Structural Evolution During Mechanical Milling of Bimodal-Sized Al_2O_3 Particles Reinforced Aluminum Matrix Composite

Ke Zhao¹ · Dan Tang¹ · Jin-Ling Liu^{2,3} · Yi-Guang Wang¹

Received: 28 November 2017 / Revised: 26 December 2017 / Published online: 14 February 2018
© The Chinese Society for Metals and Springer-Verlag GmbH Germany, part of Springer Nature 2018

Abstract

Hybrid aluminum matrix composite powders reinforced with bimodal-sized Al_2O_3 particles were synthesized by mechanical milling. Two different approaches were investigated for the addition of submicron- and nano-sized Al_2O_3 particles to the aluminum powders. It was observed that the simultaneous addition of bimodal-sized Al_2O_3 particles to the aluminum powders resulted in an equiaxed morphology of the composite powders and the average particle size stabilized after 5 h of milling, indicating that the presence of bimodal-sized particles has greater effect on accelerating milling process as compared to nano-sized particles; the grain size of the aluminum matrix in composite powders was reduced to under 40 nm, approximate to the value obtained in the separate addition case, while a lower rate of refining was observed due to hindrance of submicron-sized particles on the interactions between nano-sized particles and the aluminum matrix.

Keywords Bimodal-sized · Aluminum matrix composite · Mechanical milling · Grain refinement

1 Introduction

Particulate-reinforced aluminum matrix composites have been successfully used in aerospace, rail transit, and automotive industries owing to the unique combination of being light weight, possessing high strength and stiffness along with good creep resistances [1]. It is well known that the volume fraction, size, and distribution of the reinforcement particles in the metal matrix contribute toward the improved mechanical properties of such aluminum matrix composites. For traditional aluminum matrix composites, strengthening the aluminum matrix with micrometer particles leads to improved strength but poor ductility

[2–6]. For instance, the strength of Al 2009 alloy has been shown to increase from 439 to 566 MPa but the elongation decreases from 24% to 8%, when 15 vol% B_4C particles with average particle size of 5 μm are added [6]. When micro-sized reinforcement particles are replaced by nano-sized particles, the strength of the composites has shown to improve significantly, and a better ductility was obtained also. For instance, the tensile strength and elongation of 0.5 wt% nano-sized TiC particle reinforced Al–Cu matrix composite can reach up to 540 MPa and 19%, respectively, both higher than those of the Al–Cu matrix alloy (485 MPa and 6.6%) [7]. However, the strength of the composites was shown to rapidly decrease as the volume fraction of nano-sized particles exceeds 4% [7–10], which can be attributed to the agglomeration and poor wettability of nano-sized particles in the metal matrix. Additionally, trimodal aluminum matrix composites consisting of unmilled coarse-grained aluminum, micro-sized reinforcement particles, and nanocrystalline aluminum have also been investigated. They have been reported to exhibit a high strength and satisfactory ductility of 464 MPa and 3%, respectively, for a composite with 2.5 wt% B_4C , 50 wt% coarse-grained 5083Al, and the balance consisting of nanocrystalline 5083 Al [2]. However, the improvement in ductility was limited [2, 11], as the major contribution to the ductility comes from coarse-grained aluminum while

Available online at <http://link.springer.com/journal/40195>

✉ Jin-Ling Liu
liujinling@swjtu.edu.cn

¹ Science and Technology on Thermostructural Composite Materials Laboratory, Northwestern Polytechnical University, Xi'an 710072, China

² State Key Laboratory of Traction Power, School of Mechanics and Engineering, Southwest Jiaotong University, Chengdu 610031, China

³ Applied Mechanics and Structure Safety Key Laboratory of Sichuan Province, Southwest Jiaotong University, Chengdu 610031, China

the strength decreases with increasing content of coarse-grained aluminum.

Although aluminum matrix composites reinforced with hybrid reinforcement particles have been widely studied, they exhibit no significant advantage in mechanical properties as compared to the composites reinforced with single-sized particles [12, 13] due to drawbacks in the manufacturing process. Al 2014 matrix composites reinforced by micro-sized (4 vol%) and a small amount (1 vol%) of nano-sized SiC particles showed significantly enhanced strength (585 MPa) accompanied by good ductility (9.9%) compared to aluminum matrix composites reinforced with 4 vol% micrometer SiC particles (503 MPa and 4.9%, respectively). Hence, it is expected that adding bimodal-sized particles to the aluminum matrix may be an advantageous strategy to enhance the mechanical properties of the aluminum matrix composites. However, the strength of the composites was shown to decrease when the content of nano-sized particles exceeds 4 wt% because a continuous brittle phase was formed along the grain boundaries by the agglomeration of nano-sized particles [14, 15]. Therefore, in order to obtain a desirable microstructure and improved mechanical properties, it is essential for bimodal-sized particles involving high volume fraction nano-sized particles to be homogeneously distributed in the aluminum matrix.

