Influence of stirring speed on SiC particles distribution in A356 liquid

Yao Shasha, *Zhang Peng, Du Yunhui, Zhang Jun, and Lu Xiaopeng
(School of Mechanical & Controlled Engineering, Beijing Jiaotong University, Beijing 100044, China)

Abstract: A straight-blade mechanical stirrer was designed to stir A356-3.5vol%SiC_p liquid in a cylindrical crucible with the capability of systematically investigating the influence of rotating speed of stirrer on the distribution of SiC particles in A356 liquid. The experimental results show that the vertical distribution of SiC particles in A356 liquid can be uniform when the rotating speed of stirrer is 200 rpm, but the radial distribution of SiC particles in A356 liquid is always nonhomogeneous regardless of the rotating speed of stirrer. The radial centrifugalization ratio of SiC particles in A356 liquid between the center and the periphery of crucible increases with the rotating speed of stirrer. The results were explained in the light of SiC particles motion subject to a combination of stirring and centrifugal effect.

Key words: straight-blade mechanical stirring; influence; centrifugalization; distribution; SiC particles
CLC numbers: TG249.9/292 Document code: A Article ID: 1672-6421(2012)02-154-05

Al-SiC_p metal matrix composites possess many excellent properties such as high specific strength, high specific stiffness, small coefficient of thermal expansion (CTE) and good wear resistance, etc. [1-4], which make them good candidates for challenging applications in automotive, aerospace and sports industries [5-7].

Stir casting technique, which uses Al-SiC_p liquid stirred by a straight-blade mechanical stirrer to cast Al–SiC_p metal matrix composites, is the most economical technique to process Al-SiC_p composites [8]. However, the distribution of SiC particles in traditional stir cast Al-SiC_p composites is always nonhomogeneous (an example is shown in Fig. 1).

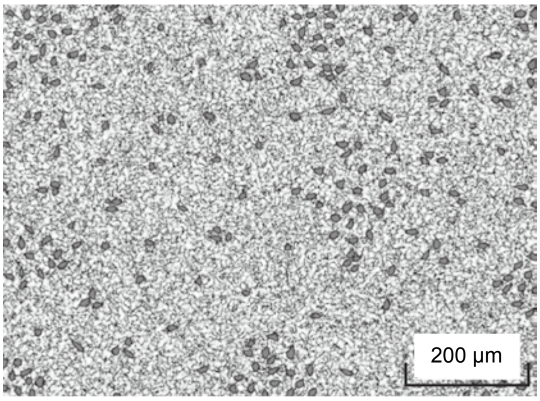


Fig. 1: Nonhomogeneous distribution of SiC particles in an as-cast A356-3.5vol%SiC_p composite

*** Zhang Peng**
Male, born in 1966, Professor, Ph.D. His research interests mainly focus on metal matrix composites and their forming technologies. He has published over 100 academic papers and held over 70 patents till now. Yao Shasha is one of his graduate students supervised by him.
E-mail: pzhang1@bjtu.edu.cn
Received: 2011-09-23; Accepted: 2012-03-20

In order to improve the distribution of SiC particles, a secondary processing of extrusion or squeeze casting was introduced [9-10].

In a mechanical stirring process, SiC particles are dispersed into the aluminum alloy liquid under shearing action induced by a straight-blade stirrer [11]. The nonhomogeneous distribution of SiC particles in aluminum alloy liquid is retained and carried onto the structure of Al-SiC_p composite after casting. Although efforts have been made, such as increasing the rotating speed of stirrer, little has been achieved in understanding the ever-persisting nonhomogeneous distribution of SiC particles in the straight-blade mechanical stirring process.

In this work, several new methods were used to investigate the distribution mechanism of SiC particles in A356-3.5vol%SiC_p liquid stirred by a straight-blade stirrer.

