Route Effect on Equal Channel Angular Pressing of Copper Tube

Faramarz Djavanroodi · Ali Asghar Zolfaghari · Mahmoud Ebrahimi · Kamran Nikbin

Abstract   A new technique to produce ultra-fine grained tubular specimen has been proposed, and the experiments have been performed using equal channel angular pressing (ECAP) with an angle of 90° between two intersecting channels and also the use of rubber pad as a mandrel during process. Commercial purity copper tubes have been pressed up to three passes through four different fundamental routes (A, B_A, B_C, and C) directions of which are identified in the text below. The influence of each route on the value, distribution, and homogeneity of hardness has been investigated by applying Vickers micro-hardness measurements at various locations of the tube's transverse planes. Significant enhancement of the hardness is observed after the first pass ECAP. Also, routes C and B_C show, respectively, better average hardness magnitude and hardness distribution uniformity. In addition, the results indicate that there is about 50% and 62% reduction of the grain size, compared to the annealed condition, following ECAP process of the copper tube sample after the first and the third pass via route B_C.

KEY WORDS: Severe plastic deformation (SPD); Equal channel angular pressing (ECAP); Tube; Route; Hardness

1 Introduction

During the last decade, there has been much interest in enhancement of various material physical, mechanical, superplastic, wear, and corrosion properties by the process of refining the grain size to ultra-fine grained (UFG) structure using severe plastic deformation (SPD) techniques [1]. These techniques include equal channel angular pressing (ECAP) [2], high pressure torsion (HPT)

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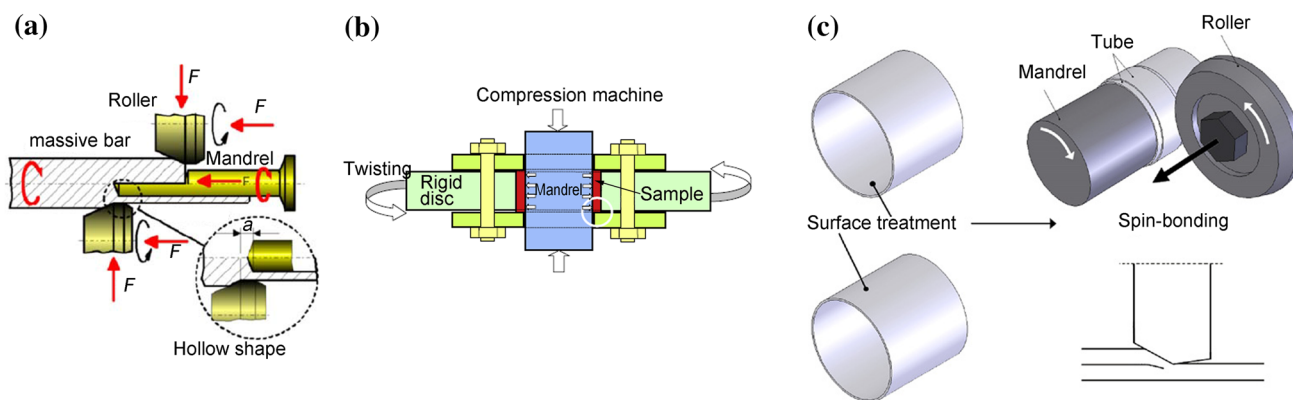and Technology, Tehran, Iran

[3], accumulative back extrusion (ABE) [4], constrained groove pressing (CGP) [5], and accumulative roll bonding (ARB) [6]. Among various SPD methods, ECAP process is the most attractive and prominent technique for imposing large plastic deformation to the material because of low set-up costs, moderately high productivity rate, accessibility fabrication, and industrial applications [7–9]. Although this method had been previously used to produce bulk-shaped samples, development of this technique has progressed to create new processes for fabricating plate [1], wire [10], and tube-shaped [11] specimens. There are less well-known methods and studies for constructing high strength tube-shaped work pieces. However, the ECAP method has been successfully used in the development of high strength tubes for the different industrial applications.

