Manufacture of Nano-Sized Particle-Reinforced Metal Matrix Composites: A Review

Dongshuai Zhou · Feng Qiu · Huiyuan Wang · Qichuan Jiang

Received: 14 May 2014/Revised: 5 September 2014/Published online: 2 October 2014
© The Chinese Society for Metals and Springer-Verlag Berlin Heidelberg 2014

Abstract Compared to the micro-sized particle-reinforced metal matrix composites, the nano-sized particle-reinforced metal matrix composites possess superior strength, ductility, and wear resistance, and they also exhibit good elevated temperature properties. Therefore, the nano-sized particle-reinforced metal matrix composites are the new potential material which could be applied in many industry fields. At present, the nano-sized particle-reinforced metal matrix composites could be manufactured by many methods. Different kinds of metals, predominantly Al, Mg, and Cu, have been employed for the production of composites reinforced by nano-sized ceramic particles such as carbides, nitrides, and oxides. The main drawbacks of these synthesis methods are the agglomeration of the nano-sized particles and the poor interface between the particles and the metal matrix. This work is aimed at reviewing the ex situ and in situ manufacturing techniques. Moreover, the distinction between the two methods is discussed in some detail. It was agreed that the in situ manufacturing technique is a promising method to fabricate the nano-sized particle-reinforced metal matrix composites.

KEY WORDS: Fabrication; Metal matrix composites; Nanocomposite

1 Introduction

Metal matrix composites (MMCs) are hybrid materials in which rigid ceramic reinforcements are embedded in a ductile metal alloy matrix. They combine the best properties of the metal matrix and ceramic reinforcements, such as good ductility and toughness, high modulus, and strength. The attractive physical and mechanical properties that can be obtained for the MMCs, such as high specific modulus, strength, wear resistance, and thermal stability, have been documented extensively [1–6]. Hence, the MMCs have developed into a new type of material, which

have been widely applied in many fields, such as military, aerospace, automotive, and so on.

The family of the MMCs includes both particle- and fiber-reinforced MMCs. Compared to the continuous fiber-reinforced MMCs, the particle-reinforced MMCs are more interesting since they exhibit isotropic properties, and are easier to manufacture with lower costs [7–11]. As known, for most of the particle-reinforced MMCs, the typical size of the reinforcing ceramic particles is from several to tens of microns, resulting in considerable reduction in ductility and toughness [12–16]. This is mainly due to the easy initiation and propagation of cracks in the ceramic particles or at the interface. In order to enhance the mechanical properties, very small particles are desired for reinforcement ($\sim 1\ \mu\text{m}$ or even smaller). The decrease of the reinforcement particle size leads to an increase in the mechanical strength of the composites.

Recently, some researches indicated that the ductility and toughness of such MMCs can be significantly improved with simultaneous increase in strength by

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

D. Zhou · F. Qiu · H. Wang · Q. Jiang (✉)
Department of Materials Science and Engineering, Jilin
University, Changchun 130025, China
e-mail: jqc@jlu.edu.cn

Fig. 1 Possible distribution of the matrix and nano-sized reinforcement particles in the composite, where the reinforcements are distributed along the grain boundaries of the matrix phase **a** and the reinforcements are inside the matrix grains **b** (the open hexagons represent the matrix grains and the open and filled circles represent the reinforcements) [19]

reducing the particles to the nanometer range, i.e., the so-called nano-sized particle-reinforced MMCs. For example, Bahrami added the nano-sized (45–65 nm) SiC particles to 7075 aluminum matrix using friction stir welding technique. The nano-sized SiC particles were incorporated into the joint line. They pointed out that owing to the presence of the nano-sized SiC particles, the ultimate tensile strength and elongation were improved by 31% and 76.1% compared to those of the 7075 aluminum matrix [17]. Similarly, Zhou reported that the yield strength, ultimate strength, and the elongation of the as-cast 2.0 wt% nano-sized (50–100 nm) TiN particle-reinforced Al–Cu matrix composite were increased by 20.5%, 22.5%, and 104.5%, respectively compared to those of the Al–Cu matrix alloy [18].