It has been reported that the homogeneous distribution of high volume fraction nano-sized particles in the metal matrix can be achieved by mechanical milling [16, 17]. Mechanical milling is a dry, high-energy ball milling technique, where the blended powder particles are loaded along with the grinding medium in a vial and subjected to heavy deformation. During this process, the powder particles are repeatedly flattened, cold weld, fractured, and reweld, until the steady state is achieved. The process is influenced by several factors such as the milling time, milling speed, miller type, milling temperature and atmosphere, ball-to-powder weight ratio, and the process control agent [18]. Although many studies have demonstrated the mechanical alloying of metal matrix composite powders reinforced with single-sized particles, the structural

evolution of aluminum matrix composite powders reinforced with bimodal-sized particles (submicron and nano) has not been well studied.

The objective of this study is to fabricate hybrid aluminum matrix composite powders with a homogeneous distribution of bimodal-sized Al_2O_3 particles and to explore the effect of the addition of bimodal-sized Al_2O_3 particles on the morphological and structural evolutions of aluminum powders during mechanical milling. The effectiveness of mechanical milling is described in terms of achieving the steady-state condition. In particular, the content of nano-sized Al_2O_3 particles was exceeded 5 vol% in this study.

2 Experimental Procedure

Aluminum powder of 99.99% purity (Shanghai ChaoWei Nanotechnology Co., Ltd., China) and Al_2O_3 powders with both sizes of 50 nm and 0.3 μm (Buehler, Ltd., Lake Bluff, IL, USA) were used as the raw materials. The as-received aluminum particles had a spherical shape and a diameter of 1–5 μm , as shown in Fig. 1a. The 50 nm Al_2O_3 powders (as shown in Fig. 1b) were also spherical in shape, but agglomerated significantly. The 0.3 μm Al_2O_3 powders were irregular in shape and had a relatively broad size distribution with a certain extent of agglomeration, as shown in Fig. 1c.

To study the effect of single- and bimodal-sized reinforcements on the milling process, Al-5 vol% (0.3 μm)-10 vol% (50 nm) Al_2O_3 composite powders were milled in a planetary mill (Nanjing Nanda Instrument Plant, China) using two methods: (i) The aluminum powders were first blended with nano-sized Al_2O_3 particles for 20 h, and the mixed powders were then blended with submicron-sized Al_2O_3 particles for 20 h, termed as Al- Al_2O_3 -A; (ii) the nano-sized Al_2O_3 particles and submicron-sized Al_2O_3 particles were simultaneously added to aluminum powders and milled for 20 h, termed as Al- Al_2O_3 -B. To minimize oxidation and contamination of powders, the powders were loaded into a stainless-steel vial and stainless-steel balls

Fig. 1 SEM micrographs of raw materials: **a** aluminum, **b** 50-nm Al_2O_3 , **c** 0.3- μm Al_2O_3

under argon atmosphere inside a glove box. The ball-to-powder ratio (wt%) was 15:1. Approximately 5 wt% ethanol (Tianjin Jindong Precision Chemical Reagent Factory, China) was added as the process control agent to prevent excessive welding and adhesion of the powders to the milling tool. The milling processes were carried out in a planetary mill, and the rotational speed was maintained at 150 rpm.

The morphology evolution of the composite powders during the milling was studied using a JEOL 6700F scanning electron microscope (SEM). The distribution of the elements in the milled powders was observed by energy dispersive spectrometer (EDS). X-ray diffraction (XRD) patterns were recorded using a Bruker D8 X-ray diffractometer with $\text{Cu K}\alpha$ radiation at a voltage and current setting of 40 kV and 40 mA, respectively. The grain size and lattice strain of the powders were determined using the Williamson–Hall method.