Presently, there are approximately five major methods to fabricate UFG tube-shaped components. These are spin extrusion (SE) [12], high pressure tube twisting (HPTT)

Fig. 1 Schematic representation of three SPD methods to fabricate UFG tube-shaped specimens: **a** spin extrusion [12]; **b** high pressure tube twisting [14]; **c** accumulative spin bonding [16]

[13, 14], accumulative spin bonding (ASB) [15, 16], tubular channel angular pressing (TCAP) [17], and deformed tubes with ECAP process using sand [11].

In the SE method, generated by Neugebauer et al. [12], the process can be described as a rotational forming under compressive circumstances. During deformation, hollow-shaped work pieces produce from the bulk materials with the circular cross-sections, see Fig. 1a. In the HPTT method initiated by Toth et al. [13, 14], tube-shaped materials are located inside a rigid disk. A mandrel is positioned into the tube which is compressed with a compression machine in its elastic regime. The mandrel then expands slightly in the radial direction because of its axial compression as observed in Fig. 1b. ASB process is based on the cold bonding of cylinders by applying the tube spinning method; see Fig. 1c. In this process, material is placed between the roller and mandrel and then, it gradually deforms to the final thickness. All of these three techniques are high cost and difficult die set up and also, limited applications. On the other hand, the other two methods shown in Fig. 2 have overcome these problems. It is noted to say that these two methods are based on the conception of ECAP technique. In the first one developed by Nagasekhar et al. [11] and represented in Fig. 2a, sand has been applied as the mandrel to maintain tubularity of samples and then, the packing of tube sample with sand is pressed in the ECAP die. This technique decreases the required punch force value, because that the friction between the sand and inner surface of tube assists in the pressing of specimen. In the second method invented by Zangiabadi and kazeminezhad [17], the tube-shape work piece is pressed in the tubular channel angular pressing as shown in Fig. 2b. During one pass with this method, three shear events could take place.

Recently, a new development of ECAP process using rubber pad has been introduced by Djavanroodi and co-workers [18] to fabricate tube-shaped specimens. The schematic representation of this method is displayed in Fig. 3. In this process, a rubber pad is inserted into tube-shaped copper sample and then, the sample with rubber pad is pressed using ECAPed die with the die channel angle of 90°.

