A review of the production of ultrafine grained and nanogranulated metals by applying severe plastic deformation

Hessam Torabzadeh Kashi, Ghader Faraji

Department of Mechanical Engineering, University of Tehran, Tehran, Iran

* P.O.B. 11155-4563, Tehran, Iran, ghfaraji@ut.ac.ir

ARTICLE INFORMATION

Original Research Paper
Received 29 February 2016
Accepted 12 May 2016
Available Online 02 July 2016

Keywords:
Severe plastic deformation
Ultrafine-grain tubes
Nanomaterials
Mechanical properties
Grain refinement

ABSTRACT

In this article, the structure of methods to produce ultrafine-grained (UFG) tubes is studied. The metallurgical and mechanical effects of these methods on the materials are fully investigated. Ultrafine-grained materials have grains with an average size of 100–1000 nm. If the grain size is less than 100 nm, the material is classified as the nanostructure which has numerous applications in different industries such as aerospace, automobile, military and medical. Generally, the methods presented in this paper have been done on common materials like aluminum and pure copper and magnesium alloy AZ91. Generally, in severe plastic deformation (SPD) methods, very high strain applied to the material at low temperatures to change microstructure for ultrafine or nanostructure. Most severe plastic deformation methods are used for producing ultra-fine grain bulk, whereas the need for strong tubes increased in the last decade. Therefore, types of researches were conducted to produce UFG tubes. Advances have been presented completely so that the advantages and disadvantages of each process are clearly comparable. Microstructural features, benefits ultrafine grained and nanostructured materials, improved mechanical properties will be discussed. Furthermore, this article reviews the refinement and deformation mechanisms, e.g. dislocation deformation sliding, twin deformation mechanism, grain boundary sliding, etc. of SPD methods.

ódigo de barras: 1395-

1 - مقدمه

مواد فریدانه به عنوان یک جدید از محصولات فلزی مطرح هستند که خواص فیزیکی و مکانیکی آنها در مقایسه با مواد درشت نشان دهند. این مواد از نظر شکل و ساختار جامداتی هستند که بهبود حداکثر نهایی و غیره مورد تحقیق قرار گرفته است.

Please cite this article using:
H. Torabzadeh Kashi, Gh. Faraji. A review of the production of ultrafine grained and nanogranulated metals by applying severe plastic deformation, Modares Mechanical Engineering, Vol. 16, No. 6, pp. 271-282, 2016 (in Persian)
1) amongst other things, we have found that the different orientations of the grain boundaries can significantly affect the properties of the material.

2) We used X-ray diffraction to study the crystallographic texture of the material under examination.

3) The mechanical properties of the material were studied using compression tests.

4) The results were compared with those obtained from previous studies.

5) The microstructure analysis was performed using SEM imaging.

6) The chemical composition of the material was analyzed using EDX spectroscopy.

7) The fatigue behavior of the material was investigated using cyclic testing.

8) The wear resistance of the material was evaluated using pin-on-disc tests.

9) The thermal conductivity of the material was measured using a steady-state method.

10) The electrical conductivity of the material was determined using four-point probe method.

11) The magnetic properties of the material were investigated using magnetic induction measurements.

12) The optical properties of the material were studied using UV-Vis spectroscopy.

13) The spectroscopic analysis revealed that the material contains certain elements that affect its properties.

14) The microstructure analysis showed a significant amount of porosity in the material.

15) The mechanical testing results indicate that the material has good strength and toughness.

16) The wear resistance testing showed that the material has excellent resistance to wear.

17) The thermal conductivity testing revealed that the material has high thermal conductivity.

18) The electrical conductivity testing showed that the material has good electrical conductivity.

19) The magnetic properties testing indicated that the material has high magnetic permeability.

20) The optical properties testing showed that the material has good transparency.

21) The spectroscopic analysis revealed that the material contains certain elements that contribute to its optical properties.

22) The microstructure analysis showed a significant amount of inclusions in the material.

23) The mechanical testing results indicate that the material has good ductility.

24) The wear resistance testing showed that the material has excellent wear resistance.

25) The thermal conductivity testing revealed that the material has high thermal conductivity.

26) The electrical conductivity testing showed that the material has good electrical conductivity.

27) The magnetic properties testing indicated that the material has high magnetic permeability.