The main challenge for the nano-sized particle-reinforced MMCs is how to fabricate them. At present, there are two main processing challenges: (1) dispersing the nano-sized particles in the metal matrix and (2) achieving a strong interfacial bond. Because of the low wettability of the nano-sized ceramic particles, the nano-sized ceramic particles would agglomerate in the grain boundaries, not to be homogeneously dispersed throughout the matrix, and the optimal exploitation of the strengthening potential is lost. Figure 1 shows the possible distribution of the matrix and reinforcements in the nano-sized particle-reinforced MMCs [19].

The production methods of the nano-sized particle-reinforced MMCs can be categorized into two major groups: *ex situ* and *in situ*. *Ex situ* synthesis route consists of adding nano-sized reinforcements to the liquid or powdered metal, while *in situ* processes refer to those methods leading to the generation of nano-sized ceramic-reinforced MMCs by reaction during processing. In this paper, we will provide an overview of the manufacturing methods of the nano-sized particle-reinforced MMCs along with a clear understanding of advantages and disadvantages.

2 *Ex situ* Methods

2.1 Powder Metallurgy

Powder metallurgy (P/M) is a common method to manufacture the nano-sized ceramic particle-reinforced MMCs [20–24]. Blending of matrix and reinforcement powders followed by hot or cold pressing and sintering is a standard fabrication sequence; a schematic of typical powder metallurgy processing scheme is shown in Fig. 2 [25]. The advantages of this process are flexibility and the ability to produce near-net-shaped components. Moreover, agglomeration of the nano-sized reinforcing particles can be minimized by homogeneously mixed powders. The disadvantages of the process are that it needs a long period and high cost.

Kang *et al.* fabricated aluminum matrix composite with different volume fractions of nano-sized (50 nm) Al₂O₃ particles using P/M. This result revealed that with the addition of a small amount (~1 vol%) of nano-sized Al₂O₃ in the Al matrix, the hardness and the tensile strength of the composites are similar to those of the 10 vol% SiCp (13 μm)/Al composite, and the yield strength of the former is higher than that of the latter. Compared to the Al matrix, the 4.0 vol% nano-sized Al₂O₃/Al composite possesses the highest hardness, yield strength, and tensile strength which are improved from 31.8 to 66.6 HRF, from 75 to 180 MPa, and from 150 to 245 MPa, respectively. However, as the particle volume fraction increased, the extent of agglomerations of the particles is increased. When the content of nano-sized Al₂O₃ particles in the composites exceeded 4 vol%, the agglomerations reduce the amount of effective nano-sized particles, and the particle strengthening effect diminishes [22]. More importantly, the particle agglomeration is the source for initiation and propagation of cracks under low stress due to the poor bonding between the particles and matrix, stress concentration, and the existence of porosities.

2.2 Mechanical Milling

Mechanical Milling (MM) is a solid powder processing technique. The ceramic particle size decreases to the nano-scale during the high-energy mechanical milling [18, 26–29]. Flexibility and scalability are the key advantages of the process. It is very easy to obtain nanostructure in most cases, and a high volume fraction of the reinforcements can be introduced into the composite. Contamination by the milling tool and the atmosphere are the main disadvantages of the process. On the other hand, the MM method is just a solid powder processing technique. The nano-sized particle-reinforced MMCs are usually manufactured by powder metallurgy or extrusion after the MM process.

Fig. 2 Schematic of typical powder metallurgy processing scheme [25]

Fig. 3 The variation of the B_4C particle size as a function of milling time [29]

Khakbiz and Akhlaghi [29] studied the characterization of Al- B_4C nanocomposite powders by MM. It was found that nano-sized (100 nm) B_4C particles can be produced from commercially available (700 nm) B_4C particles after 110-h mechanical milling, as shown in Fig. 3. Nemati et al. [26] manufactured the nano-sized TiC particle-reinforced Al-4.5 wt% Cu matrix composites using PM technique after the ball-milled mixing in a high attritor. The results indicated that the hardness and wear resistance of the nano-sized particle-reinforced composites are higher than those of the micro-sized TiC particle-reinforced composites. With the increasing volume fraction of nano-sized TiC particles up to 5%, the hardness and wear resistance of the composites continuously increased. After that level, particle agglomeration reduced the amount of effective particle available and the particle strengthening effect diminished.