During the ECAP process, there are four fundamental routes between each repetitive compression stage: Route A that the sample is repetitively pressed without any rotation; route B_A that the sample is rotated by 90° in the alternative direction between each pass; route B_C that the sample is rotated in the same direction by 90°; route C that the sample is rotated by 180° between each consecutive pass [1, 19]. These routes result in the development of different slip systems in the specimen, and so, various microstructure and mechanical properties can be obtained by paying attention to the applied route [20–22]. The numerical investigation by Xu et al. [23] on the pressing route of ECAP process showed that uniform effective strain distribution cannot be achieved using route A, because of its inheriting characteristic of non-uniform deformation distribution of the first pass. In addition, routes B and C can lead to uniform effective strain dispersal; but, route B has better uniform effective strain distribution than route C in the deformed sample. The hardness measurement of ECAPed pure aluminum billet by Alhajeri et al. [24] showed that although the average microhardness magnitude improves significantly after the first pass, there is a region of lower hardness at the regions adjacent to the top and bottom surfaces of the billets. Subsequent passes up to six passes by route B_C indicated that additional but much smaller enhancement has been obtained at the hardness value. Also, high degree of uniformity is attained after six passes of process although there remains a very small area of lower hardness adjacent to the bottom surface.
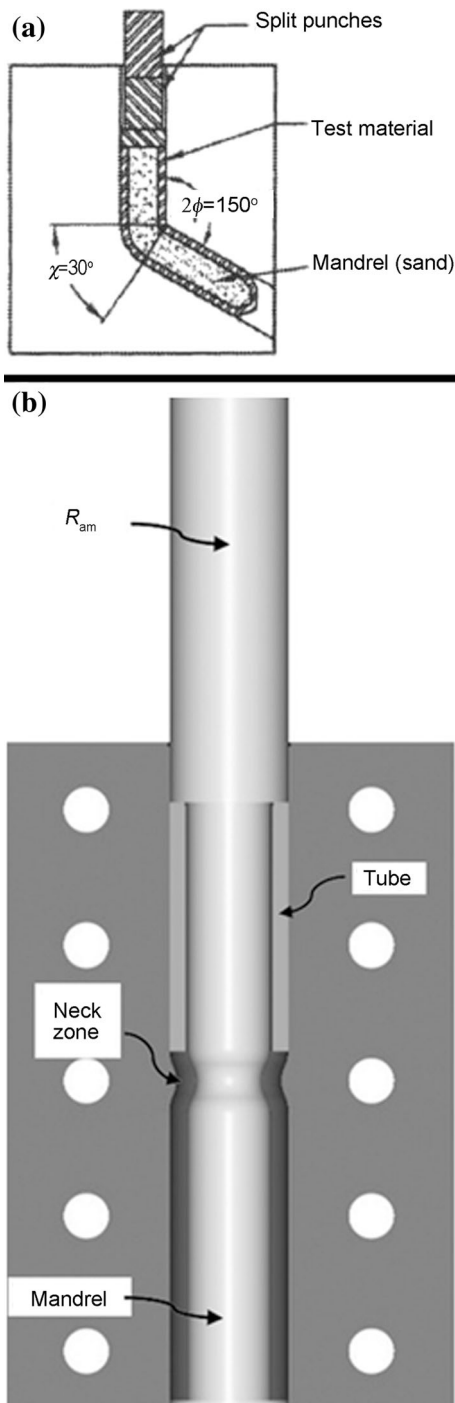
Fig. 2 Schematic representation of two SPD methods to produce UFG tube-shaped samples: **a** ECAP with sand [11]; **b** tubular channel angular pressing [17]

In this paper, commercial purity copper specimens have been ECAPed by up to three passes by four fundamental routes (A, B$_A$, C, and B$_C$) following which the hardness magnitude and distribution of the ECAPed specimens have been analyzed and compared.

2 Experimental

The experiments were conducted using commercial purity (CP) copper in the shape of tube. All tube samples were machined and prepared from the billet as a test material (outer diameter of 19 mm, thickness of 3.5 mm, and length of 140 mm). All specimens were annealed at the 500 °C for 1 h and slowly cooled at the furnace before operation. Flexible polyurethane rubber with a shore A (HD90) was inserted as a mandrel inside the copper tube work pieces before process. ECAP die with the die channel angle of 90°, outer corner angle of 17°, and channel diameter of 19.1 mm was designed and manufactured as shown in Fig. 3. Molybdenum disulfide (MoS$_2$) was used as a lubricant to decrease frictional effects between die and outer surface of tube. The ECAP process was performed at the ambient temperature using hydraulic press with a pressing speed of 1.5 mm/s.

Copper tube specimens have been pressed by up to three passes using the four fundamental routes: A, B$_A$, B$_C$, and C. Then, Vickers micro-hardness measurements have been performed for both un-ECAPed and ECAPed conditions with a force of 0.5 N for a dwell time of 15 s at the three transverse planes (cross-sectional area). In addition, microstructure evaluation using optical microscopy (OM) has been employed to confirm grain size refining during deformation of tube sample.