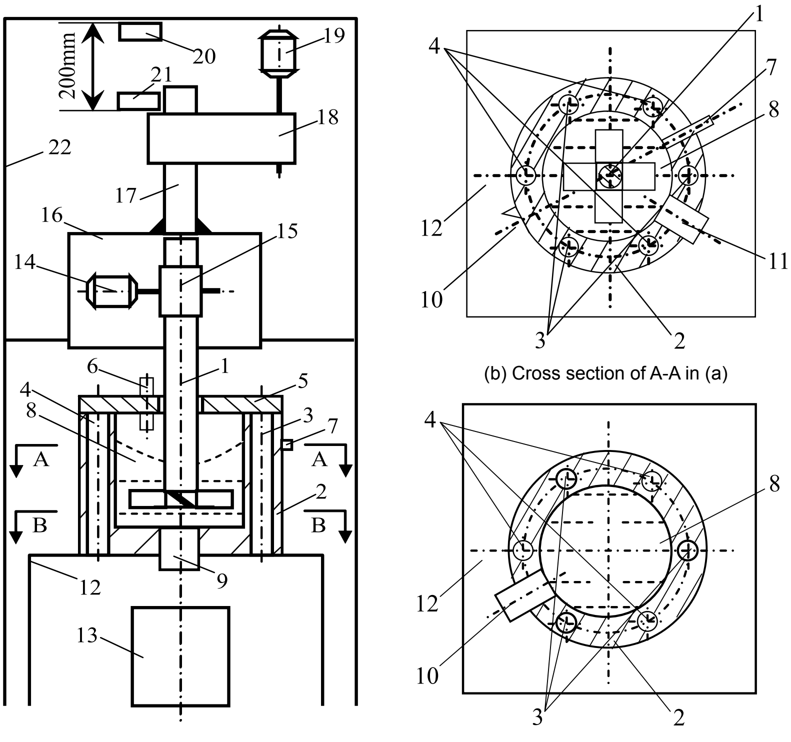
1 Experimental details

1.1 Experimental materials

The materials used in this experiment were 625-mesh black SiC powder (about 20 μm) and commercially available cast A356 alloy with a nominal composition (wt.%) of Al-6.3Si-0.2Mg-0.04Cu-0.015Zn-0.037Ni-0.15Fe-0.19Ti.

1.2 Experimental equipment

The schematic of the experimental setup is shown in Fig. 2. Stirrer 1, driven by rotating motor 14 of 3 kW rating power via rotating gearing 15, is used to stir A356-SiC_p liquid 8 in a 200 mm-inner diameter stainless steel crucible 2 (this part is fixed on lower bracket 12). The stirrer moves vertically between the surface and the bottom of A356-SiC_p liquid in the crucible 2 (~200 mm distance), and this movement is accomplished by a



(a) Whole setup configuration

(b) Cross section of A-A in (a)

(c) Cross section of B-B in (a)

1—stirrer; 2—crucible; 3—cooling pipes; 4—heating rods; 5—cover; 6—Ar gas pipe; 7—thermocouple; 8—Al-SiC_p liquid; 9—center stopple; 10—lower side stopple; 11—upper side stopple; 12—lower bracket; 13—water tank; 14—rotating motor; 15—rotating gearing; 16—moving board; 17—moving screw; 18—moving gearing; 19—moving motor; 20—upper switch; 21—lower switch; 22—upper bracket.

Fig. 2: Drawing of experimental equipment

series of parts of moving board 16, a moving screw 17 driven by the moving motor 19 and moving gearing 18, and upper switch 20 and lower switch 21 on the upper bracket 22. Thermocouple 7, cooling pipes 3 and heating rods 4 in the wall of crucible are used to monitor and control the temperature of A356-SiC_p liquid. Ar gas pipe 6 inserted in the cover 5 on crucible is employed to minimize the oxidation of A356-SiC_p liquid. Center stopple 9, lower side stopple 10 and upper side stopple 11 are utilized for pouring A356-SiC_p liquid at the center and the periphery of crucible into the water tank 13.

The straight-blade stirrer made of heat-resistant ceramic is illustrated in Fig. 3. Four 8-mm-thick flat blades B_1, B_2, B_3 and B_4 are normal to the axis of stirring rod R with a diameter of 40 mm at the top. Each blade allocates along the diagonal of side of square lower end S, making a tilt angle α of 35° to the horizontal plane (Fig. 3). The length between the center of rotation axis O and the outer point T is 95 mm.

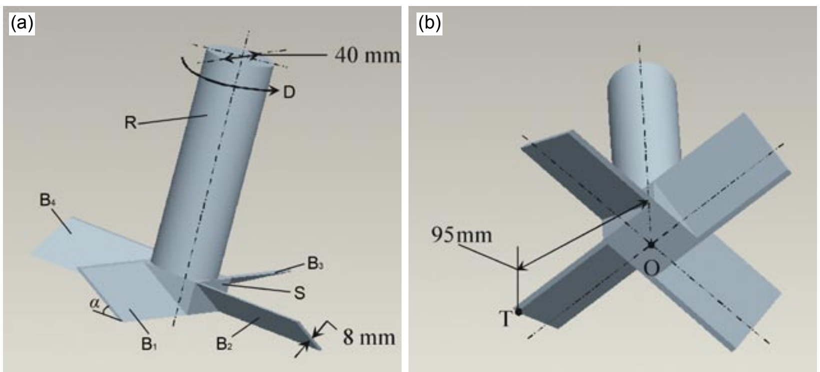


Fig. 3: Illustration of straight-blade stirrer: (a) side view; (b) bottom view

1.3 Experimental procedure

The experiment was carried out in the following steps.