3 Results and Discussion

According to previous studies [13, 16, 19], the changes in morphology of aluminum matrix composite powders reinforced with nano-sized particles during milling process are similar to that of the aluminum alloy powders. Flake-like shapes are observed in the initial milling stages due to plastic deformation of the soft matrix followed by cold-welded laminar structures in the intermediate milling stages. In the later milling stages, fragmentation of the flakes leading to equiaxed particles is observed. Subsequently, when welding and fracture reach equilibrium, the steady state is achieved. Figure 2 shows the SEM micrographs of $\text{Al-Al}_2\text{O}_3\text{-A}$ powders processed under different milling time. The initial spherical shape of the aluminum powder developed into different irregular shapes, and large aggregates with a small aspect ratio were formed after 5 h milling, consisting of smaller submicron-welded particles and nano-sized Al_2O_3 particles attached on the surface of aluminum particles. This observation indicates that welding is the predominant mechanism during this period [20]. Because the presence of Al_2O_3 particles decreases the weldability of the aluminum powder, finer irregular aluminum particles were also observed. With the milling time increasing, work hardening activated the fracture mechanism, large aggregates were cracked by more intensive impacts, the composite powders had become rounded, and the particle sizes decreased, as shown in Fig. 2b and c. As the milling time was increased to 20 h, the composite powders exhibited equiaxed morphology (Fig. 2c) and the particle size stabilized, indicating that a balance between welding and fracture processes was achieved. Notably, no flake-like particles were observed, considering the size,

shape, and composition of raw materials play an important role in milling process, and this may be due to the significantly smaller raw aluminum powder particles in comparison with those used in previous studies (several micros) [13, 16–19], and the accelerating effect of high volume fraction (10%) hard nano-sized particles on fracture process of the aluminum particles [21, 22].

When submicron-sized Al_2O_3 particles were added to the nanocomposite powders, the morphology of the composite powders essentially remained the same with an equiaxed structure as increasing milling time, but the powders particle size showed a broader distribution. As shown in Fig. 2d and e, some large particles appeared in the composite powders milled for 25 and 30 h, respectively. As the milling time increased to 35 h, these large particles were still observed (Fig. 2f). This may be due to that the composite powders with coarse reinforcements are more prone to assemble into a large particle, which suggests excessive cold welding [13]. Therefore, it is challenging to obtain a narrow size distribution of aluminum powders when the bimodal-sized Al_2O_3 particles were added to aluminum powder separately.

A different morphological evolution of $\text{Al-Al}_2\text{O}_3\text{-B}$ composite powders was observed compared to $\text{Al-Al}_2\text{O}_3\text{-A}$ composite powders. As shown in Fig. 3a, near equiaxed particles were formed after 5 h milling, smaller than that of $\text{Al-Al}_2\text{O}_3\text{-A}$ powder with the same milling time. With the milling time increasing, no obvious change was observed in the size and morphologies of the powders (Fig. 3b and c). Only a minor decrease in the particles size was observed after 20 h milling (Fig. 3d). This indicates that it is an effective way to reduce the milling time to achieve the steady-state condition when simultaneously adding the bimodal-sized particles to aluminum powders.

For a better understanding of the role of the presence of bimodal-sized Al_2O_3 particles in the effectiveness of milling process, the average particle size of $\text{Al-Al}_2\text{O}_3\text{-B}$ composite powders at different milling time was estimated based on SEM images, along with those of $\text{Al-Al}_2\text{O}_3\text{-A}$ composite powders as compared, as shown in Fig. 4. For the $\text{Al-Al}_2\text{O}_3\text{-A}$ composite powders, there was a significant increase of particle size when a milling time of 5 h was achieved, then longer milling time caused a notable decrease in particle size and maintained a relatively stable value. The observed changes in the particle size during the milling operation are consistent with the general trend that has been reported for nano-sized particles reinforced aluminum matrix composites [23–25], i.e., an increase in the particle size followed by a decrease and then reached steady state. This is because plastic deformation and cold welding are the dominating mechanisms in the initial milling stages due to ductile nature of the aluminum powder. As a result, flake-like particles are

Fig. 2 Morphologies of Al–Al₂O₃–A composite powders milled for different time: **a** 5 h, **b** 10 h, **c** 20 h, **d** 25 h, **e** 30 h, **f** 35 h

observed with increasing particle size, these particles harden and then fracture predominantly with continued milling, resulting in decrease of particle size until the steady state is obtained. In contrast, in the case of Al–Al₂O₃–B composite powders, the average particle size remained approximately the same throughout the entire milling process, even if there was a slight increase at initial stage followed by a decreasing trend, which suggests that the milling steady state had reached after 5 h of milling, and the morphological and structural changes occurred in a shorter time as compared with the case of Al–Al₂O₃–A composite powders. This indicates that bimodal-sized reinforcements have a greater effect on accelerating the milling process compared to single-sized reinforcement.