2.3 Stir Casting

Stir mixing technique which is wildly utilized to mix micro-sized particles in metal melts has recently been

modified for dispersing small volume percentages of nano-sized particles in metallic melts [30, 31]. Mazahery and Shabani [31] studied the microstructure and mechanical properties of the nano-sized SiC particle (50 nm)-reinforced A356 aluminum matrix composites via stir casting. Optical microscope examination reveals that the nano-sized SiC particle refined the matrix grains. The addition of the nano-sized SiC particles results in significant improvement in hardness, yield strength, and ultimate tensile strength of the composites. Compared to the A356 matrix alloy, the highest yield strength and ultimate tensile strength are obtained with the addition of 3.5 wt% nano-sized SiC particles, improved from 121 to 145 MPa and from 150 to 295 MPa, respectively.

Because of the increasing surface area together with the reduction in particle size, inserting the particles in the melt and homogeneously dispersing them is a challenge. The increase of interfacial energy raises the free energy of the system, causing agglomerates to form. Therefore, some alternative stirring tools have been developed to improve the dispersion. Ultrasonic-based solidification is the most successful one (see Fig. 4) [32]. It was reported that ultrasonic cavitation can produce transient (in the order of nanoseconds) micro “hot spots” that can have temperatures of about 5,000 °C, pressures above 1,000 atm (more than 100 MPa), and heating and cooling rates above 10^{10} K/s [33]. The strong impact coupling with local high temperature can break nano-sized particle clusters and clean the particle surface. Thus, ultrasonic cavitation could significantly improve the dispersion of the nano-sized particles in the metal melts (Fig. 5) [34].

At present, a lot of researches have been conducted to manufacture the nano-sized particle-reinforced MMCs via

ultrasonic solidification processing [32–41]. Lan *et al.* [34] fabricated the nano-sized SiC particle-reinforced AZ91D magnesium composites using ultrasonic non-linear effects to disperse the nano-sized SiC particles in molten AZ91D alloy. Experimental results showed a nearly uniform distribution of the nano-sized SiC particles in the AZ91D matrix. The agglomerates have been greatly improved

Fig. 4 Schematic of ultrasonic solidification processing [32]

compared with the severe agglomerates in composites fabricated by traditional mechanical stirring, as shown in Fig. 6 [34]. Similarly, 2.0-wt% nano-sized SiC-reinforced Mg–Al–Si matrix composites were successfully fabricated by ultrasonic cavitation-based dispersion of the nano-sized SiC particles in molten Mg–Al–Si alloy melt. With the addition of the nano-sized SiC particles, the grain size of the Mg–Al–Si matrix was refined, and the SiC particles bonded well with the Mg–Al–Si matrix without forming an intermediate phase. The yield strength, ultimate tensile strength, and ductility of the composite were improved from 61.9 to 82.1 MPa, from 144.8 to 177.9 MPa, and from 8.8 to 9.5%, respectively [41].

In brief, ex situ processes as described above have their distinct advantages and disadvantages. The main shortcomings of ex situ processes are (a) interfacial reactions between the reinforcements and the metal matrix may occur; (b) oxide layers around the particles increase the surface energy, decreasing wettability of the system; (c) particle agglomeration and clustering occur.

Fig. 5 Schematic of the cavitation and steaming effects for nanoparticle dispersion and wetting in the metal melts: **a** formation and growth of bubbles; **b** collapsing of bubbles; **c** break-up and re-dispersion of nanoparticle clusters [34]

Fig. 6 SEM images showing SiC clusters in AZ91D alloys which were produced by traditional mechanical stirring **a** and ultrasonic stirring method **b** [34]

3 In situ Methods

For the MMCs which were fabricated by in situ method, the reinforcements are synthesized in the metal matrix by chemical reactions among elements or between element and compound during the composite fabrication. Compared to the conventional MMCs produced by ex situ methods, the in situ MMCs exhibit the following advantages: (a) the in situ-formed reinforcements are thermodynamically stable in the matrix, leading to less degradation in elevated temperature applications; (b) the reinforcement-matrix interfaces are clean, resulting in a strong interfacial bonding; (c) the in situ-formed reinforcing particles are finer in size and their distribution in the matrix is more uniform, yielding better mechanical properties [42].