(a) Prepare A356 liquid. The temperature of A356 liquid was held at 700 ℃ after degassing.

(b) Mix SiC particles and A356 liquid. SiC particles (total amount was calculated to make A356-3.5vol%SiC_p composite) was initially poured into the pre-heated crucible (~ 500 ℃). After flatting the SiC particles at the bottom of crucible, a 0.5-mm-thick A356 sheet with a diameter of 200 mm was placed on the SiC particles as a cushion. A356 liquid was then poured into the crucible. The crucible was subsequently purged by Ar gas to avoid the oxidation of A356-SiC_p liquid.

(c) Stir A356-SiC_p liquid. After the crucible temperature being adjusted to 650 ℃ and stabilized, the stirrer was turned on at a required rotating speed to stir the A356-SiC_p liquid and the stirrer also moved vertically at a constant speed of 10 $mm \cdot s^{-1}$.

(d) Cast A356-SiC_p ingot. After 8 minutes stirring, the center stopple, the lower side stopple and the upper side stopple were pulled out and plugged up so that A356-SiC_p liquid at the corresponding locations was directly water quenched. The water quenched ingots at the center of crucible top were prepared using a ladle.

(e) Conduct microstructural analysis. The A356-SiC_p ingots were sectioned into metallographic samples of 10 mm × 10 mm × 5 mm. The samples were then grinded and polished successively using diamond pastes of 30, 9, 6, 3 and 1 μm. Keller's reagent was used to etch the polished samples to reveal microstructure for optical microscopic observations using an OLYMPUS BX61 microscope.

2 Results and discussion

2.1 SiC_p content in A356 liquid

In the straight-blade mechanical stirring of A356-SiC_p liquid, the SiC_p content is constant at any place in A356 liquid if SiC particles distribute homogeneously. However, if SiC particles distribute nonhomogeneously, the SiC_p contents in A356 liquid will be different in both vertical and radial directions of crucible. Unfortunately, the crucible and the A356 liquid are opaque, and the distribution of SiC particles cannot be observed with naked eyes.

In this work, the specially-designed crucible is capable of providing samples at different locations to monitor SiC_p particles distribution (both vertical and radial) in A356 liquid at the center and the periphery of crucible (both bottom and top). This offers experimental data for resolving a long existing ubiquitous problem in materials processing [12]. The 0.5-mm-thick A356 cushion sheet on the SiC particles at the bottom of crucible was used to eliminate the impact of A356 liquid turbulence at the bottom of crucible and ensures a uniform distribution of SiC particles at the bottom of crucible prior to stirring.

Figure 4 shows the variation of SiC_p contents at the center and the periphery of crucible bottom as a function of rotating speed of stirrer. It can be seen that the SiC_p content decreases monotonically with the increasing of the rotating speed regardless of the location; and the SiC_p content at the periphery of crucible is always greater than that at the center of crucible given the same rotation speed. Furthermore, the difference of SiC_p contents between the periphery and the center of crucible increases with the increasing of rotating speed of stirrer. This tendency strongly indicates that radial centrifugalization of SiC particles occurs in this processing, and the bigger the rotating speed of stirrer is, the more severe the radial centrifugalization becomes.

However, SiC_p content varies quite differently at the crucible top. As shown in Fig. 5, SiC_p content at the periphery of crucible top increases with the increasing of the rotating speed of the stirrer and the SiC_p content at the periphery is also generally greater than that at the center of crucible. Similar to SiC particles in the crucible bottom, the difference of SiC_p contents between the periphery and the center of crucible increases with increasing the rotating speed of stirrer. A close data analysis shows that the SiC_p content at the center of crucible top increases initially with the rotating speed of the stirrer until 150 rpm, and then gradually decreases. The significant variation of SiC_p contents in A356 at different locations at both the top and the bottom of the crucible (Figs. 4 and 5) fully supports the postulation that the radial centrifugalization of SiC particles occurs in the straight-blade mechanical stirring of A356-SiC_p liquid.

