Review on preparation techniques of particle reinforced metal matrix composites

*HAO Bin, CUI- Hua, LI Yong-bing, YANG Bin, ZHANG Ji-shan
(State Key Laboratory for Advanced Metals and Materials, Beijing University of Science and Technology, Beijing 100083, P. R. China)

Abstract: This paper reviews the investigation status of the techniques for preparation of metal matrix composites and the research outcomes achieved recently. The mechanisms, characteristics, application ranges and levels of development of these preparation techniques are analyzed. The advantages and the disadvantages of each technique are synthetically evaluated. Lastly, the future directions of research and the prospects for the preparation techniques of metal matrix composites are forecasted.

Key words: metal matrix composites; preparation techniques; advantages and disadvantages

CLC numbers: TG146.2; TG249 Document code: A Article ID: 1672-6421(2006)01-0009-06

The need for new engineering materials with the advancement of modern technology in the areas of aerospace, automotive and numerous other industries has lead to a rapid development of metal matrix composites (MMCs) [1]. They can be tailored to have outstanding mechanical and physical properties such as high specific strength and stiffness, good wear resistance, enhanced high-temperature performance, and better thermal and mechanical fatigue and creep-resistance than that of monolithic materials. Among the various matrix materials available, aluminum and its alloys are widely used in the fabrication of MMCs. This is because they are light weight, cost-competitive, suitable for production by various processing techniques and possess high strength and good corrosion resistance. In recent years, SiC particle reinforced Al matrix composites have received considerable attention to meet the challenges of thermal management in the rapidly increased power of advanced electronics.

Particle reinforced metal matrix composites are thought of as ideal structure materials. They have higher strength, higher rigidity ratio, higher Young's modulus, good wear-resisting properties and heat resisting properties, etc. The improved mechanical properties offered by MMCs have been attracting growing interest. It is predicted that the properties of many MMCs can be improved further if the factors that affect the mechanical behavior are better understood.

Over the last 30 years, more and more countries all over the world have been studying and competitively developing metal matrix composites, significant advances have been made in the matrix, reinforcement, preparation techniques, microstructures, mechanical property and rupture strength, etc. of MMCs materials. At present, particle reinforced metal matrix composites have been widely used in worldwide in aerospace and traffic transport industries, etc and have gradually gone to a modern industrial scale. For example, SiCp/Al composites prepared by Navy Flight Dynamical Laboratory of America have been used for manufacturing satellite transmission platforms and strutting pieces[2].

1 Preparation methods

There are many kinds of preparation methods by which we can produce particle reinforced metal matrix compositions. Here we introduce only a few of them.

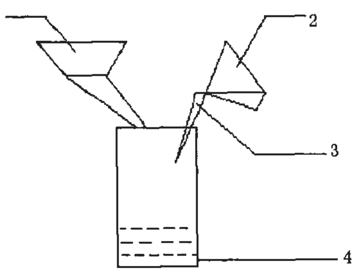
1.1 Suspension casting method

Figure 1 is suspension casting process with which MMCs can be made. The technical factors that affect the suspension results include: (1) the tapping temperature of the metal liquid; (2) the size of the suspending agent particles; (3) suspending agent volume fraction; (4) the melting time of the suspending agent.

Suspension casting method is a valuable production technology. It could control effectively the solidification process of the steel and iron castings[3]. Compared with the

*HAO Bin: Female, born in 1975, Ph. D. Research direction: The preparation of metal matrix composites.
E-mail: xiumeixiu@163.com

Received date: 2005-03-09 Accepted date: 2005-12-29



1. Suspending agent; 2. Crucible; 3. Molten liquid;
4. Suspension casting's liquid

Fig. 1 Schematic drawing of suspension casting

conventional casting method, suspension casting can improve the cooling velocity, refine microstructure, reduce the segregation of the micro-ingredients and improve the mechanical properties [4]. And this method is easy to operation, low cost and can achieve very good interface coherence between reinforcement particles and matrix, but it is difficult to make the suspending agent disperse uniformly in the molten liquid.