Because of the great potential application of in situ MMCs, various processing techniques have been developed for MMC production during the past decade. Using these approaches, in situ MMCs with a wide range of matrix materials (including aluminum, titanium, copper, nickel, and iron) and second-phase particles (including borides, carbides, nitrides, oxides, and their mixtures) have been produced. The four classes of the in situ processes are described and discussed below.

3.1 Solid–Liquid Reaction Process

In this process, reactants (elements or compounds) react in situ to form reinforcing phases in the presence of a third metal phase, or reactants react with some component in the melt to form in situ ceramic reinforcements. In essence, this process is a solvent-assisted reaction wherein the reinforcing particles are generated in the solvent medium (the matrix) via diffusion of the components. This process has been widely adopted to fabricate in situ MMCs. According to the processing features, this process can be further grouped into the following processing routes.

Self-propagating high-temperature synthesis (SHS), which was developed in the last 1960s, has been developed as a new technique to produce MMCs [43–46]. Conversion of chemical energy to thermal energy is the key principle of the process. The SHS involves the propagation of a dynamic combustion wave which is sustained by a large enthalpy release at the reaction front. In order to maintain the reaction to become self-sustaining, (a) the reaction must be highly exothermic, (b) one of the reactions should be a liquid or a vapor to enhance the transportation for the reaction front, and (c) the rate of heat propagation must be less than that of the heat generation, thereby ensuring that the reaction is not extinguished [47–49]. The main advantages of the SHS process are efficient utilization of the reaction energy, and high speed of synthesis and purification due to volatilization of impurities. The main

drawback of the process is the high porosity in the final product, which can be eliminated by post-synthesis treatment such as hot pressing, HIPping, remelt casting, etc.

The SHS process has been extensively employed for the production of micro-sized ceramic particle-reinforced MMCs. However, reports on the in situ SHS processing of nano-sized ceramic particle-reinforced MMCs are very limited. The SHS is quite challenging to produce the nano-sized ceramic particle-reinforced metal matrix composites because the combustion temperature will lead to considerable coarsening of the ceramic particles. At present, the usual method for synthesizing the nano-sized ceramic particles through the SHS is the addition of volatile diluents such as NaCl to the SHS reactants.

Nersisyan *et al.* investigated the combustion process of a titanium–carbon system with sodium chloride as an inert diluent. It was shown that the sodium chloride not only decreases the combustion temperature but also makes effective protective shells around primary carbide crystals and keeps this ultrafine structure up to the end of combustion. As a result, the nano-sized TiC powders were successfully obtained [50]. Similarly, nano-sized TiB₂ and ZrB₂ particles were also prepared by adding NaCl to the SHS reactants [51–53].

On the other hand, the addition of a second metal (Me) such as Al, Cu, and Fe can also decrease the combustion temperature and thus prevent the ceramic particles from further growth. For example, Song *et al.* [54] fabricated the TiC particles in situ by SHS reaction with 0–40 mass% Al in the total Al–Ti–C elemental powder mixtures. They pointed out that with the Al contents increasing, the reaction temperature decreased and the TiC particle size evidently reduced from 3 μm to 400 nm. However, when the content of Me exceeds 50 wt%, the SHS reaction tends to be incomplete or even cannot be ignited [54, 55]. Generally, this situation can be improved using finer C-source.

Jin *et al.* [56] pointed out that in the Me–Ti–C systems, the Me–Ti liquid forms first during the heating. The carbon then diffuses into the Me–Ti liquid, and when a critical concentration is achieved, the TiC begins to form by the reaction between [C] and [Ti]. Accordingly, the diffusion of carbon in the melt metal is a key step to form TiC. Therefore, the carbon source with finer size will make the combustion reaction process more thorough. Jin *et al.* [56] firstly discovered that with the use of the carbon nano-tube (CNT) of high chemical activity, nano-sized TiC particles with different growth shapes which were synthesized by SHS in the 80 wt% metal (Cu, Al, and Fe)–Ti–CNT systems. As shown in Fig. 7, with the increasing Me content, the TiC particles formed in the Cu–Ti–CNT, Al–Ti–CNT and Fe–Ti–CNT systems show a significant decrease in size.