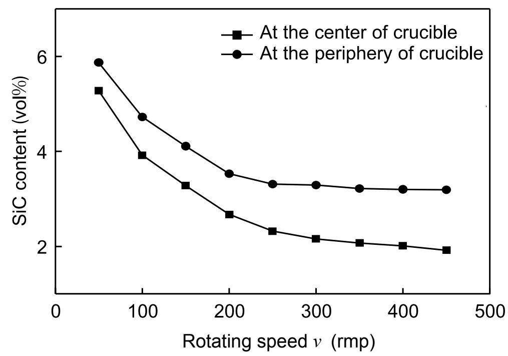


Fig. 4: Rotating speed *v* of stirrer and SiC_p content at the crucible bottom

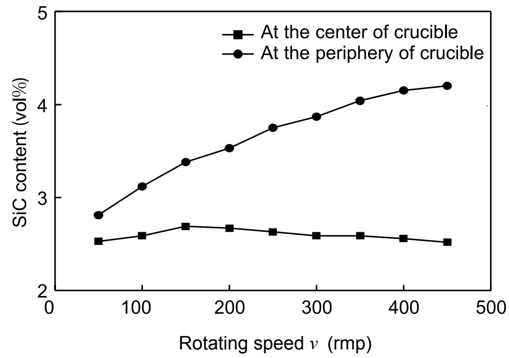


Fig. 5: Rotating speed *v* of stirrer and SiC_p content at the crucible top

2.2 Relationship between rotating speed of stirrer and radial centrifugalization ratio of SiC particles in A356 liquid

The degree of radial centrifugalization (also called centrifugalization ratio) of SiC particles in the straight-blade mechanical stirring of A356-SiC_p liquid can be quantified by a variable *d*:

$$d = \frac{\left| C_p - C_c \right|}{C_c} \qquad (1)$$

where c_p is SiC_p content in A356 liquid at the periphery of crucible, c_c is SiC_p content in A356 liquid at the center of crucible. Obviously, $d = 0$ if a homogenous distribution of SiC particles along the radial of crucible can be obtained. When the radial centrifugalization of SiC particles occurs along the radial of crucible, c_p is greater than c_c and *d* becomes positive. *d* value directly reflects the significance of the radial centrifugalization of SiC particles.

Using the data presented in Figs. 4 and 5, the radial centrifugalization ratio *d* of SiC particles (at the center and periphery of crucible) in A356 liquid can be calculated as a function of rotating speed *v* of stirrer, and the result is shown in Fig. 6. It can be seen from Fig. 6 that the radial centrifugalization ratio of SiC particles in A356 liquid at the crucible bottom is close to that at the crucible top. Using a nonlinear regressive analysis, the average *d* value is:

$$d = 0.015 + 0.0019v - 9.35 \times 10^{-7}v^2 \quad (2)$$

and the regression coefficient R_1 is 0.99023, which indicates that regressive equation (2) has built a correct relationship between v and d.

It can be seen from Fig.6 and Equ. (2) that the radial centrifugalization ratio of SiC particles in A356 liquid increases with increasing the rotating speed of stirrer. From Fig. 4 and Fig. 5, one can see that when the rotating speed of stirrer is 200 rpm, the SiC_p contents at the center and the periphery of crucible bottom are equal to those at same locations of crucible top, that is, SiC particles distribute evenly along the vertical direction. However, under this condition the radial centrifugalization ratio of SiC particles is 0.32 (i.e. the radial centrifugalization of SiC particles still exists). It can then be concluded that radial centrifugalization of SiC particles is the major factor causing the nonhomogeneous distribution of SiC particles in A356 liquid in the straight-blade mechanical stirring process.

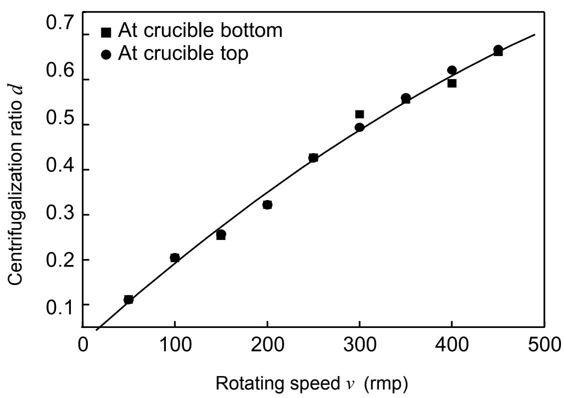


Fig. 6: Rotating speed *v* of stirrer and radial centrifugalization ratio *d* of SiC particles in A356 liquid

