The Uniform Distribution of SiC Particles in an A356-SiC_p Composite Produced by the Tilt-blade Mechanical Stirring

Yunhui DU, Peng ZHANG[†], Yujie WANG, Jun ZHANG, Shasha YAO and Chengyu LI

School of Mechanical & Controlled Engineering, Beijing Jiaotong University, Beijing 100044, China

[Manuscript received 22 February 2012, in revised form 30 May 2012]

© The Chinese Society for Metals and Springer-Verlag Berlin Heidelberg

The tilt-blade mechanical stirring of A356-2.5vol.%SiC_p liquid was conducted in a cylindrical crucible to solve the problem of nonhomogeneous radial distribution of SiC particles in conventional straight-blade mechanical stirring. The radial distribution of SiC particles in A356 liquid was studied under the conditions of 25° for horizontal tilt angle α of the blade, 200 r/min for rotating speed of stirrer and 10 mm/s for speed of moving up and down of stirrer. The results show that there exists a nonlinear relationship between circumferential tilt angle β of the blade and radial relative deviation d of SiC_p content in A356 liquid. When β is smaller than 26°, the d of SiC_p content in A356 liquid between the center and the periphery of crucible decreases with increasing β . Conversely, when β is bigger than 26°, d increases with increasing β . Only when β is about 26°, d can be equal to nought *i.e.* uniform radial distribution of SiC particles can be realized. It can be seen that the nonhomogeneous radial distribution of SiC particles in conventional straight-blade mechanical stirring can be eliminated in this tilt-blade mechanical stirring of A356-SiC_p liquid.

KEY WORDS: Tilt-blade mechanical stirring; Relationship; Uniform distribution

1. Introduction

Al-SiC_p metal matrix composites possess many outstanding properties in comparison to conventional aluminum alloys^[1–3], thereby making them very attractive for numerous applications in various fields^[4–5]. As an example, the typical parts in the automotive industry have included pistons, piston ring inserts, cylinder liners, brake rotors, brake pads, calipers and connecting rods, *etc.*

Three main kinds of fabrication techniques, including powder metallurgy, spray deposition and stir casting^[5–8], are available to produce Al-SiC_p metal matrix composites. For several decades, extensive work about the most economical stir casting technique which cast Al-SiC_p composites utilizing Al-SiC_p liquids stirred by straight-blade mechanical stirrer, has been carried out. However, for the stir cast Al-SiC_p composites, the distribution of SiC particles is always

inhomogeneous in aluminum alloy matrix. In an effort to improve the distribution of SiC particles, other further techniques such as extrusion processing and squeeze casting have to be adopted^[9–10], resulting in the more waste of energy and the high cost.

For Al-SiC_p liquid stirred by straight-blade mechanical stirrer, it is the shearing action induced by straight-blade stirrer that disperses the SiC particles into aluminum alloy liquid^[11]. Nevertheless, the centrifugal movement of SiC particles will result in the nonhomogeneous radial distribution of SiC particles in the aluminum alloy liquid^[12]. Consequentially, the nonhomogeneous radial distribution of SiC particles in Al-SiC_p liquid can not be eliminated in straight-blade mechanical stirring and the uniform distribution of SiC particles is never processed by stir casting directly.

In this paper, a specially-designed mechanical stirrer with the tilt blade was used to stir A356-2.5 vol.% SiC_p (containing 2.5% SiC particles in volume) liquid. The radial distribution of SiC particles in tilt-blade mechanical stirring was researched and the influence of circumferential tilt angle of the blade on radial relative deviation of SiC_p content in A356

[†] Corresponding author. Prof., Ph.D.; Tel: +86 10 51682226; Fax: +86 10 51688253; E-mail address: pzhang1@bjtu.edu.cn (Peng ZHANG)

liquid between the center and the periphery of crucible was determined. The long existing problem of non-homogeneous distribution of SiC particles in straight-blade mechanical stirring of Al-SiC_p liquid was solved.

2. Experimental

Commercially available casting A356 was used as the matrix material, the chemical composition is given in Table 1. 625-mesh black SiC powders with an average size of 20 μm , without suffering any additional treatment, were directly used in this work.

Fig. 1 is the experimental equipment. A356-SiC_p liquid in a stainless steel crucible is stirred by stirrer. The crucible is fixed on lower bracket. Its inner diameter is 200 mm. Thermocouple, cooling-pipes and heating-rods in the wall of crucible are used to control the temperature of A356-SiC_p liquid. The stirrer is driven by a rotating motor with 3 kW rating power via rotating gearing. It can also move up and down with moving board at a distance of 200 mm between the surface and the bottom of A356-SiC_p liquid in crucible. The moving board is driven by a moving motor via moving screw and moving gearing under

the controlling of upper switch and a lower switch on the upper bracket. Ar gas pipe is inserted in the cover of crucible. The oxidation of A356-SiC_p liquid is avoided by Ar gas. Center stopple, lower side stopple and upper side stopple are utilized for pouring the resulting A356-SiC_p liquid at the center and the periphery of crucible into the water tank to prepare the water quenching ingots.