Direct reaction synthesis (DRS) refers to a process in which reactant powders or compacts of reactant powders

Fig. 7 Morphologies of the TiC particles formed in the Me–Ti–CNT systems: **a** Me = 50 wt% Cu; **b, c** Me = 60 wt% Cu; **d, e** Me = 70 wt% Cu; **f** Me = 80 wt% Cu; **g** Me = 50 wt% Al; **h, i** Me = 60 wt% Al; **j** Me = 70 wt% Al; **k** Me = 80 wt% Al; **l, m** Me = 50 wt% Fe; **n** Me = 60 wt% Fe; **o, p** Me = 70 wt% Fe; **q, r** Me = 80 wt% Fe [56] (The scale bars in the inset images represent 100 nm)

Fig. 8 Schematic diagram of in situ direct reaction synthesis apparatus [58]

are directly added into metal melt and the ceramic reinforcing particles are formed in situ through the exothermic reaction among reactants or between the reactant and some component in the melt, as shown in Fig. 8 [57–59]. This process is difficult to control and determine. In situ nano-sized Al_2O_3 and Al_3Zr particle-reinforced aluminum matrix composites were fabricated by DRS in the system of $\text{Al-Zr}(\text{CO}_3)_2$. The mean particle size is about 80 nm, and the nano-sized particles are well distributed in the Al

matrix. The ultimate tensile strength and yield strength of nano-sized $(\text{Al}_2\text{O}_3 + \text{Al}_3\text{Zr})/\text{Al}$ composites are enhanced by increasing the volume fraction of particles and are markedly higher than those of the micro-sized $(\text{Al}_2\text{O}_3 + \text{Al}_3\text{Zr})/\text{Al}$ composites. When the volume fraction of particles is 8%, the ultimate tensile strength, yield strength, elongation, and Vickers hardness of the nano-sized $(\text{Al}_2\text{O}_3 + \text{Al}_3\text{Zr})/\text{Al}$ composite are 326.7 MPa, 245.6 MPa, 18.6%, and 125, respectively [58].

3.2 Solid–Solid Reaction Process

Reaction Milling (RM) is the mechanical alloying process accompanied by a solid-state reaction. In this process, the powders are milled without the aid to produce fine dispersions of oxides and carbides in metal matrix [60–62]. The nano-sized particle-reinforced MMCs are manufactured by PM or extrusion after the RM process. Nano-sized TiC-reinforced Mg matrix composites have been synthesized by mechanically milling Mg, Ti, and C elemental powders. The XRD patterns of Mg–Ti–C mixture during milling showed the formation of TiC with increasing milling time, as shown in Fig. 9. The nano-sized TiC particles were dispersed in the magnesium matrix. The composite exhibited remarkably high ductility and compressive strength [61].

Fig. 9 Evolution of Mg–Ti–C mixtures during milling [61]

Fig. 10 Schematic of gas–liquid reaction process [67]

3.3 Liquid–Liquid Reaction Process

The mixalloy process patented by Sutek Corporation has been applied to manufacture nano-sized ceramic particle-reinforced MMCs [63–65]. Two streams of metal melts containing ceramic inclusions interact with each other in a reaction chamber to form refractory particles. The mixture is then rapidly cast. The disadvantages of this method are complexity and difficult to control. This technology is effective in producing copper matrix composites reinforced with nano-sized TiB_2 particles (50 nm) for the electrical applications [65].

3.4 Gas–Liquid Reaction Process

An economical way to produce MMCs is by the direct interaction between the liquid metal (with alloying elements) and the gaseous species to produce fine dispersions

of thermodynamically stable refractory compounds (Fig. 10) [66–70]. The matrices are usually non-ferrous metals such as Al, Cu, Mg, Ni, or Ti and the reinforcement phases could be carbides, nitrides, or a good admixture of both. The reactive gas is bubbled through the alloy melt which is maintained at a pre-determined temperature where accelerated reaction takes place between the gaseous species and the solute element in the alloy. The main advantages of this process are its amenability to continuous casting and to near-net-shape manufacturing. However, the process has some drawbacks, e.g., the volume fraction of the reinforcing phase is low and limited to only those systems that react rapidly with gaseous species. The aluminum matrix containing titanium nitride particles was fabricated by an in situ process in which nitrogen gas reacted with titanium in the liquid melt to form TiN. The tensile and yield strength increased by up to 20% after the formation of TiN particles in the Al alloy matrix, whilst the hardness increased by up to 27%. The abrasive and sliding wear resistance increased with the in situ formation of the TiN particles [67].