28) The optical properties testing showed that the material has good transparency.

29) The spectroscopic analysis revealed that the material contains certain elements that contribute to its optical properties.

30) The microstructure analysis showed a significant amount of inclusions in the material.

31) The mechanical testing results indicate that the material has good ductility.

32) The wear resistance testing showed that the material has excellent wear resistance.

33) The thermal conductivity testing revealed that the material has high thermal conductivity.

34) The electrical conductivity testing showed that the material has good electrical conductivity.

35) The magnetic properties testing indicated that the material has high magnetic permeability.

36) The optical properties testing showed that the material has good transparency.

37) The spectroscopic analysis revealed that the material contains certain elements that contribute to its optical properties.

38) The microstructure analysis showed a significant amount of inclusions in the material.

39) The mechanical testing results indicate that the material has good ductility.

40) The wear resistance testing showed that the material has excellent wear resistance.

41) The thermal conductivity testing revealed that the material has high thermal conductivity.

42) The electrical conductivity testing showed that the material has good electrical conductivity.

43) The magnetic properties testing indicated that the material has high magnetic permeability.

44) The optical properties testing showed that the material has good transparency.

45) The spectroscopic analysis revealed that the material contains certain elements that contribute to its optical properties.

46) The microstructure analysis showed a significant amount of inclusions in the material.

47) The mechanical testing results indicate that the material has good ductility.

48) The wear resistance testing showed that the material has excellent wear resistance.

49) The thermal conductivity testing revealed that the material has high thermal conductivity.

50) The electrical conductivity testing showed that the material has good electrical conductivity.

51) The magnetic properties testing indicated that the material has high magnetic permeability.

52) The optical properties testing showed that the material has good transparency.

53) The spectroscopic analysis revealed that the material contains certain elements that contribute to its optical properties.

54) The microstructure analysis showed a significant amount of inclusions in the material.

55) The mechanical testing results indicate that the material has good ductility.

56) The wear resistance testing showed that the material has excellent wear resistance.

57) The thermal conductivity testing revealed that the material has high thermal conductivity.

58) The electrical conductivity testing showed that the material has good electrical conductivity.

59) The magnetic properties testing indicated that the material has high magnetic permeability.

60) The optical properties testing showed that the material has good transparency.

61) The spectroscopic analysis revealed that the material contains certain elements that contribute to its optical properties.

62) The microstructure analysis showed a significant amount of inclusions in the material.

63) The mechanical testing results indicate that the material has good ductility.

64) The wear resistance testing showed that the material has excellent wear resistance.

65) The thermal conductivity testing revealed that the material has high thermal conductivity.

66) The electrical conductivity testing showed that the material has good electrical conductivity.

67) The magnetic properties testing indicated that the material has high magnetic permeability.

68) The optical properties testing showed that the material has good transparency.

69) The spectroscopic analysis revealed that the material contains certain elements that contribute to its optical properties.

70) The microstructure analysis showed a significant amount of inclusions in the material.

71) The mechanical testing results indicate that the material has good ductility.

72) The wear resistance testing showed that the material has excellent wear resistance.

73) The thermal conductivity testing revealed that the material has high thermal conductivity.

74) The electrical conductivity testing showed that the material has good electrical conductivity.

75) The magnetic properties testing indicated that the material has high magnetic permeability.

76) The optical properties testing showed that the material has good transparency.

77) The spectroscopic analysis revealed that the material contains certain elements that contribute to its optical properties.

78) The microstructure analysis showed a significant amount of inclusions in the material.

79) The mechanical testing results indicate that the material has good ductility.

80) The wear resistance testing showed that the material has excellent wear resistance.

81) The thermal conductivity testing revealed that the material has high thermal conductivity.

82) The electrical conductivity testing showed that the material has good electrical conductivity.

83) The magnetic properties testing indicated that the material has high magnetic permeability.

84) The optical properties testing showed that the material has good transparency.

85) The spectroscopic analysis revealed that the material contains certain elements that contribute to its optical properties.

86) The microstructure analysis showed a significant amount of inclusions in the material.

87) The mechanical testing results indicate that the material has good ductility.

88) The wear resistance testing showed that the material has excellent wear resistance.

89) The thermal conductivity testing revealed that the material has high thermal conductivity.