1.2 Powder metallurgy

Because of the difficulty in wetting ceramic particles with molten metal, the powder metallurgy was the first method developed. First, blend the matrix powder and the reinforcement particle powder and mill them. Next dry the mixture of particles and heat-press sinters them under different technology conditions. By this method, LI Ru-tie [5] had fabricated copper matrix composite; FAN Jian-zhong[6] had fabricated aluminum matrix composite.

The powder metallurgy route has several attractive features:

(1) It allows essentially any alloy to be used as the matrix.

(2) It also allows any type of reinforcement to be used because reaction between the matrix and reinforcement can be minimized by using solid state processing.

(3) Non-equilibrium alloys can be used as the matrix by using rapidly solidified material. This is particularly important where the composite is to be used for high temperature, and rapidly solidified alloys have much better elevated temperature strength than that of conventional alloys.

(4) High volume fractions of reinforcement are possible, thus maximizing the modulus and minimizing the thermal expansion coefficient of the composite.

The powder route also has some major disadvantages: it involves handling large quantities of highly reactive, potentially explosive, powders and the manufacturing route is relatively complex and limited in the initial product forms it can produce. As a result, the product is expensive in comparison with conventional wrought aluminum alloys, but this should be decreased with future scale-up.

1.3 Liquid infiltration

In 1986, the American Lanxide Corporation brought forward that alloy melt itself can infiltrate, i.e. infiltration method [7], for the first time. Liquid infiltration include: pressure infiltration and pressure-less infiltration. In the pressure infiltration process, a packed bed of ceramic particles is evacuated and then infiltrated by a pressurized melt to form a integrated composite hardener. The pressure infiltration route is a means of producing composite with a high volume fraction of reinforcement, and since the system is evacuated, the integrated composite has very low porosity. In the pressureless infiltration process, a packed bed of ceramic powder is infiltrated by a matrix alloy without any applied pressure in a nitrogen atmosphere. For example, ZHANG Jian-yun [8] fabricated aluminum matrix composite reinforced by SiC and Al_2O_3 by the pressureless infiltration method. Under the atmosphere, seeping agent can make the matrix liquid intermingle into the interspaces of reinforcement particles so that the composite can be formed easily. The fabricating steps are as follows:

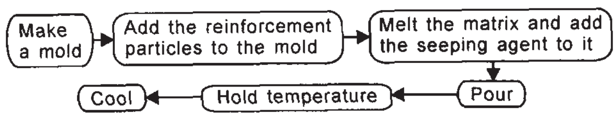


Fig. 2 The fabrication steps of pressureless infittration method

This pressure-less infiltration method does not need any additional pressure or vacuum, but how to choose the model of seeping agent and match the ratio are key questions. Here the seeping agent should have the properties of improving the surface oxide layer to increase the wettability between the matrix and the reinforcement particle and avoid a reaction happening between them, so that they can integrate fully. In addition, the pouring temperature, the holding temperature and the holding time for which the temperature is held are very important. (i) Pouring temperature: if the pouring temperature is too high, the effective ingredients of the seeping agent are easily burned so they can not carry out their functions; but if the pouring temperature is too low, the viscosity of the matrix liquid will be very high and the running quality will be very bad, which will prevent the matrix liquid from filling fully the interspaces of reinforcement particles. (ii) Holding temperature: if the temperature is too high, it will consume unnecessary energy and possibly damage the equipment. If the temperature is too low, the resulting material will have more cavities, then the fluidity of the matrix liquid is very bad and the seeping agent can not improve the wettability very well. (iii) Holding time: it will affect the thickness of infiltration and the compact property of the composite.

The infiltration method with simple technique does not need special equipment, and also the reinforcement particles do not need to be treated ahead of time. However, the reinforcement particles are not distributed uniformly in the matrix, the packed beds are easy to deform, and the size of grain is very large.

