \\
\frac{d\bar{N}_b}{d\gamma} = C_4 \bar{N} - C_5 \bar{N}_b \\
\frac{d\bar{S}}{d\gamma} = \frac{C_5 \bar{N}_b}{\bar{S} + \bar{S}_0} \\
\frac{d\Theta}{d\gamma} = \frac{3}{C_3 \bar{N}^2 d_c^{-3} v - C_6 \Theta}
\]

- \(N\) - number of AZ per unit of the cross section area
- \(S\) - total length of the high-angle boundaries per unit of the cross section area
- \(\bar{S}_0\) - number of embryo of the high-angle boundary per unit of the cross section area
- \(\bar{S}_0\) - total length of the high-angle boundaries per unit of the cross section area
- \(N_p\) - number of voids per unit of the cross section area
- \(\Theta\) - porosity

\[
d = \frac{1}{S}
\]
Simple shear provide the most intensive grain refinement process.

$\theta$ – porosity

$d$ – average grain size

$P_{n\theta} = 600 \text{ MPa}$
Pressure leads to increasing the intensity of grain refinement and repression microporosity formation

\[ P_{n\theta} \approx 0.1 \text{ MPa} \]

\[ P_{n\theta} = 1000 \text{ MPa} \]

\( \theta \) – porosity

\( d \) – average grain size
Resume
Metal Deformation under Twist Extrusion

We showed that most of the deformation achieved by Twist Extrusion is Simple Shear at the ends of the twist channel.
We showed that most of the deformation achieved by Twist Extrusion is Simple Shear at the ends of the twist channel.
Influence of TE path

Clockwise

Accumulated strain

Non-accumulative strain

Contraclockwise

Number of TE passes

Twist line slope angle, degrees

Number of TE passes

-60  -40  -20  0  20  40  60

-0.6  -0.4  -0.2  0.0  0.2  0.4  0.6

0  1  2  3  4  5  6  7  8  9  10
Powder consolidation

\[ \frac{p^2}{\Psi(\Theta)} + \frac{\tau^2}{\varphi(\Theta)} = (1-\Theta)\left(k_0 + \alpha p^2\right) \]

Yield surfaces for the powder at the various levels of porosity:
1-30%, 2-20%, 3-10%, 4-3%.
Porosity produced by strain and consolidation by strain under pressure.
Twist Extrusion: Two in One

- Consolidation
- Twist Extrusion
- Fragmentation
Fragmentation

- Grains refinement. UFG materials
- Breaking of a brittle particles
TE processing of $Cp$ Ti and Ti alloys
Twist extrusion of the Ti

Initial state

After 3 passes

Results are obtained with Professor V.Stolyarov, IPSM UGATU, Russia
Yield strength data

Cold TE under pressure 700 MPa

- as-received (longitudinal)
- as-received (transverse)
- 3 passes TE + annealing
- 3 passes TE + cold rolling (reduction 50%)

Warm TE

- as-received (longitudinal)
- as-received (transverse)
- 4 passes TE (400°C) + annealing
- 4 passes TE (400°C) + warm rolling (reduction 80%) + annealing

Obtained with Prof. V.Stolyarov, IPAM UGATU, Russia
Uniform elongation

Cold TE under pressure 700 MPa

Warm TE

Obtained with Prof. V. Stolyarov, IPSM UGATU, Russia
Plates for traumatology and orthopedic are made from UFG titanium

<table>
<thead>
<tr>
<th>Properties</th>
<th>CpTi</th>
<th>CpTi After treated</th>
<th>Ti6-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield stress, MPa</td>
<td>375</td>
<td>760</td>
<td>850</td>
</tr>
<tr>
<td>Uniform elongation, %</td>
<td>22</td>
<td>15</td>
<td>12</td>
</tr>
</tbody>
</table>
TE processing of Cu alloys
Cu, 2 TE passes through 60 deg. die

- YS distribution
  - Mean: 419.32
  - Min: 385
  - Max: 462
  - Range: 77

- UTS distribution
  - Mean: 430.35
  - Min: 396
  - Max: 469
  - Range: 73

Obtained with Dr. A.I. Korshunov, Russian Federal Nuclear Center VNIIEF, Sarov, Russia
Cu, 2 TE passes through 60 deg. die

- Elongation distribution

<table>
<thead>
<tr>
<th>Mean</th>
<th>Min</th>
<th>Max</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.47</td>
<td>11.4</td>
<td>13.8</td>
<td>2.4</td>
</tr>
</tbody>
</table>

- Reduction in area distribution

<table>
<thead>
<tr>
<th>Mean</th>
<th>Min</th>
<th>Max</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>78.11</td>
<td>67.4</td>
<td>85.4</td>
<td>18</td>
</tr>
</tbody>
</table>

Obtained with Dr. A.I. Korshunov, Russian Federal Nuclear Center VNIEF, Sarov, Russia
Cu, 4 TE passes through 60 deg. die

<table>
<thead>
<tr>
<th>Mean</th>
<th>Min</th>
<th>Max</th>
<th>Range</th>
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</thead>
<tbody>
<tr>
<td>415.68</td>
<td>393</td>
<td>436</td>
<td>43</td>
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</table>

- **YS distribution**

<table>
<thead>
<tr>
<th>Mean</th>
<th>Min</th>
<th>Max</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>426.13</td>
<td>403</td>
<td>450</td>
<td>47</td>
</tr>
</tbody>
</table>

- **UTS distribution**

Obtained with Dr. A.I. Korshunov, Russian Federal Nuclear Center VNIEF, Sarov, Russia
Cu, summary of mechanical properties after TE processing