These results can be explained by the effect of the Al₂O₃ particles on the welding and fracturing behavior of the aluminum particles. It is known that the welding process is

driven by cold deformation and there is a critical deformation above which a higher deformation will produce welding [19]. The presence of nano-sized Al₂O₃ particles between aluminum particles during welding increases local deformation in the vicinity of nano-sized Al₂O₃ particles, improving the particle welding process. On the other hand, it lowers the fracture toughness of the aluminum particles leading to an increased deformation hardening [26], which results in an improvement of the fracture process. This improvement in the welding and fracture mechanisms makes the completion of entire milling process in a shorter time. However, as known that the nano-sized Al₂O₃ particles are prone to agglomeration leading to decreasing overall particle size distribution, such agglomerates may smear on the surface of the aluminum particles and need to be broken down by repeated collision of balls, delaying the plastic deformation and micro-welding of aluminum

Fig. 3 Morphologies of Al- Al_2O_3 -B composite powders milled for different time: **a** 5 h, **b** 10 h, **c** 15 h, **d** 20 h

Fig. 4 Average particle size as a function of milling time for Al- Al_2O_3 -A and B composite powders

particles. It is to be noted that if nano-sized particles were spread throughout the aluminum matrix with a better homogeneity, they should considerably accelerate the work hardening of the aluminum matrix and thus on their fracture; moreover, the nano-sized particles can penetrate more hardly into the finer as-received aluminum particles [23]. It has also been shown that the presence of nano-sized particles may increase the ductility of metal matrix composites enhancing their welding [27]. These factors lead to the increased average particle size occurring after 5 h milling for Al- Al_2O_3 -A composite powders. However, with the presence of bimodal-sized Al_2O_3 particles in Al- Al_2O_3 -B

composite powders, the submicron-sized Al_2O_3 particles can be not only act as milling media to accelerate milling action, but also destruct the clustering of nano-sized particles at the initial stage of mechanical milling leading to decreased volume fraction of free nano-sized Al_2O_3 particles within the aluminum particles, which results in a still greater deformation of the aluminum particles and accelerates the milling process even more. Furthermore, the presence of submicron-sized Al_2O_3 particles decreases the ductility of Al matrix composite [22], so fracture occurs before cold-welding causes the formation of aggregates.

The uniform dispersion of Al_2O_3 particles in Al- Al_2O_3 -B composite powders was confirmed by EDS. As shown in Fig. 5, the O element denotes the location of submicron- and nano-sized Al_2O_3 particles on the surface of aluminum particle, and the volume of the selected region is a light element Al. When the milling time was increased to 20 h, a uniform dispersion of the Al_2O_3 particles in the aluminum powder was obtained. Moreover, comparing with the micrographs shown on the left side, it indicates the aluminum particle size was reduced as the milling time increasing.

Figure 6a shows the XRD patterns of Al- Al_2O_3 -B composite powders after different milling time. The peaks were identified as α - Al_2O_3 and Al; no new phases were detected in the powders. With the milling time increasing, the general trend of the aluminum peaks showed a decrease in the peak intensity and an increase in the width at half

Fig. 5 X-ray mapping of O element showing the distribution of bimodal-sized Al_2O_3 particles in $\text{Al–Al}_2\text{O}_3\text{–B}$ composite powders after different milling time: **a** 5 h, **b** 20 h

Fig. 6 XRD patterns of $\text{Al–Al}_2\text{O}_3\text{–B}$ composite powders after different milling time

peak for the diffraction peaks (Fig. 6b). This observation indicates a decrease in the crystal size and the accumulation of lattice strain during the milling due to the characteristic processes of mechanical milling, which involves repeated deformation, cold welding, and fragmentation. A similar result was obtained for $\text{Al–Al}_2\text{O}_3\text{–A}$ composite powders. A minor shift in the position of the aluminum

peaks was also noticed (Fig. 6b), related to the presence of contamination in the milled aluminum lattice either from the milling media (vessel and balls) or from the process control agent. The grain size and lattice strain were calculated from Fig. 5 using the Williamson–Hall method as the following equation [28]:

$$\beta_S \cos \theta = \frac{K\lambda}{d} + 2\varepsilon \sin \theta. \quad (1)$$

where β_S is the full width at half-maximum (FWHM), θ is the diffraction angle, K is the Scherrer constant (1.05), λ is the X-ray wavelength ($\lambda_{\text{CuK}\alpha} = 0.15406$ nm), d is the crystallite size, and ε is the internal strain (an approximate upper limit of the lattice distortion).