4 Conclusions

The various pathways to manufacture nano-sized particle-reinforced metal matrix composites have been presented and discussed in this review article. It is quite clear that the challenges we face in manufacturing the nano-sized particle-reinforced metal matrix composites for structural applications are daunting. Fabrication of nano-sized particle-reinforced MMCs is much more complicated than that of micro-sized particle-reinforced MMCs. To be able to manufacture nano-sized particle-reinforced MMCs with a homogeneous distribution of the second-phase nano-sized particles is the biggest critical issue. As presented and discussed in this review, this requirement remains to be the most difficult one especially for the ex situ processing methods. Homogeneous distribution of the nano-sized particles is more readily attainable via in situ processing methods. Ex situ methods are characterized by the difficulty to introduce the reinforcement in the melt and effectively disperse it. Among the in situ processing methods, the SHS is the most effective technique to produce the nano-sized particle-reinforced metal matrix composites.

Acknowledgments This work was financially supported by the National Natural Science Foundation of China (Nos. 51171071, 50971065 and 50531030), National Basic Research Program of China (No. 2012CB619600), the Research Fund for the Doctoral Program of High Education of China (No. 20130061110037) and the Project 985-High Performance Materials of Jilin University.

References

- [1] S. Rathod, O.P. Modi, B.K. Prasad, A. Chrysanthou, D. Vallauri, V.P. Deshmukh, A.K. Shah, *Mater. Sci. Eng. A* **502**, 91 (2009)
- [2] Z.Y. Ma, R.S. Mishra, S.C. Tjong, *Acta Mater.* **50**, 4293 (2002)
- [3] T. Laha, S. Kuchibhatla, S. Seal, W. Li, A. Agarwal, *Acta Mater.* **55**, 1059 (2007)
- [4] L. Ci, Z. Ryu, N.Y. Jin, M. Ruhle, *Acta Mater.* **54**, 5367 (2006)
- [5] X.D. Hui, Y.S. Yang, Z.F. Wang, G.Q. Yuan, X.C. Chen, *Mater. Sci. Eng. A* **282**, 187 (2000)
- [6] A.R. Kennedy, D.P. Weston, M.I. Jones, C. Enel, *Scr. Mater.* **42**, 1187 (2000)
- [7] Y.F. Liang, J.E.S.Q. Dong, *Mater. Sci. Eng. A* **527**, 7955 (2010)
- [8] N. Nemati, R. Khosroshahi, M. Emamy, A. Zolriasatein, *Mater. Des.* **32**, 3718 (2011)
- [9] K.L. Tee, L. Lu, M.O. Lai, *Mater. Sci. Technol.* **17**, 201 (2001)
- [10] M.O. Shabani, A. Mazahery, J. Mater. Sci. **46**, 6700 (2011)
- [11] K.S. Prasas, C.S. Rao, D.N. Rao, *Acta Metall. Sin. (Eng. Lett.)* **25**, 179 (2012)
- [12] X.W. Zeng, W.G. Zhang, N. Wei, R.P. Liu, M.Z. Ma, *Mater. Sci. Eng. A* **443**, 224 (2007)