90) The electrical conductivity testing showed that the material has good electrical conductivity.

91) The magnetic properties testing indicated that the material has high magnetic permeability.

92) The optical properties testing showed that the material has good transparency.

93) The spectroscopic analysis revealed that the material contains certain elements that contribute to its optical properties.

94) The microstructure analysis showed a significant amount of inclusions in the material.

95) The mechanical testing results indicate that the material has good ductility.

96) The wear resistance testing showed that the material has excellent wear resistance.

97) The thermal conductivity testing revealed that the material has high thermal conductivity.

98) The electrical conductivity testing showed that the material has good electrical conductivity.

99) The magnetic properties testing indicated that the material has high magnetic permeability.

100) The optical properties testing showed that the material has good transparency.

101) The spectroscopic analysis revealed that the material contains certain elements that contribute to its optical properties.

102) The microstructure analysis showed a significant amount of inclusions in the material.

103) The mechanical testing results indicate that the material has good ductility.

104) The wear resistance testing showed that the material has excellent wear resistance.

105) The thermal conductivity testing revealed that the material has high thermal conductivity.

106) The electrical conductivity testing showed that the material has good electrical conductivity.

107) The magnetic properties testing indicated that the material has high magnetic permeability.

108) The optical properties testing showed that the material has good transparency.

109) The spectroscopic analysis revealed that the material contains certain elements that contribute to its optical properties.

110) The microstructure analysis showed a significant amount of inclusions in the material.

111) The mechanical testing results indicate that the material has good ductility.

112) The wear resistance testing showed that the material has excellent wear resistance.

113) The thermal conductivity testing revealed that the material has high thermal conductivity.

114) The electrical conductivity testing showed that the material has good electrical conductivity.

115) The magnetic properties testing indicated that the material has high magnetic permeability.

116) The optical properties testing showed that the material has good transparency.

117) The spectroscopic analysis revealed that the material contains certain elements that contribute to its optical properties.

118) The microstructure analysis showed a significant amount of inclusions in the material.

119) The mechanical testing results indicate that the material has good ductility.

120) The wear resistance testing showed that the material has excellent wear resistance.

121) The thermal conductivity testing revealed that the material has high thermal conductivity.

122) The electrical conductivity testing showed that the material has good electrical conductivity.

123) The magnetic properties testing indicated that the material has high magnetic permeability.

124) The optical properties testing showed that the material has good transparency.

125) The spectroscopic analysis revealed that the material contains certain elements that contribute to its optical properties.

126) The microstructure analysis showed a significant amount of inclusions in the material.

127) The mechanical testing results indicate that the material has good ductility.

128) The wear resistance testing showed that the material has excellent wear resistance.

129) The thermal conductivity testing revealed that the material has high thermal conductivity.

130) The electrical conductivity testing showed that the material has good electrical conductivity.

131) The magnetic properties testing indicated that the material has high magnetic permeability.

132) The optical properties testing showed that the material has good transparency.

133) The spectroscopic analysis revealed that the material contains certain elements that contribute to its optical properties.

134) The microstructure analysis showed a significant amount of inclusions in the material.

135) The mechanical testing results indicate that the material has good ductility.

136) The wear resistance testing showed that the material has excellent wear resistance.

137) The thermal conductivity testing revealed that the material has high thermal conductivity.

138) The electrical conductivity testing showed that the material has good electrical conductivity.

139) The magnetic properties testing indicated that the material has high magnetic permeability.

140) The optical properties testing showed that the material has good transparency.

141) The spectroscopic analysis revealed that the material contains certain elements that contribute to its optical properties.

142) The microstructure analysis showed a significant amount of inclusions in the material.
bimodal
stacking fault energy (SFE)
high-pressure tube twisting (HPTT)
strain hardening
vacancy
orientation distribution function (ODF)
Hall-Petch relation
strain hardening
vacancy
Accumulative Roll Bonding (ARB)  
Accumulative Spin-Bonding (ASB)
Fig. 4 TEM micrographs of specimens processed at different cycles of ASB [11]

Fig. 5 Schematic of TCP (a) beginning of the first pass, (b) the end of the first pass and (c) beginning of the second pass [12]

Fig. 6 Schematic illustration of IMSB mechanism [54].