Fig. 2 is the tilt-blade stirrer which is made of heat-resistant ceramic. Four 8 mm-thick flat blades, B₁, B₂, B₃ and B₄ are respective stuck in the four sides of the top square end S whose four sides are the tangents of the stirring rod R with a 40 mm diameter. Each blade allocates along the diagonal of each side of the top square end, making a tilt angle α of 25° to the horizontal plane and a required tilt angle β to the normal of each side of the top square end along the rotating direction *D* of stirrer (as shown in Fig. 2(a)). The length between the center of rotation *O* and the ultimate outer point *T* (as shown in Fig. 2(b)) is 95 mm.

The procedures and the conditions to investigate A356-SiC_p liquid in this work were as follows:

(1) Preparing A356 liquid, the temperature of which was held at 700 °C after degassing.

(2) Pouring the above A356 liquid and the SiC particles (2.5 vol.% in A356-SiC_p liquid) into the crucible which was preheated to the temperature of 500 °C by the heating-rods in the wall of crucible.

Table 1 Chemical composition of A356 (wt.%)

Si	Mg	Cu	Zn	Ni	Fe	Ti	Al
6.3	0.2	0.04	0.015	0.037	0.15	0.19	Bal.

Fig. 1 Drawing of the experimental equipment: (a) the whole setup configuration; (b) cross section of A-A in Fig. 1 (a); (c) cross section of B-B in Fig. 1 (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).

After fastening the cover on the crucible, Ar gas was poured *via* the Ar gas pipe to avoid the oxidation of A356-SiC_p liquid.

(3) Switching on the stirrer to stir the A356-SiC_p liquid, meanwhile, adjusting the temperature of A356-SiC_p liquid to 650 °C using the cooling-pipes and the heating-rods in the wall of crucible under the controlling of thermocouple. The rotating speed of the stirrer was 200 r/min and the speed of moving up and down of the stirrer was 10 mm/s. The temperature precision was ± 1 °C.

(4) 15 minutes later, pulling out the stopples and pouring some A356-SiC_p liquid into the water tank to prepare the water quenching ingots for identifying the distribution of SiC particles in A356 liquid. The water quenching ingots of the A356-SiC_p liquid at the center of crucible top were prepared using a ladle.

(5) Sectioning the resulting A356-SiC_p ingots into metallographic samples of dimension 10 mm×10 mm×5 mm using a wire cut machine. A grinding machine was employed for the grinding of samples using a grinding disc with 30 μ m diamond suspended in water lubricant and, the polishing, with 9, 6, 3 and 1 μ m diamond suspended in water as a lubricant. Keller's reagent was also used to etch the polished sections. An OLYMPUS BX61 optical microscopy was used to research the distribution of SiC particles in the metallographic samples.

Fig. 2 Illustration of tilt-blade stirrer: (a) side view; (b) bottom view

3. Results and Discussion

3.1 SiC_p contents in A356 liquid

Fig. 3 and Fig. 4 show the variations of SiC_p contents at the center and the periphery of crucible bottom and top as a function of circumferential tilt angle β of the blade. It can be seen that SiC_p contents at the crucible bottom are almost the same as those at the crucible top, namely, SiC particles can distribute uniformly along the axis of the crucible under the condition of 25° for the horizontal tilt angle α of blade, 200 r/min for rotating speed of stirrer and 10 mm/s for speed of moving up and down of stirrer. However, the radial distribution of SiC particles in crucible is quite different. From Fig. 3 and Fig. 4, SiC_p content at the center of crucible increases with increasing the circumferential tilt angle β of the blade. Nevertheless, SiC_p content at the periphery of the crucible decreases with increasing β . Specially, when β is about 26°, SiC_p content at the center of the crucible is equal to that at the periphery of the crucible. This indicates strongly that the inhomogeneous radial distribution of SiC particles existing in conventional straight-blade mechanical stirring of Al-SiC_p liquid

Fig. 3 SiC_p content at the center and periphery of crucible bottom *vs.* circumferential tilt angle β of the blade

Fig. 4 SiC_p content at the center and periphery of crucible top *vs.* circumferential tilt angle β of the blade

can be eliminated using this tilt-blade stirrer.