To investigate the hardness magnitude and its distribution uniformity, three separate cross-sections were chosen at the position of 30 mm from each other along sample's length as shown in Fig. 4a. The positions of hardness test are displayed in Fig. 4c. At every location, average values of two recording were obtained in order to minimize the errors in the results. A total number of 36 Vickers hardness records were performed for each specimen. In total, 216 Vickers hardness tests were obtained for this investigation. These Vickers hardness measurements were carried out at the top, bottom, and lateral locations of ECAPed copper tubes for as-received, first pass, and third pass specimens by four fundamental routes. Furthermore, inhomogeneity factor (F_I) was employed to investigate hardness distribution uniformity described as follows:

$$F_1 = \frac{\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(H_{V-i} - H_{V-ave}\right)^2}}{H_{V-ave}}, \tag{1}$$

where H_{V-i} is Vickers hardness value at each point, H_{V-ave} is the average magnitude of Vickers hardness records, and n is the number of data. Lower value for inhomogeneity factor means that better hardness distribution uniformity for ECAPed sample. Equation (1) takes the all-measured hardness values of the sample into account; therefore, it is believed that the IF parameter is more convenient and

Fig. 3 ECAP die set up with the rubber pad sample and formed work piece after one pass ECAP
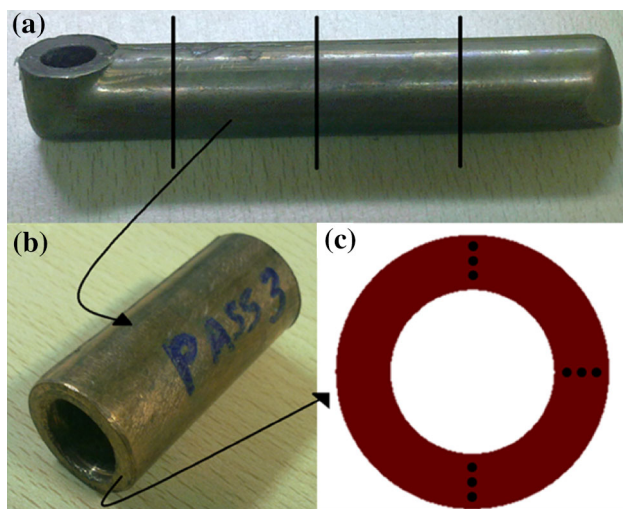

Fig. 4 Locations of Vickers hardness tests for samples before and after the first and also, third passes by routes A, B_A, B_C, and C

reliable for examining the level of hardness distribution homogeneity within the tube.

Fig. 5 CP Cu tube samples before and after ECAP process using routes A, B_A, B_C, and C

3 Results and Discussion

Figure 5 shows CP Cu tube specimens before and after the first and third passes of ECAP process by routes A, B_A, B_C, and C at room temperature using a hydraulic press and a die with the channel angle of 90° and outer corner angle of about 17°. As seen from Fig. 5, the samples become shorter with increasing number of passes. This defect is related to the nature of this process, and it cannot be avoided. For lubrication and fitting purposes, the diameter of the die channel is greater than the sample diameters (in the experimental setup, ECAP die channel and sample diameters were 19.1 and 19 mm, respectively). Assuming volume constancy and also, constant tube wall thickness during the process, the tube shortens by approximately 3%

at each pass. In addition, ECAPed specimens were machined after each pass to obtain an initial diameter (19 mm) for further pressings. Therefore, ECAPed specimens with more passes are expected to be shorter than ones with less passes.