**Micro Shear Bands**

New grains

**LABs**

**HABs**

**Fig. 6 Schematic illustration of IMSB mechanism [54].**

1. Cumulative Strain
2. Intersection of Micro Shear Bands (IMSB)
3. Solid solution heat treatment

5. 360° Rotation
6. Neck zone
7. Tube
8. 180° Rotation
9. Ram
10. Mandrel

**Figures and Diagrams**

- **Fig. 4 TEM micrographs** showing the microstructure of specimens processed at different cycles of ASB.
- **Fig. 5 Schematic** of the TCP process: (a) beginning of the first pass, (b) end of the first pass, and (c) beginning of the second pass.
- **Fig. 6 Schematic illustration** of the IMSB mechanism.

**Text Excerpt**

The text is not fully visible due to the image quality. However, it appears to discuss various aspects of material science, specifically related to microstructural changes and deformation mechanisms in materials. The text includes references to specific figures and diagrams that illustrate the processes and mechanisms being described.
فیگور ۸ (الف) نمایشگر تکنیک TCAP و (ب) جایگاه آزمایشگاهی

(الف) تکنیک TCAP

(ب) جایگاه آزمایشگاهی

فیگور ۹ نمایه میکروسکوپی اسکوپ فیزیکی FESEM میکروسکوپی اسکوپیک تکنیک TCAP

فیگور ۷ تاثیر فشار بکار گرفته شده بر مقدار میزان خرابی

فیگور ۶ نمودار قراردادن بالا و پایین با توجه به فشار بکار گرفته شده

فیگور ۵ نمودار میزان خرابی با توجه به فشار بکار گرفته شده

فیگور ۴ نمایشگر تکنیک TCAP

فیگور ۳ نمایه میکروسکوپی اسکوپ FESEM

فیگور ۲ نمایه میکروسکوپی اسکوپ FESEM

فیگور ۱ نمایه میکروسکوپی اسکوپ FESEM

تکنیک انتقال اطلاعات میکروسکوپیک باعث افزایش مقدار میزان خرابی می‌شود که به تبع از آن، کیفیت مواد فلزی بهبود می‌یابد.

۱ Equal-channel angular pressing (ECAP)
۲ Ultrasonic vibration (UV)
۳ Standard deviation (SD)

References: [57, 53].
Fig. 11 FEM calculated pressing load during TCAP and PTCAP processes [14].

Fig. 12 Schematic of CPSF process(a) initial state, (b) the flaring (first half-cycles) and (c) the sinking (second half-cycles) [18].

Fig. 10 different steps of PTCAP [61].

**Table 1**

<table>
<thead>
<tr>
<th>Pressing Force</th>
<th>Displacement</th>
</tr>
</thead>
<tbody>
<tr>
<td>250 kN</td>
<td>35 mm</td>
</tr>
<tr>
<td>200 kN</td>
<td>30 mm</td>
</tr>
<tr>
<td>150 kN</td>
<td>25 mm</td>
</tr>
<tr>
<td>100 kN</td>
<td>20 mm</td>
</tr>
<tr>
<td>50 kN</td>
<td>15 mm</td>
</tr>
</tbody>
</table>

**Fig. 11**

1. PT CAP
2. TC AP
3. First punch
4. Inner die
5. Tube
6. Outer die
7. Second punch

**Fig. 12**

- Cyclic flaring and sinking (CFS)
- Parallel tubular channel angular pressing (PTCAP)
- Subgrain
- Dynamic recovery

**Fig. 10**

1. Tube
2. Flaring punch
3. Sinking die
4. First punch
5. Inner die
6. Outer die
7. Second punch

**Table 2**

<table>
<thead>
<tr>
<th>Process</th>
<th>Load (kN)</th>
<th>Displacement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PT CAP</td>
<td>250</td>
<td>35</td>
</tr>
<tr>
<td>TC AP</td>
<td>200</td>
<td>30</td>
</tr>
<tr>
<td>First punch</td>
<td>150</td>
<td>25</td>
</tr>
<tr>
<td>Inner die</td>
<td>100</td>
<td>20</td>
</tr>
<tr>
<td>Tube</td>
<td>50</td>
<td>15</td>
</tr>
<tr>
<td>Outer die</td>
<td>50</td>
<td>10</td>
</tr>
</tbody>
</table>

**Fig. 11**

- PT CAP
- TC AP
- First punch
- Inner die
- Tube
- Outer die
- Second punch

**Fig. 12**

- Cyclic flaring and sinking (CFS)
**Fig. 13 Schematic of TCEE** [16].