1.4 High temperature and high pressure method

By this method, LIU Hao-zhe had fabricated aluminum matrix nano-composite reinforced by SiC particle [9]. The sequence go as follows:

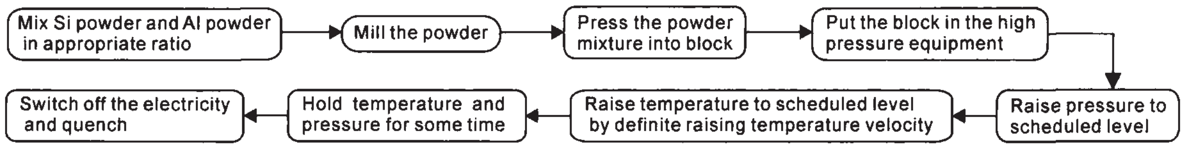


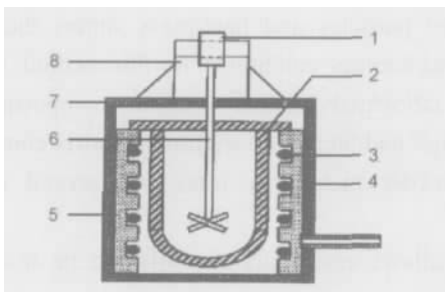
Fig. 3 The sequence of fabricating aluminum matrix composite reinforced by SiC partices using high temperature and high pressure method

The experimental results show that ultra-high pressure can effectively depress the boundary reaction, enhancing the condensed density, and improving the boundary bonding conditions. It is at the same time that this method can restrain the interface reaction between matrix and reinforcement, increase the density, and improve the interface connection. But it has a higher cost, because it needs special equipment to provide high pressure or vacuum.

1.5 Stirring casting method

At first, Surappa and Rohtgi [10] prepared particle reinforced metal matrix composites by the stirring casting method. Stirring casting is to add the reinforcement to the liquid matrix, and at the same time, stir the melt so as to make them mix uniformly to improve wettability between matrix and reinforcement. Stirring casting method is widely used in producing MMCs. There are four questions in the method. First, the wettability between the reinforcement particles and the matrix is very bad. Second, the reinforcement particles can easily aggregate in the matrix alloy. Third, it is easy to have an interface reaction between the matrix and the reinforcement particles. Fourth, it is easy to produce pores in the composite under no vacuum condition [11, 12]. Stirring casting methods include vacuum stirring casting and non-vacuum stirring casting. YUAN Guang-jiang [13], LI Ming-wei [14], GUI Man-chang [15] also prepared MMCs by this method.

The wettability problem between SiC particle and Al liquid can be solved successfully by this method [14]. The mechanical force provided by mechanical stirring will distribute the aggregated SiC particles into the Al liquid. Stirring casting method with a lower cost is easy to produce complex products. It needs relatively simple equipment, suitable for batch production. Figure 4 is the schematic drawing of vacuum stirring casting equipment [13]. The fabricating steps of stirring casing method are shown in Fig. 5.



1- d. c. motor; 2- crucible; 3- heater; 4- shell; 5- lining; 6- stirrer; 7- cover; 8- motor support

Fig. 4 Schematic drawing of vacuum stirring casting equipment

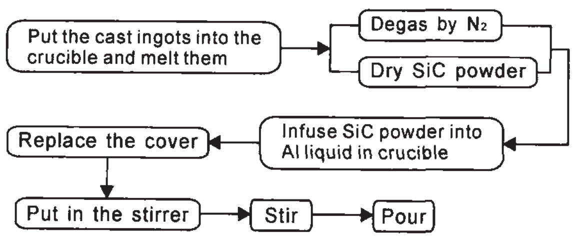


Fig. 5 The fabricating steps of stirring casting method

1.6 Spray deposition technology

The spray deposition process for unreinforced alloys had been developed by Singer[16]. The spray deposition process is a variant of the basic process, where ceramic particles are introduced into the spray and codeposited with the alloy droplets. By spray deposition technology, ZHANG Ji-shan[17] produced SiCp/Al composite. The experimental results show that the tensile strength, yield strength and elastic modulus of composites are higher than those of matrix alloy after adding SiC particle. This method has a wide application range and it can be used with any matrix and ceramic particle reinforcement phase.