Figure 6 displays the average magnitudes of Vickers hardness for the un-ECAPed condition and also, the first and third passes of deformed specimens using routes A, B_A, B_C, and C. As seen, significant hardness enhancement has taken place after the first pass of process which has been increased to 120 HV from 91 HV (about 32%). Also, subsequent passes lead to improvement of the hardness value irrespective to the route type. The results indicate that the third pass-deformed copper materials using routes
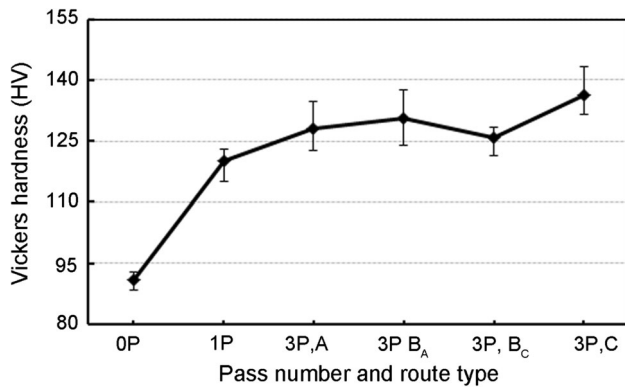
Fig. 6 Average hardness magnitudes for Cu-ECAPed tube specimens before and after one and three pass pressings by *routes A, B_A, B_C*, and *C*
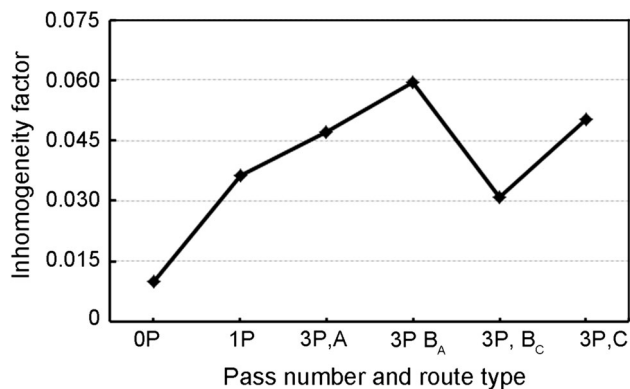

Fig. 7 Magnitudes of inhomogeneity factor for ECAPed tube work pieces after one and three pass pressings by routes A, B_A, B_C, and C

C, B_A, A, and B_C lead to enhancement at the hardness magnitudes which are equal to 50%, 43%, 40%, and 38% as compared to the un-ECAPed tube sample (magnitudes of 136.4, 130.5, 128, and 126 HV for the third pass-ECAPed tubes by routes C, B_A, A, and B_C, respectively).

Hence, it is clear that route C is better than the others from the average hardness magnitude point of view.

Figure 7 presents inhomogeneity of hardness distribution for the various first and third passes of tube samples using four fundamental routes and also, annealed condition. The least inhomogeneity factor among these six variations belongs to the annealed sate, because the heat treatment leads to equiaxed structure at the copper tube work piece. The microstructure observation for the as-received condition is exhibited in Fig. 8a. The average grain size of the sample at the annealed condition is approximately 80 μm according to ASTM E112. Although, one pass ECAP process result in high level of improvement at the hardness value and, therefore, improve the mechanical properties, subsequent passes by route B_C lead to uniformity in the distribution of hardness within the material. So, it can be concluded that route B_C has the best uniformity in the hardness distribution as compared to the other three routes.

Furthermore, during ECAP processing, dislocations develop and multiply locking them in place. At this stage, the low angle grain boundaries (LAGBs) are made. This leads to the formation of roughly elongated grains at the first pass of process, see Fig. 8b. Afterward, high angle grain boundaries (HAGBs) are formed by adding pass numbers and finally, UFG materials with the equiaxed structure are produced [25, 26]. Figure 8c shows OM image of the copper tube sample after the third pass ECAP by route B_C. The average grain sizes of the first pass- and the third pass-ECAPed tube by route B_C are about 40 and 30 μm, respectively. About 50% and 62% reductions at the grain size of ECAPed specimen have been observed after the first and the third passes by this route as compared to the un-ECAPed configuration.