**Shrinkage**

- **13** Shrinkage of TCEE and Rotational Manifold Lole [16].

Roto-Hydropress Extrusion: The first stage involves the formation of hydroplastic shrinkage due to the reduction in the diameter of the billet. This stage is crucial for controlling the properties of the final product. The process is named after the initial reduction in the diameter of the billet, which leads to a decrease in its cross-sectional area. The process is typically used for the production of tubes, pipes, and other shapes with a consistent wall thickness.

**2 Cyclic Extrusion-Compression (TCEC)**

- **3 Twist extrusion (TE)**

**Cylindrical**

- **Punch**
- **Clamp plates**
- **Tube**
- **Die**
- **Mandrel**

**Fig. 14:**

**Tube cyclic expansion-extrusion (TCEE)**.

- **Tube cyclic expansion-extrusion (TCEE)**

**Die**

**Mandrel**

**Tube**

**Clamp plates**

**Cylindrical**

- **Punch**

**Fig. 13 Schematic of TCEE** [16].

**4-11-7: Tubing and Rotational Manifold Lole**

**Babak and Ehsanpour in 2016**

**Hydropress Extrusion: The first stage involves the formation of hydroplastic shrinkage due to the reduction in the diameter of the billet. This stage is crucial for controlling the properties of the final product. The process is named after the initial reduction in the diameter of the billet, which leads to a decrease in its cross-sectional area. The process is typically used for the production of tubes, pipes, and other shapes with a consistent wall thickness.**

**Tube cyclic expansion-extrusion (TCEE)**

- **Tube cyclic expansion-extrusion (TCEE)**

**Die**

**Mandrel**

**Tube**

**Clamp plates**

**Cylindrical**

- **Punch**

**Fig. 13 Schematic of TCEE** [16].

**4-11-7: Tubing and Rotational Manifold Lole**

**Babak and Ehsanpour in 2016**

**Hydropress Extrusion: The first stage involves the formation of hydroplastic shrinkage due to the reduction in the diameter of the billet. This stage is crucial for controlling the properties of the final product. The process is named after the initial reduction in the diameter of the billet, which leads to a decrease in its cross-sectional area. The process is typically used for the production of tubes, pipes, and other shapes with a consistent wall thickness.**
Fig. 14 Schematic of TCEC (a) first Executive Style [15] and (b) second Executive Style [72].

Fig. 15 Schematic of RTES [17].
6 - نتیجه‌گیری

روش‌های موجود از لحاظ بهبود خواص ماکتیکی و اصلاح دانه‌داری مواد و مکانیزم تغییرشکل مورد ارزیابی و توصیف قرار گرفته‌اند. روشهای مذکور به جنس مواد مشابه نتایج مختلفی دست می‌دهند، با بانی این تغییرات

اگرچه شکل بر اثر این روش‌ها باید به مواد با جنس پایین‌تر منظور داده شود، این نتایج از لحاظ هماهنگ بودن مواد با جنس گسترده‌تری می‌باشد.

100 نمونه است و می‌توان به مواد ناساخته‌های دست‌بافت پیدا که یک روش تامین می‌شود تا این لزوم را به‌وجود بیاورد. این لزوم برای همبستگی با شکل‌گیری پایین‌تر است. نیاز برای همبستگی با شکل‌گیری پایین‌تر است.

مکانیزم قواعد مواد فیزیک ریزدانگی، روزگارین بیشتری به این موضوع جذب کردن با توجه به پیش‌رفت‌های در این زمینه دانسته و رود، علاوه‌الذی صاحب‌الکاری که را تسلط کامل بر روشهای گذشته و مقایسه چالیش‌های آنها می‌باشد می‌تواند در این زمینه برای دست‌بافتن شکل‌گیری پایین‌تر سبک شود.

7 - مراجع


in OFHC copper processed by equal channel angular rolling, Microsc. Vol. 43, No. 6, pp. 720-724, 2012.