Compared with conventional materials, spray-formed MMCs have a finer structure, near zero segregation and improved mechanical properties resulting from rapid solidification. A further benefit of spray forming is that it gives greater freedom to add any second or third phase, liquid or solid by entraining a stream of the added phase into the atomized spray before deposition. The spray-forming route can offers a cheap product that is usually intermediate in cost between stirring casting and powder metallurgy. It also has the advantage of avoiding or reducing the problem of an added phase. It is applicable to most systems and has the added advantage of having a fine non-segregated structure and good mechanical property of the composite.

1.7 XD™ process

The XD™ process is a patented composite manufacturing method developed initially by the Martin Marietta Corp.[18], in which ceramic particles are produced in-situ in a melt. It makes use of the exothermic reaction either between metal and metal or between metal and compound to in-situ produce a new desirable compound which becomes the ceramic reinforcement in the composite. A wide range of ceramic compounds can be formed by this process, but the two which have received most attention are TiB_2 and TiC, which can be formed by the following reactions:

$$2B+Ti+Al=TiB_2+Al$$
$$C+Ti+Al=TiC+Al$$

During production of the MMCs by XD™ technology, the reinforcement phase particles can be moistened by liquid metal and the combination of interface is very firm. But if the particle is too fine, it will obviously increase melt viscosity, so that it brings some difficulty to casting molding.The flow chart of XD™ process is shown in Fig.6.

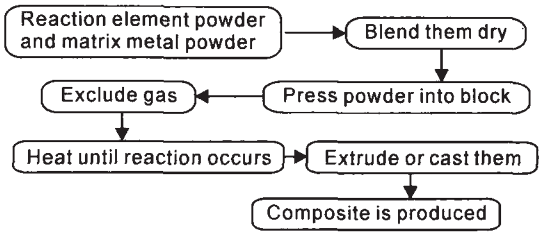


Fig. 6 Flow chart of XD™ process

1.8 Squeeze cast

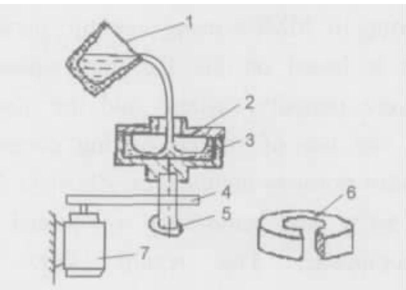
First, press reinforcement particles into packed beds and put them into the squeeze cast die, the die closes. Then matrix alloy liquid is pumped in and pressured during a controlled solidification process to have matrix liquid filter packed beds. Squeeze casting has become one of the accepted liquid metal routes for efficient and effective manufacturing of MMCs using ceramic performs. This acceptance is based on the fact that squeeze casting produces zero porosity castings and the assumption is made that the use of similar casting parameters also produces zero porosity composites. ZHANG Xue-nan [19] produced SiCw and nano-SiCp reinforced aluminum matrix composite. The results show that the reinforcements distribute homogenously in the matrix, and the interfacial bonding between matrix and reinforcement is good. Compared with the matrix alloy, the tensile strength and elastic modulus of the hybrid composite is obviously increased. When the volume fraction of SiC whiskers is kept constant, the tensile strength of the hybrid composite increases with an increased content of SiC particles. This method has a short production cycle and is easy to conduct batch production. The matrix liquid needs only a short infiltration time and has a rapid cooling rate that can reduce or eliminate interface reaction. But this method is not suitable for producing parts that have complex shape. When infiltration pressure is very big, the die and product's integrity will be affected.