Figure 9 compares hardness magnitudes for the un-ECAPed state and the first pass and also, the third pass of ECAPed specimens at the top, bottom, and lateral locations using route A, B_A, B_C, and C. As seen, the magnitude of
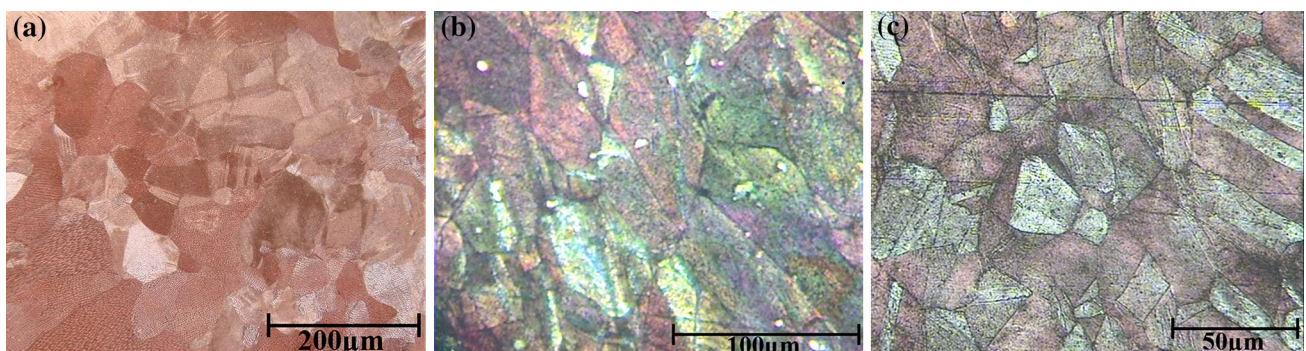

Fig. 8 Optical microstructural observation of copper tube samples: **a** as annealed; **b** after the first pass of ECAP process by route B_C; **c** after the third pass of ECAP process by route B_C
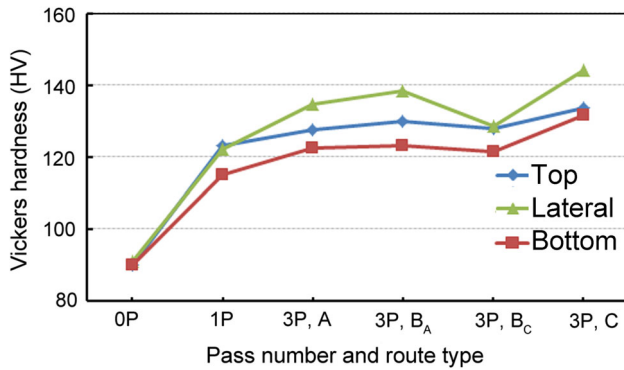
Fig. 9 Magnitudes of Vickers hardness at the *top*, *bottom*, and *lateral* locations of the first and third passes of ECAPed tube specimens by *routes A, B$_A$, B$_C$, and C*

Vickers hardness is the same at the top and lateral sections of material after one pass. The same trend is observed for the tube sample after three passes by route B$_C$. Maybe, equal values for top and lateral locations lead to less inhomogeneity factor for the third pass tube by route B$_C$. In addition, different magnitudes were used for various sections of third pass tube sample by route B$_A$ result in more F_I value (see Fig. 7) which causes hardness distribution heterogeneity for this case.

4 Conclusions

In this research, new method to fabricate UFG copper tube specimen has been proposed and introduced using ECAP with rubber pad technique. Commercial purity copper tube samples are subjected up to three passes using four fundamental pressing routes (A, B$_A$, B$_C$, and C). The effect of processing routes on the hardness behavior including of average hardness magnitude and hardness distribution homogeneity has been investigated at the top, bottom, and lateral locations of deformed work pieces. The results indicated that significant enhancement at the hardness value can be obtained after the first pass up to 32% (increases to 120 HV from 91 HV). Also, subsequent pressing of tubular samples up to three passes using four different routes showed that routes C and B$_C$ are the best ones from the average hardness magnitude and hardness distribution uniformity points of view, respectively. In addition, grain size of the first and the third passes of ECAPed specimen by route B$_C$ was decreased about 50% and 62%, respectively. In short, it can be summarized that new ECAP development is a promising technique for the enhancement of tubular material properties. Furthermore, more studies are required to investigate other processing parameters for ECAPing tube materials and develop a full characterization work.