3.2 Relationship between circumferential tilt angle β of blade and radial relative deviation d of SiC_p content in A356 liquid

The radial relative deviation d of SiC_p content in A356 liquid between the center and the periphery of the crucible, used for describing the radial distribution of SiC particles in A356 liquid quantitatively, is calculated according to the follow equation

$$d = \frac{|c_p - c_c|}{2.5} \quad (1)$$

where c_p (vol.%) is the mean SiC_p content at the periphery of crucible top and bottom, c_c (vol.%) is the mean SiC_p content at the center of the crucible top and bottom, and 2.5 is the mean SiC_p content in the whole A356 liquid. Obviously, if a homogeneous distribution of SiC particles along the radial of crucible is obtained, $d=0$. When the nonhomogeneous radial distribution of SiC particles occurs along the radial of crucible, c_p is not equal to c_c and d becomes positive. Apparently, the more nonhomogeneous the radial distribution of SiC particles becomes, the larger the d value will be. Thus the d of SiC_p content in A356 liquid can describe the radial distribution of SiC particles in A356 liquid quantitatively. Fig. 5 shows the relationship between circumferential tilt angle β of the blade and d of SiC_p content in A356 liquid. It can be seen that the circumferential tilt angle β of blade exerts a direct influence on the radial relative

Fig. 5 Radial relative deviation d of SiC_p content between the center and the periphery of the crucible *vs.* circumferential tilt angle β of the blade

deviation d of SiC_p content. After regressive analysis using nonlinear theory, the regressive equation is

$$d = 0.37198 - 0.02784\beta + 5.42727 \times 10^{-4}\beta^2 \quad (2)$$

The regression coefficient R is 0.99864. This indicates that regressive Eq. (2) has built a correct relationship between β and d . Let the derivative of regressive Eq. (2) equal to nought, when $\beta \approx 26^\circ$, the condition for the smallest d is got, and the smallest $d \approx 0$. The further experimental data according to this condition are shown in Table 2. It can be seen that, in tilt-blade mechanical stirring of A356-2.5 vol.% SiC_p liquid, the reasonable stirring conditions are 26° for circumferential tilt angle β of the blade, 25° for horizontal tilt angle α of the blade, 200 r/min for rotating speed of stirrer and 10 mm/s for speed of moving up and down of stirrer.

3.3 Discussion

In straight-blade mechanical stirring of A356- SiC_p liquid, SiC particles can move from the center to the periphery of the crucible under the action of centrifugal force and thus resulting in a nonhomogeneous distribution of SiC particles in A356 liquid along the radial of crucible.

In this experimental equipment, a tilt-blade stirrer which can generate an inward movement of SiC particles is used. The schematic of the acting force on A356- SiC_p liquid from a tilt blade with a circumferential tilt angle β is shown in Fig. 6. D is the rotating direction of the stirrer. The acting force on the A356- SiC_p liquid from any acting point of the blade (such as $\vec{F}_A$ from A) is normal to the straight line (such as OA) passing the rotating center O and the acting point. This acting force can be divided into two components along the fore-and-aft direction (such as $\vec{F}_{Av}$) and the right-and-left direction (such as $\vec{F}_{Ah}$). On any acting line in fore-and-aft direction on the blade (such as AB), the acting force component in fore-and-aft direction at any acting point (such as $\vec{F}_{Av}$ at A) always points forwards. An integrative force in fore direction $\vec{F}_v$ is exerted on A356- SiC_p liquid via the tilt blade. Therefore, A356- SiC_p liquid can be driven to flow circumferentially under the action of the rotating blade and an outward centrifugal movement of SiC particles

Table 2 SiC_p contents (vol.%) at the different positions and the radial relative deviation d in different samples

Sample	C_{ct} /vol.%	C_{pt} /vol.%	C_{cb} /vol.%	C_{pb} /vol.%	
1	2.51	2.50	2.50	2.5	≈ 0
2	2.50	2.49	2.49	2.5	≈ 0
3	2.49	2.50	2.51	2.5	≈ 0

Note: C_{ct} , C_{pt} , C_{cb} and C_{pb} are the SiC_p contents at the center of crucible top, the periphery of crucible top, the center of crucible bottom and the periphery of crucible bottom, respectively.

Fig. 6 Schematic of acting force to A356-SiC_p liquid from a tilt blade with a circumferential angle β

will originate. However, owing to the blade tilting an angle β circumferentially, the angles between the acting force and the acting line at AC side (such as θ_1 and θ_2) are bigger than those corresponding angles at BE side (such as θ'_1 and θ'_2). Thus the acting force components in right-and-left direction at AC side (such as $\vec{F}_{Ah}$ and $\vec{F}_{Ch}$) are bigger than those at BE side (such as $\vec{F}_{Bh}$ and $\vec{F}_{Eh}$). Then an integrative force in left direction $\vec{F}_h$ is exerted on A356-SiC_p liquid via the tilt blade, resulting in an inward movement of SiC particles which can weaken the outward centrifugal movement of SiC particles. This is the technological thought of eliminating the nonhomogeneous radial distribution of SiC particles in mechanical stirring of Al-SiC_p liquid.