The variation in the calculated grain size and lattice strain of aluminum matrix in Al–Al₂O₃ composite powders as a function of milling time is shown in Fig. 7. As it is clear that the grain size decreased and the lattice strain increased as increasing milling time, at final milling stages the minimum grain size of 36 and 39 nm and a lattice strain of 0.157 and 0.141% were obtained for aluminum matrix in Al–Al₂O₃–A and B composite powders, respectively. Although the final grain size and lattice strain of aluminum matrix in Al–Al₂O₃–A and B composite powders were almost the same, the variations of the processes were quite different. The grain size of aluminum matrix in Al–Al₂O₃–A powders decreased rapidly in the first 5 h of milling and leveled off at prolonged milling time, which is in agreement with the general trend reported in previous studies [13, 22, 23]. The rapid decrease in the grain size refers to the incorporation of nano-sized Al₂O₃ particles into the aluminum particles. The nano-sized Al₂O₃ particles interacted with the dislocations in the aluminum particles generated by the cycle loading and thermal expansion coefficient mismatch between the aluminum matrix and reinforcement particles [23], leading to the generation of sub-boundaries which in turn resulted in the decomposition of the initial large grains into smaller grains. The hindering of dislocation movement by nano-sized Al₂O₃ particles increased the dislocation density, thus accelerating the grain refining progress. A slight decrease in the grain size was observed when the submicron-sized Al₂O₃ particles were added to the Al–Al₂O₃ nanocomposite powders after 20 h milling. After 35 h milling, a balance between grain

refinement and thermal recovery due to the material itself was achieved, leading to the unchanged grain size.

The grain size of aluminum matrix in Al–Al₂O₃–B composite powders showed a zigzag decrease with the increase in the milling time and stabilized after 15 h of milling time, longer than that for Al–Al₂O₃–A composite powders. This indicates that the presence of bimodal-sized particles decreases the grain refining rate of the aluminum matrix in composite powders as compared with nano-sized particles. Considering the fact that the small particles are easily contained between the large particles, nano-sized particles may exist between the submicron-sized particles, which may hinder the interaction between the nano-sized particles and the metal matrix. This can lead to a decrease in dislocation density and a subsequent delay in the grain refinement process. Therefore, an increase in milling time is needed to raise the amount of plastic deformation of the metal matrix as well as dislocation density for grain refinement.

4 Conclusion

In this study, hybrid aluminum matrix composite powders reinforced with bimodal-sized Al₂O₃ particles were successfully produced by mechanical milling. Particularly, a 10% volume fraction of nano-sized Al₂O₃ particles was achieved. Two different methods were employed for the addition of Al₂O₃ particles into the aluminum powders. The structural evolution during the mechanical milling of the composite powders was studied using a combination of SEM, EDS, and XRD. The results show that when the submicron- and nano-sized Al₂O₃ particles were simultaneously added to the aluminum powders, the equiaxed morphology was observed, and the average particle size decreased and stabilized after 5 h of milling, the milling time to reach the steady state was shorter than that when they were added separately; at the same time, a more narrow particle size distribution was obtained, along with a more uniform distribution of Al₂O₃ particles in the aluminum matrix. This is because the presence of submicron-sized particles can destroy the clustering of nano-sized particles at the early stage of milling and decrease the ductility of composite powders, the fracture occurs before cold-welding causes the formation of aggregates. Simultaneous addition of submicron- and nano-sized Al₂O₃ particles resulted in decreasing grain size of aluminum matrix, although the grain size of aluminum matrix after completion of milling process is similar to the case where they were separately added, the grain refining rate of aluminum matrix decreased, arising from the decreased interaction between the nano-sized Al₂O₃ and aluminum matrix by adding the submicron-sized Al₂O₃ particles.

Fig. 7 Grain size and lattice strain as functions of milling time for Al–Al₂O₃–A and B composite powders

Acknowledgements The authors greatly acknowledge the financial support from the State Key Laboratory of Traction Power (Grant No. 2015TPL_Z01), the State Key Laboratory of Solidification Processing (Grant Nos. 82-TZ-2013 and SKLSP201609), the Fundamental Research Funds for the Central Universities (Grant No. 2682017CX090), and the “111” Project (B08040).