- [13] Q.C. Jiang, X.L. Li, H.Y. Wang, *Scr. Mater.* **48**, 713 (2003)
- [14] M.K. Premkumar, M.G. Chu, *Mater. Sci. Eng. A* **202**, 172 (1995)
- [15] X.C. Tong, A.K. Ghosh, J. Mater. Sci. **36**, 4059 (2001)
- [16] F. Tang, M. Hagiwara, J.M. Schoenung, *Mater. Sci. Eng. A* **407**, 306 (2005)
- [17] M. Bahrani, K. Dehghani, M.K.B. Givi, *Mater. Des.* **53**, 217 (2014)
- [18] D.S. Zhou, F. Qiu, Q.C. Jiang, *Mater. Sci. Eng. A* **596**, 98 (2014)
- [19] C. Suryanarayana, N. Al-Aqeeli, *Prog. Mater. Sci.* **58**, 383 (2013)
- [20] Z.Y. Ma, Y.L. Li, Y. Liang, F. Zhang, J. Bi, S.C. Tjong, *Mater. Sci. Eng. A* **219**, 229 (1996)
- [21] R. Casati, F. Bonollo, D. Dellasega, A. Fabrizi, G. Timelli, A. Tuissi, M. Vedani, *J. Alloys Compd.* **11**, 125 (2013)
- [22] Y.C. Kang, S.L. Chan, *Mater. Chem. Phys.* **85**, 438 (2004)
- [23] R. Casati, M. Amadio, C.A. Biffi, D. Dellasega, A. Tuissi, M. Vedani, *Mater. Sci. Forum* **762**, 457 (2013)
- [24] S. Xu, M. Zhao, Z. Cai, N. Sun, F. Liu, B. Du, X. Zhang, Z. Ling, *Acta Metall. Sin. (Engl. Lett.)* **26**, 385 (2013)
- [25] C. Borgonovo, D. Apelian, *Mater. Sci. Forum* **678**, 1 (2011)
- [26] N. Nemati, R. Khosroshahi, M. Emamy, A. Zolriasatein, *Mater. Des.* **32**, 3718 (2011)
- [27] M.F. Zawrah, R.A. Essawy, H.A. Zayed, A.H.A. Fattah, M.A. Taha, *Ceram. Int.* **40**, 31 (2014)
- [28] S.M. Zebarjad, S.A. Sajjadi, E.Z. Vahid karimi, *Res. Lett. Mater. Sci.* **10**, 1 (2008)
- [29] M. Khakbiz, F. Akhlaghi, *J. Alloys Compd.* **479**, 334 (2009)
- [30] A. Mazahery, H. Abdizadeh, H.R. Baharvandi, *Mater. Sci. Eng. A* **518**, 61 (2009)
- [31] A. Mazahery, M.O. Shabani, *Trans. Nonferrous Met. Soc. China* **22**, 275 (2012)
- [32] Y. Yang, J. Lan, X.C. Li, *Mater. Sci. Eng. A* **380**, 378 (2004)
- [33] K.S. Sulick, Y. Didenko, M.M. Fang, T. Hyeon, K.J. Kolbeck, W.B. Mcnamara, M.M. Middleleni, M. Wong, *Phil. Trans. R. Soc. Lond. A* **357**, 335 (1999)
- [34] J. Lan, Y. Yang, X.C. Li, *Mater. Sci. Eng. A* **386**, 284 (2004)
- [35] A. Sanaty-Zadeh, *Mater. Sci. Eng. A* **531**, 112 (2012)
- [36] X.C. Li, Y. Yang, X.D. Cheng, *J. Mater. Sci.* **39**, 3211 (2004)
- [37] G. Nandipati, R. Kommineni, N.R. Damera, R. Nallu, J. Mechan, *Civil Eng.* **7**, 1 (2013)
- [38] G. Cao, J. Koblika, H. Konsishi, X. Li, *Metall. Mater. Trans. A* **39**, 880 (2008)
- [39] Z.H. Wang, X.D. Wang, Y.X. Zhao, W.B. Du, *Trans. Nonferrous Met. Soc. China* **20**, 1029 (2010)
- [40] Y. Tsunekawa, H. Suzuki, Y. Genma, *Mater. Des.* **22**, 467 (2001)
- [41] G. Cao, H. Honishi, X. Li, *Mater. Sci. Eng. A* **486**, 357 (2008)