1.9 Catalytic method

Under definite conditions, a kind or kinds of ceramic particles which have high rigidity and high Young's modulus are produced in-situ by a reaction between elements, or element and compound, in order to achieve the aim of strengthening the matrix. Press C (or B) and Ti etc. in the form of a powder into a prefabricated block, then add the matrix alloy melt which has an appropriate temperature so that the reaction takes place to get TiC (or TiB_2) etc. reinforcement particles. Stir and cast to get the MMCs reinforced by particles[20]. SHEN Yu-tian[21], Wang Zidong [22], and Dong Shengquan [23] found that particles produced in-situ can be distributed in the matrix and that the strength of the particles is higher than that of matrix. As the fine particles are produced within liquid metal, their surface has no pollution. There is basically no interface reaction. Production cost is relatively low too, But the preparation technique and the volume fraction are difficult to control.

1.10 Centrifugal casting

Centrifugal casting is a casting method which liquid metals are poured in rotary mold, then filled in it by centrifugal force and solidified. Electromotor is necessary to make casting rotate in centrifugal casting. Sketch map of vertical centrifugal casting is showed in Fig 7. By centrifugal casting, FENG Pei-zhong [24] fabricated WC particle reinforced steel matrix composites.



1-pouring ladle; 2-mold; 3-liquid metal; 4- strap wheel and strap; 5-rotation axis; 6-cast; 7-electromotor

Fig.7 sketch map of vertical centrifugal casting

The results show that the technique of centrifugal casting gave a fine microstructure. The distribution of WC particles in the composites was uniform with no apparent particle segregation. WANG Qu-dong[25] also produced Zn matrix composite by the centrifugal method. This method needs only simple equipment, and has a high production efficiency, low cost, does not need any emitting holes, so it increases the utilization ratio of liquid metal. That fact that the liquid metal solidifies under centrifugal force can give fine structures, but it is easy to produce density segregation.

1.11 Combined stirring cast and in-situ reaction

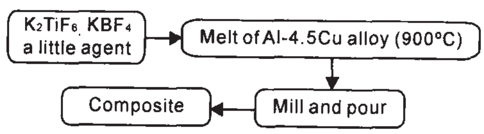
This method is to combine stirring cast and in-situ reaction. ZHAO De-gang [26] produced (TiB_2+SiC)/ZL109 composite by this method. First, melt the matrix alloy ZL 109 and heat it to about 780 ℃ in a medium frequency induction furnace. Then put KFB_4, K_2TiF_6 and SiC particle powders that are mixed equally into the Al matrix liquid and stir the melt using a graphite stick. After the reaction ends and the temperature falls to 730 ℃, add Al-P alloy to have metal modification. Lastly, pour the liquid alloy into the casting mold. This method solves the problem that stir casting produces a single SiC particle reinforced composite, which has a poor mechanical performance under ordinary pressure. The composite produced by the combined method has a higher rigidity than that of the composite reinforced by SiC particles only, and the particles are generally distributed uniformly in the matrix, but there are some areas where particles aggregate.

1.12 Self-propagating high-temperature synthesis (SHS) method

An important feature of SHS reactions is the self-sustaining reaction front. Typically, the green compact of reactants is ignited and the reaction front subsequently propagates in a wavelike fashion through the sample until completion. This method has several advantages, such as high-purity products, rapid formation and no need for high temperature furnace processing. But there are three requirements. Firstly, the reaction must be highly exothermic. Secondly, one of the reactants should form a liquid or vapor phase, in order to facilitate the diffusion of the fluid phase reactant to the reaction front. Thirdly, the rate of heat dissipation must be less than the rate of heat generation. CHEN Kan-ghua produced SiCp/Al composite by this technology[27]. The results show that a composite with high SiC content can be got by gravity precipitation of coated SiC particles in an Al melt at 800 ℃. It was also shown that SHS reaction has little effect on the coefficient of thermal expansion of the composite. The intense SHS reaction can harm the thermal conductivity factor of the composite because of the low heat transfer rate of the coating of the SiC particles. Proper SHS can be used to produce a composite with low coefficient of thermal expansion and high conductivity.