References

[1] R.Z. Valiev, T.G. Langdon, Prog. Mater Sci. **51**, 881 (2006)
[2] M. Furukawa, Y. Iwahashi, Z. Horita, M. Nemoto, T.G. Langdon, Mater. Sci. Eng. A **257**, 328 (1998)
[3] A.P. Zhilyaev, T.G. Langdon, Prog. Mater Sci. **53**, 893 (2008)
[4] S.M. Fatemi-Varzaneh, A. Zarei-Hanzaki, Mater. Sci. Eng. A **504**, 104 (2009)
[5] D.H. Shin, J.J. Park, Y.S. Kim, K.T. Park, Mater. Sci. Eng. A **328**, 98 (2002)
[6] Y. Saito, N. Tsuji, H. Utsunomiya, T. Sakai, R.G. Hong, Scr. Mater. **39**, 1221 (1998)
[7] S.D. Wu, Z.G. Wang, C.B. Jiang, G.Y. Li, I.V. Alexandrov, R.Z. Valiev, Mater. Sci. Eng. A **387–389**, 560 (2004)
[8] F. Djavanroodi, M. Ebrahimi, Mater. Sci. Eng. A **527**, 1230 (2010)
[9] A. Mishra, B.K. Kad, F. Gregori, M.A. Meyers, Acta Mater. **55**, 13 (2007)
[10] G.J. Raab, R.Z. Valiev, T.C. Lowe, Y.T. Zhu, Mater. Sci. Eng. A **382**, 30 (2004)
[11] A.V. Nagasekhar, U. Chakkingal, P. Venugopal, J. Mater. Process. Technol. **173**, 53 (2006)
[12] R. Neugebauer, R. Glass, M. Kolbe, M. Hoffmann, J. Mater. Process. Technol. **125–126**, 856 (2002)
[13] A. Pougi, L.S. Toth, O. Bouaziz, J.J. Fundenberger, D. Barbier, R. Arruffat, Scr. Mater. **66**, 773 (2012)
[14] L.S. Toth, M. Arzaghi, J.J. Fundenberger, B. Beausir, O. Bouaziz, R. Arruffat-Massion, Scr. Mater. **60**, 175 (2009)
[15] M.S. Mohebbi, A. Akbarzadeh, Mater. Sci. Eng. A **528**, 180 (2010)
[16] M.S. Mohebbi, A. Akbarzadeh, J. Mater. Process. Technol. **210**, 510 (2010)
[17] A. Zangiabadi, M. Kazeminezhad, Mater. Sci. Eng. A **528**, 5066 (2011)
[18] F. Djavanroodi, A.A. Zolfaghari, M. Ebrahimi, Acta Metall. Sin. (Engl. Lett.) **26**, 574 (2013)
[19] T.G. Langdon, Mater. Sci. Eng. A **462**, 3 (2007)
[20] O.V. Mishin, J.R. Bowen, Metall. Mater. Trans. A **40**, 1684 (2009)
[21] Y.C. Choi, H.S. Kim, S.I. Hong, Met. Mater. Int. **15**, 733 (2009)
[22] P. Venkatachalam, S.R. Kumar, B. Ravisankar, V.T. Paul, M. Vijayalakshmi, Trans. Nonferrous Met. Soc. China **20**, 1822 (2010)
[23] S. Xu, G. Zhao, Y. Luan, Y. Guan, J. Mater. Process. Technol. **176**, 251 (2006)
[24] S.N. Alhajeri, N. Gao, T.G. Langdon, Mater. Sci. Eng. A **528**, 3833 (2011)
[25] M. Reihanian, R. Ebrahimi, N. Tsuji, M.M. Moshksar, Mater. Sci. Eng. A **473**, 189 (2008)
[26] F. Djavanroodi, B. Omranpour, M. Ebrahimi, M. Sedighi, Prog. Nat. Sci. Mater. Int. **22**, 452 (2012)