References

- [1] A. Mortensen, J. Llorca, *Annu. Rev. Mater. Res.* **40**, 243 (2010)
- [2] A. Abdollahi, A. Alizadeh, H.R. Baharvandi, *Mater. Sci. Eng., A* **608**, 139 (2014)
- [3] M. Alizadeh, M. Alizadeh, R. Amini, *J. Mater. Sci. Technol.* **29**, 725 (2013)
- [4] L. Lu, M.O. Lai, C.W. Ng, *Mater. Sci. Eng., A* **252**, 203 (1998)
- [5] M.R. Rezaei, S.G. Shabestari, S.H. Razavi, *J. Mater. Sci. Technol.* **33**, 1031 (2017)
- [6] J.H. Nie, J.Z. Fan, S.M. Zhang, S.H. Wei, T. Zuo, Z.L. Ma, Z.B. Xiang, *Acta Metall. Sin. (Engl. Lett.)* **27**, 875 (2014)
- [7] M. Tavoosi, F. Karimzadeh, M.H. Enayati, *Mater. Lett.* **62**, 282 (2008)
- [8] L.J. Zhang, F. Qiu, J.G. Wang, Q.C. Jiang, *Mater. Sci. Eng., A* **626**, 338 (2015)
- [9] D.S. Zhou, F. Qiu, Q.C. Jiang, *Mater. Sci. Eng., A* **596**, 98 (2014)
- [10] A. Alizadeh, E. Taheri-Nassaj, M. Hajizamani, *J. Mater. Sci. Technol.* **27**, 189 (2015)
- [11] J.C. Ye, B.Q. Han, Z. Lee, B. Ahn, S.R. Nutt, J.M. Schoenung, *Scr. Mater.* **53**, 481 (2005)
- [12] B. VijayaRamnath, C. Elanchezhian, M. Jaivignesh, S. Rajesh, C. Parswajinan, A.S.A. Ghias, *Mater. Des.* **58**, 332 (2014)
- [13] I. Ozdemir, S. Ahrens, S. Mücklich, B. Wielage, J. Mater. Process. Technol. **205**, 111 (2008)
- [14] M. TabandehKhorshid, S.A. JenabaliJahromi, M.M. Moshksar, *Mater. Des.* **31**, 3880 (2010)
- [15] L.J. Zhang, F. Qiu, J.G. Wang, H.Y. Wang, Q.C. Jiang, *Mater. Sci. Eng., A* **637**, 70 (2015)
- [16] Z. RazaviHesabi, A. Simchi, S.M. SeyedReihani, *Mater. Sci. Eng., A* **428**, 159 (2006)
- [17] B. Prabhu, C. Suryanarayana, L. An, R. Vaidyanathan, *Mater. Sci. Eng., A* **425**, 192 (2006)
- [18] K.A. Annelise, P.B. Carlos, A.B. Felipe, *Novel Synthesis and Characterization of Nanostructured Materials* (Springer, Berlin, 2013)
- [19] J.B. Fogagnolo, F. Velasco, M.H. Robert, J.M. Torralba, *Mater. Sci. Eng., A* **342**, 131 (2003)
- [20] C. Suryanarayana, *Prog. Mater. Sci.* **46**, 1 (2001)
- [21] S.S. RazaviTousi, R. Yazdani Rad, E. Salahi, I. Mobasherpour, M. Razavi, *Powder Technol.* **192**, 346 (2009)
- [22] C. Suryanarayana, N. Al-Aqeeli, *Prog. Mater. Sci.* **58**, 383 (2013)
- [23] M. Khakbiz, F. Akhlaghi, *J. Alloys Compd.* **479**, 334 (2009)
- [24] J.L.H. Rivera, J.J.C. Rivera, V.P. del Ángel, V.G. Febles, O.C. Alonso, R. Martínez-Sánchez, *Mater. Des.* **37**, 96 (2012)
- [25] R. Gostariani, R. Ebrahimi, M.A. Asadabad, M.H. Paydar, *Acta Metall. Sin. (Engl. Lett.)* (2017). <https://doi.org/10.1007/s40195-017-0640-1>
- [26] K.H. Chung, J.H. He, D.H. Shin, J.M. Schoenung, *Mater. Sci. Eng., A* **356**, 23 (2003)
- [27] L. Lu, M.O. Lai, W. Liang, *Compos. Sci. Technol.* **64**, 2009 (2004)
- [28] Y. Saberi, S.M. Zebajrad, G.H. Akbari, *J. Alloys Compd.* **484**, 637 (2009)