1.13 Reaction of mixed salt

This method that the London Scandinavian Metallurgy Company put forward in terms of aluminum alloy thinning crystal particle technology is a new technology by which metal-matrix composites can be prepared [28]. Salts which contain Ti (such as K_2TiF_6) and B (such as KBF_4) are put into a high-temperature matrix metal melt. The Ti and B from salts will be deoxidized by metal and react to produce TiB_2 reinforcement particles after excluding by product. Pour the melt and get TiB_2 particle reinforced MMCs[29].



2 Prospect

Metal matrix composites can be made in a number of ways, each of which has certain advantages coupled with disadvantages and each of which tends to satisfy a different niche of the market. We can choose a method that can satisfy our needs. With the development of science and technology, the more and better preparation techniques can produce better particle-reinforced metal matrix composites, which have better synthetical properties.

To sum up, many research organizations and production units all over the world have thought much about particle-reinforced metal matrix composites. Metal matrix composites must bring into play important roles in the fields of new material metallurgy, aviation, aerospace, automotive, etc. in the 21st century.

Reference:

[1] LEE K B, KWON H. Interfacial reaction in SiCp/Al composite fabricated by pressure-less infiltration. Scripta Materialia., 1997, 36 (8): 847-852.

[2] CUI Yan. Aerospace applications of silicon carbide particulate reinforced aluminum matrix composite. Journal of Materials Engineering, 2002 (6): 3-6. (in Chinese)

[3] WANG Jin-hua. Suspension Casting. Beijing: National Defence Industry Press, 1982. (in Chinese)

[4] WANG Hong-xia, Chang Yan-hong, XU Lin. The effect of suspension casting on the microstructure and properties of ZA27 alloy. Research Studies on Foundry Equipment, 2002 (2): 4-6. (in Chinese)

[5] LIU Ru-tie, LI Xi-bin. Particle-reinforced copper matrix composites for heat-sinks. Materials Science and Engineering, 2002, 20 (4): 534-536.

[6] FAN Jian-zhong, SANG Ji-mei, ZHANG Yong-zhong, et al. The special distribution of reinforcements in aluminum matrix composite. Acta Metallurgica Sinica. 1998, 34 (11): 1199-1204.

[7] URQUHART A W. Molten metals sire MMCs, CMCs. Advanced Materials and Processes. 1991 (7): 25-28.

[8] ZHANG Jian-yun, HUA Xiao-zhen, ZHOU Xian-liang. New technique of making aluminum matrix composite reinforced by ceramic particles and its wear resistant properties. Materials for Mechanical Engineering. 1996, 20 (4): 26-28. (in Chinese)

[9] LIU Hao-zhe, HE Hong-liang, WANG Lu-hong, et al. Synthesis of SiCp/Al nanocomposite under ultra-high pressure. Chinese Journal of High Pressure Physics, 1999, 13 (1): 1-6. (in Chinese)

[10] REN De-liang, QI Hai-bo, DING Zhan-lai, et al. Study on the stir mixing fabricating process of SiCp/Al composites. Cast Technology, 1999(2): 41-43. (in Chinese)

[11] ZHANG Guo-ding, ZHAO Chang-zheng. Metal Matrix Composite. Shanghai: Shanghai Jiaotong University Press, 1999. (in Chinese)

[12] CLYNE T W, WITHERS P J. An Introduction to Metal Matrix Composite. Cambridge: Cambridge University Press, 1993.