2.3 Discussion

In the straight-blade mechanical stirring of A356-SiC_p liquid, SiC particles are dispersed in A356 liquid gradually under the shearing action of stirrer. The surface of blade, which inclines 35°, can generate a suitable rising movement of SiC particles and the SiC particles at the bottom of crucible will rise up to fill the whole crucible. However a centrifugal movement of SiC particles also occur as long as the resistance of A356 liquid to SiC particles is smaller than the centrifugal force F of SiC particles [13]:

$$F = m \times \omega^2 \times r \quad (3)$$

where m is the mass of SiC particle, ω is the rotating angular speed of SiC particle and r is the distance of SiC particle from the central axis of crucible. SiC particles will move from the center of crucible to the periphery of crucible, thus resulting in radial centrifugalization of SiC particles in A356 liquid between the center and the periphery of crucible.

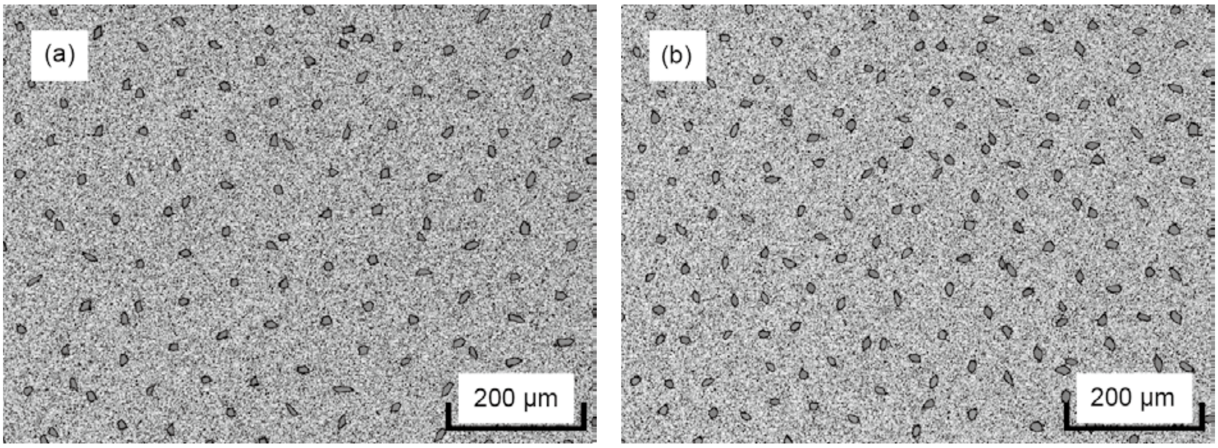
In this study, when the rotating speed of stirrer was low as 50 rpm, the shearing action of stirrer to A356–SiC_p liquid was weak and the rising movement of SiC particles generated by the inclining blade was small as well as the centrifugal movement of SiC particles was tiny. Thus, the majority of SiC particles stayed at the bottom of crucible and the radial centrifugalization ratio of SiC particles was small. With increasing the rotating speed of stirrer, the shearing action of stirrer, the rising and the centrifugal movements of SiC particles all increased. Thus the SiC_p gradually accumulated at the periphery of crucible top together with the increased radial centrifugalization ratio. At very high rotating speed of stirrer, the SiC_p contents became larger at the crucible top and periphery, hence the radial centrifugalization ratio was also greater. Not surprisingly, the shearing action of stirrer and the rising movement of SiC particles are moderate if an intermediate rotating speed of stirrer is chosen (such as 200 rpm). Under this condition, SiC particles distribute homogeneously along the vertical direction of crucible. However, the centrifugal movement of SiC particles still exists and the ratio is 0.32 for the 200 rpm of stirrer rotating speed (as shown in Fig. 6). Figure 7 shows typical microstructures of A356-3.5vol%SiC_p liquid at the center and the periphery of crucible bottom corresponding to 200 rpm stirrer rotating speed. It can be seen that the dark SiC particles at both locations are more uniformly distributed under this condition (compared with as-cast microstructure Fig. 1), however SiC_p density at the periphery of crucible bottom is higher than that at the center of crucible bottom. The situation can be worse in the process of re-mixing of A356-SiC_p liquid for pouring from crucible during casting, and the nonhomogeneous distribution of SiC particles such as that in Fig. 1 can occur. It can be summarized that the radial centrifugalization of SiC particles is the major factor causing the nonhomogeneous distribution of SiC particles in A356 liquid. If the radial centrifugalization of SiC particles can be eliminated (e.g. by altering the rotating speed, adjusting the casting temperature to control the molten viscosity, etc.) the distribution of SiC particles in A356 matrix will be uniform.