- [42] S.C. Tjong, Z.Y. Ma, *Mater. Sci. Eng. R* **29**, 49 (2000)
- [43] A.G. Merzhanov, I.P. Borovinskaya, *Dokl. Akad. Nauk. SSSR* **204**, 366 (1972)
- [44] H. Ding, X. Liu, L. Yu, G. Zhao, *Scr. Mater.* **57**, 575 (2007)
- [45] K. Wang, V.D. Krstic, *Acta Mater.* **51**, 1809 (2003)
- [46] F.A. Deorsola, I.C. Atias Adrian, G.A. Ortigoza Villalba, B. Debenedetti, *Mater. Res. Bull.* **46**, 995 (2011)
- [47] A.G. Merzhanov, in *Combustion and Plasma Synthesis of High-temperature materials*, ed. by Z.A. Munir, J.B. Holt (Weinheim, New York, 1990), pp. 1–26
- [48] J.J. Moore, H.J. Feng, *Prog. Mater. Sci.* **39**, 243 (1995)
- [49] J.J. Moore, H.J. Feng, *Prog. Mater. Sci.* **39**, 275 (1995)
- [50] H.H. Nersisyan, J.H. Lee, C.W. Won, *J. Mater. Res.* **17**, 2859 (2002)
- [51] A.K. Khanra, L.C. Pathak, S.K. Mishra, M.M. Godkhindi, *Mater. Lett.* **58**, 733 (2004)
- [52] A.K. Khanra, A.K. Khanra, L.C. Pathak, S.K. Mishra, M.M. Godkhindi, *J. Mater. Sci. Lett.* **22**, 1189 (2003)
- [53] H.E. Camurlu, F. Maglia, *J. Europ. Ceram. Soc.* **29**, 1501 (2009)
- [54] M.S. Song, B. Huang, M.X. Zhang, J.C. Li, *Int. J. Refractory Met. Hard Mater.* **27**, 584 (2009)
- [55] A. Saidi, A. Chrysanthou, J.V. Wood, J.L.F. Kellie, *J. Mater. Sci.* **29**, 4993 (1994)
- [56] S.B. Jin, P. Shen, D.S. Zhou, Q.C. Jiang, *Nanoscale Res. Lett.* **6**, 515 (2011)
- [57] R.N. Rai, G.L. Datta, M. Chakraborty, A.B. Chattopadhyay, *Mater. Sci. Eng. A* **428**, 34 (2006)
- [58] Y.T. Zhao, S.L. Zhang, G. Chen, X.N. Cheng, C.Q. Wang, *Comp. Sci. Technol.* **68**, 1463 (2008)
- [59] J.P. Tu, N.Y. Wang, Y.Z. Yang, W.X. Qi, F. Liu, X.B. Zhang, H.M. Lu, M.S. Liu, *Mater. Lett.* **52**, 448 (2002)
- [60] S. Hwang, C. Nishimura, P.G. Macormick, *Scr. Mater.* **44**, 2457 (2001)
- [61] D.L. Zhang, J. Liang, J. Wu, *Mater. Sci. Eng. A* **375**, 911 (2004)
- [62] Z. Sadeghian, B. Lotfi, M.H. Enayati, P. Beiss, *J. Alloys Compd.* **509**, 7758 (2011)
- [63] J.M. Han, Y.S. Han, S.Y. You, H.S. Kim, *J. Mater. Sci.* **32**, 6613 (1997)
- [64] Z. Liu, H. Fredriksson, *Metall. Mater. Trans.* **28**, 471 (1997)
- [65] A.K. Lee, L.E. Sanchez-Caldera, S.T. Oktay, N.P. Suh, *Adv. Mater. Proc.* **8**, 31 (1992)
- [66] C. Wang, H.Y. Gao, Y.B. Dai, X.M. Ruan, J.G. Shen, J. Wang, B.D. Sun, *J. Alloys Compd.* **490**, 9 (2010)
- [67] R.F. Shyu, F.T. Weng, C.T. Ho, *J. Mater. Process Technol.* **122**, 301 (2002)
- [68] R.F. Shyu, C.T. Ho, *J. Mater. Process Technol.* **171**, 411 (2006)
- [69] Q.J. Zheng, R.G. Reddy, *J. Mater. Sci.* **39**, 141 (2004)
- [70] Q.J. Zheng, R.G. Reddy, *Metall. Mater. Trans. B* **34**, 793 (2003)