[13] YUAN Guang-jiang, ZHANG Wen-feng, WANG Dian-bin, et al. Preparation and cutting property of SiC particles reinforced alumininum matrix composite. Acta Materiae Compositae Sinica, 2000, 17 (2): 38-42. (in Chinese)

[14] LI Ming-wei, HAN Jian-min, LI Wei-jing, et al. Abstraction research on porosity of SiCp/ZL101 composites by stirring cast. Journal of Northern Jiaotong University, 2004, 28 (1): 100-103. (in Chinese)

[15] GUI Man-chang, WU Jie-jun, WANG Dian-bin, et al. Study on castable ZL101A/SiCp composites. Foundry, 2001, 50 (6): 332-336. (in Chinese)

[16] LLOYD D J. Particle reinforced aluminum and magnesium matrix composites. Int. Mater. Rev., 1994, 39 (1): 1-22.

[17] ZHANG Ji-shan, ZHANG Wei-jun, CUI Hua, et al. Mechanical properties of spray deposited Ni_3Al alloys and 2618Al+SiCp metal matrix composites. Journal of University of Science and Technology Beijing, 1997, 19 (1): 7-14. (in Chinese)

[18] JIANG W-h, SONG G-h, HAN X-l, et al. Synthesis of TiC/Al composites in liquid aluminum. Material Letters, 1997, 32 (2-3): 63-65.

[19] ZHANG Xue-nan, GENG Lin, ZHENG Zhen-zhu, et al. Fabrication and evaluation of Al-based hybrid composites reinforced with SiC whiskers and SiC nano-particles. The Chinese Journal of Nonferrous Metals, 2004, 14 (7): 1101-1105. (in Chinese)

[20] LI Jin-feng, ZHANG Zhao, ZHANG Jian-qing. Review on In-situ particle-reinforced metal-matrix composites (MMCs). Material Science and Engineering, 2002, 20 (3): 453-456.

[21] SHEN Yu-tian, CUI Chun-xiang, MENG Fan-bin, et al. Fabrication of Cu-Al_2O_3 composites with high strength and electrical conductivity. Acta Metallurgica Sinica, 1999, 35 (8): 888-892.

[22] WANG Zi-dong, ZENG Song-yan, LI Qing-chun. Preparation of in-situ TiC reinforced Al composite by contact-reaction. Acta Metallurgica Sinica, 1994, 30 (7): 314-317.

[23] DONG Sheng-quan, GUO Yong-chun, LI Gao-hong. The study on synthesizing process and mechanical propertites of the nano-particulate-reinforcement aluminum matrix composites. Hot Working Technology, 2002(3): 43-44. (in Chinese)

[24] FENG Pei-zhong, QIANG Ying-huai, WANG Xiao-hong, et al. Microstructure and fracture characteristics of WC particles reinforced steel matrix composites by centrifugal casting. Foundry, 2004, 53 (6): 428-431. (in Chinese)

[25] WANG Qu-dong, WEI Yin-hong, CHEN Wen-zhou, et al. In-situ (Mg_2Si+Si)/Zn matrix composite fabricated by centrifugal casting. The Chinese Journal of Nonferrous Metals, 2003, 13 (6): 1441-1446. (in Chinese)

[26] ZHAO De-gang, LIU Xiang-fa, BIAN Xiu-fang. Fabrication and mechanical properties of (TiB_2+SiC)/ZL109 composites. Foundry, 2004, 53 (2): 97-100. (in Chinese)

[27] CHEN Kang-hua, XIE Sheng-hui, LIU Hong-wei, et al. Reactive process and thermal properties of self-propagated SiCp/Al composites. The Chinese Journal of Nonferrous Metals, 2000, 10 (S1): 19-22. (in Chinese)

[28] DAVIES P, KELLIE J L F, WOOD J V. Development of cast aluminum MMCs. Key Engineering Materials, 1993, 77: 357-362.

[29] CHEN Zi-yong, CHEN Yu-yong, SHU Qun, et al. TiB_2/Al-4.5Cu composite by reaction of mixed salts in molten metal. Special Casting and Nonferrous Alloys, 1997(6): 1-4. (in Chinese)