- Mean values of tensile tests data

Obtained with Dr. A.I. Korshunov, Russian Federal Nuclear Center VNIEF, Sarov, Russia
# Twist extrusion + Cold rolling of the Cu

<table>
<thead>
<tr>
<th>State</th>
<th>Section</th>
<th>$H_\mu$, MPa</th>
<th>Minimal grain size $b$, $\mu$m</th>
<th>Maximal grain size $l$, $\mu$m</th>
<th>$k=l/b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>THE</td>
<td>normal to THE axis</td>
<td>1080</td>
<td>0.26</td>
<td>0.64</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>parallel to THE axis</td>
<td>1040</td>
<td>0.18</td>
<td>1.01</td>
<td>5.6</td>
</tr>
<tr>
<td>Rolling normal to THE axis</td>
<td>parallel to rolling axis</td>
<td>1270</td>
<td>0.13</td>
<td>0.24</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td>normal to rolling axis</td>
<td>1230</td>
<td>0.12</td>
<td>0.82</td>
<td>6.8</td>
</tr>
<tr>
<td>Rolling in parallel to THE axis, centre</td>
<td>parallel to rolling axis</td>
<td>1300</td>
<td>0.09</td>
<td>0.24</td>
<td>2.7</td>
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<tr>
<td></td>
<td>normal to rolling axis</td>
<td>1230</td>
<td>0.13</td>
<td>0.79</td>
<td>6.1</td>
</tr>
<tr>
<td>Rolling in parallel to THE axis, edge</td>
<td>parallel to rolling axis</td>
<td>1320</td>
<td>0.11</td>
<td>0.26</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>normal to rolling axis</td>
<td>1280</td>
<td>0.12</td>
<td>0.74</td>
<td>6.2</td>
</tr>
</tbody>
</table>
Twist Extrusion of phosphorous Cu (9% P)

Initial state

1 pass

<table>
<thead>
<tr>
<th>Treatment</th>
<th>YS, MPa</th>
<th>δ, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Extrusion, μ=4.5</td>
<td>360</td>
<td>4</td>
</tr>
<tr>
<td>Twist Extrusion</td>
<td>420</td>
<td>11</td>
</tr>
</tbody>
</table>

Back pressure = 200 MPa, T= 623 K
TE processing of Al alloys
Twist extrusion of the Al-Mg-Sc-Zr alloy

Chemical composition:
Al - 3 wt.%Mg - 0,3 wt.%Sc – 0,10 wt.%Zr

Initial grain size $d_{av}=100 \ \mu m$

Standard direct extrusion:
$T=280-300^\circ C$

$d_{av}=0.455 \ \mu m$
$d_{min}=0.129 \mu m$
$d_{max}=1.032 \ \mu m$

Twist extrusion: $T=280-300^\circ C$
5 passes CW + 1 pass CCW

$d_{av}=0.325 \ \mu m$
$d_{min}=0.077 \mu m$
$d_{max}=0.671 \ \mu m$

Results are obtained with Professor Y. Mil'man, IPM NASU, Ukraine
Twist extrusion of the Al-Mg-Sc-ZR alloys

Chemical composition:
Al – 3 wt.%Mg - 0,3 wt.%Sc – 0,15 wt.%Zr

SEM, As-deformed structure,
TE – 5 passes, $T_{\text{def}}=280-300^\circ\text{C}$
Longitudinal section

Results are obtained with Professor Y. Mil’man, IPM NASU, Ukraine
TE of recycle Al alloy

Al-88% ; Si-9.5%

\[ \sigma_y = 50 \text{MPa} \quad \delta = 1\% \]

\[ \sigma_y = 205 \text{MPa} \quad \delta = 14\% \]
Consolidation
Consolidation of nanostructural Cu powder by Twist Extrusion

Back pressure = 200 MPa, T= 473 K
Initial powder, D=250 µm

1 pass
2 passes
3 passes+
deformation φ12 мм

99,2%
Density 99,6%
99,2%
Consolidation of nanostructural Cu powder by Twist Extrusion

<table>
<thead>
<tr>
<th>State</th>
<th>Density, %</th>
<th>Diameter of the coherent-scattering region, L, nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>powder</td>
<td>-</td>
<td>100</td>
</tr>
<tr>
<td>TE, 1 path</td>
<td>99.2</td>
<td>36</td>
</tr>
<tr>
<td>TE, 2 paths</td>
<td>99.6</td>
<td>55</td>
</tr>
</tbody>
</table>
Consolidation of amorphous Al$_{86}$Ni$_6$Co$_2$Gd$_6$ melt-spun ribbons by Twist Extrusion

XRD traces from consolidates produced by TE: (a) at 523 K (3 passes) and (b) at 573 K (4 passes).

Microhardness of the amorphous ribbons before and after consolidation (left axis) and the volume fraction crystallized in the compacted samples (right axis) as function of the extrusion temperature. Numbers represent the number of TE passes.
As-prepared melt-spun amorphous $\text{Al}_{86}\text{Gd}_6\text{Ni}_6\text{Co}_2$ ribbon (a) and TE-processed billet (b) compacted at 523 K.
a) Compacted specimen (a), c) macrostructure of central part (b) peripheric part (c).
Consolidation of the cutting of the recycled Al alloy by Twist Extrusion

d=12 mm

Yield stress = 180-220 MPa;  El= 20-24%
Consolidation of the cutting of the recycled Mg alloy by Twist Extrusion
Acknowledgments

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