3 Conclusions

(1) Strong radial centrifugalization of SiC particles occurs in the straight-blade mechanical stirring of A356-3.5vol%SiC_p liquid. With 35° blade gradient angle α and 10 mm·s^{-1} stirrer moving speed, the relationship between stirrer rotating speed v and radial centrifugalization ratio d of SiC particles in A356 liquid between the center and the periphery of crucible is obtained as follows:

$$d = 0.015 + 0.0019v - 9.35 \times 10^{-7}v^2$$

(2) In the straight-blade mechanical stirring, strong radial centrifugalization of SiC particles causes the nonhomogeneous distribution of SiC particles in A356 liquid regardless of the stirrer rotating speed. If the radial centrifugalization of SiC particles can be eliminated at the beginning of processing Al-SiC_p composite, the distribution of SiC particles in aluminum alloy matrix can be improved dramatically.



(a) At the center of crucible bottom (b) At the periphery of crucible bottom

Fig. 7: Micrographs of A356-3.5vol%SiC$_p$ liquid stirred by straight-blade stirrer

References

[1] Ekici R, Apalak M K, Yildirim M. Effects of random particle dispersion and size on the indentation behavior of SiC particle reinforced metal matrix composites. Materials and Design, 2010, 31(6): 2818–2833.

[2] Kumar S, Balasubramanian V. Effect of reinforcement size and volume fraction on the abrasive wear behaviour of AA7075Al/SiC$_p$ P/M composites — A statistical analysis. Tribology International, 2010, 43(1–2): 414–422.

[3] Mousavi Abarghouie S M R, Seyed Reihani S M. Investigation of friction and wear behaviors of 2024 Al and 2024 Al/SiC$_p$ composite at elevated temperatures. Journal of Alloys and Compounds, 2010, 501(2): 326–332.

[4] Bozic D, Dimcic B, Dimcic O. Influence of SiC particles distribution on mechanical properties and fracture of DRA alloys. Materials and Design, 2010, 31(1):134–141.

[5] Hayajneh M, Hassan A M, Alrashdan A B. Prediction of tribological behavior of aluminum-copper based composite using artificial neural network. Journal of Alloys and Compounds, 2009, 470(1–2): 584–588.

[6] Mondal D P, Das S, Suresh K S. Compressive deformation behaviour of coarse SiC particle reinforced composite: effect of age-hardening and SiC content. Materials Science and Engineering A, 2007, 460–461: 550–560.

[7] Alizadeh M, Paydar M H. Fabrication of Al/SiC$_p$ composite strips by repeated roll-bonding (RRB) process. Journal of Alloys and Compounds, 2009, 477(1–2): 811–816.

[8] Bindumadhavan P N, Chia T K, Chandrasekaran M. Effect of particle-porosity clusters on tribological behavior of cast aluminum alloy A356-SiC$_p$ metal matrix composites. Materials Science and Engineering A, 2001, 315(1–2): 217–226.

[9] Dutta B, Samajdar I, Surappa M K. Particle redistribition and matrix microstructure evaluation during hot extrusion of cast SiC$_p$ reinforced aluminium alloy matrix composites. Materials Science and Technology, 1998, 14: 36–46.

[10] Mindivan H, Kayali E S, Cimenoglu H. Tribological behaviour of squeeze cast aluminium matrix composites. Wear, 2008, 265(5–6): 645–654.

[11] Naher S, Brabazon D, Looney L. Development and assessment of a new quick quench stir caster design for the production of metal matrix composites. Journal of Materials Processing Technology, 2005, 166(3): 430–439.

[12] Naher S, Brabazon D, Looney L. Simulation of the stir casting process. Journal of Materials Processing Technology, 2003, 143–144: 567–571.

[13] Zhang Yeying. Acting force on fluid in equilibrium. In: Hydromechanics, Ed.: Zhnag Yeying, Beijing: Higher Education Press, 2000: 50–55. (in Chinese)

This work was financially supported by the National Natural Science Foundation of China (No. 50974010), the Natural Science Foundation of Beijing (No. 3093023 and No.2102039) and the Fundamental Research Funds for the Central Universities (No. 2009JBM091).