In this work, when β was nought, the stirring was the conventional straight-blade mechanical stirring. Under the conditions of 25° for horizontal tilt angle α of the blade, 200 r/min for rotating speed of stirrer and 10 mm/s for speed of moving up and down of stirrer, a suitable rising movement of SiC particles could generate and SiC particles could distribute uniformly along the axis of the crucible. Nevertheless, no inward movement of SiC particles generated and a nonhomogeneous radial distribution of SiC particles resulted from the outward centrifugal movement of SiC particles. Thus the d of SiC_p content in A356 liquid between the center and the periphery of crucible was big. Nevertheless, the integrative force in left direction exerting on A356-SiC_p liquid via the tilt blade enlarged gradually with increasing β , and the inward movement of SiC particles became stronger and stronger. Consequentially, the outward centrifugal movement of SiC particles was weakened continuously. Therefore d grew to be smaller and smaller, namely, the distribution of SiC particles became evenner and evenner. Specifically, when β was about 26° , the outward centrifugal movement of SiC particles was eliminated by the inward movement of SiC particles and the nonhomogeneous radial distribution of SiC particles was restrained. Accordingly, the uniform distribution of SiC particles was gotten. However, when β was bigger than 26° , the strong inward movement of SiC particles not only eliminated the outward centrifugal move-

ment of SiC particles but also resulted in an excessive inward movement of SiC particles which generated the segregation of SiC particles at the center of the crucible. The bigger the β was, the more serious the segregation of SiC particles at the center of the crucible became. Consequently, the radial relative deviation of SiC_p content increased gradually.

Fig. 7 and Fig. 8 show the micrographs of A356-2.5vol.%SiC_p composites which are cast from A356-2.5vol.%SiC_p liquids whose d of SiC_p content are 0.37 and 0 respectively. Permanent mould of $300^\circ\text{C}/\text{min}$ cooling rate is used. The dark parts are SiC particles. It can be seen that the distribution of SiC particles in the A356-SiC_p composite cast from A356-SiC_p liquid with large radial relative deviation of SiC_p content is rather uneven. However, the structure of A356-SiC_p composite cast from uniform A356-SiC_p liquid is very homogeneous. It can be seen that the tilt-blade mechanical stirring of Al-SiC_p liquid can solve the long existing problem of nonhomogeneous distribution of SiC particles in conventional straight-blade mechanical stirring of Al-SiC_p liquid.

Fig. 7 Uneven distribution of SiC particles in cast A356-2.5vol.%SiC_p composite

Fig. 8 Uniform distribution of SiC particles in cast A356-2.5vol.%SiC_p composite

4. Conclusions

(1) The nonhomogeneous radial distribution of SiC particles in conventional straight-blade mechanical stirring can be eliminated in tilt-blade mechanical

stirring of A356-SiC_p liquid by adjusting the circumferential tilt angle β of tilt-blade.

(2) Under the conditions of 25° for horizontal tilt angle α of blade, 200 r/min for rotating speed of stirrer and 10 mm/s for speed of moving up and down of stirrer, the relationship between radial relative deviation d of SiC_p content in A356-2.5 vol.%SiC_p liquid and circumferential tilt angle β of blade is $d=0.37198-0.02784\beta+5.42727\times10^{-4}\beta^2$.

(3) The reasonable tilt-blade mechanical stirring parameters of A356-2.5vol.%SiC_p liquid are 26° for circumferential tilt angle β of blade, 25° for horizontal tilt angle α of blade, 200 r/min for rotating speed of stirrer and 10 mm/s for speed of moving up and down of stirrer.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (No. 50974010) and the Natural Science Foundation of Beijing (No. 2102039).

REFERENCES

- [1] M. Song and Y.H. He, *Mater. Des.* **31** (2010) 985.
- [2] R. Ekici, M. K. Apalak and M. Yildirim, *Mater. Des.* **31** (2010) 2818.
- [3] K.R. Brown, M.S. Venie and R.A. Woods, *JOM* **47** (1995) 20.
- [4] H. Wang, R. Zhang and X. Hu, *J. Mater. Process. Technol.* **197** (2008) 43.
- [5] M.J. Tan and X. Zhang, *Mater. Sci. Eng. A* **244** (1998) 80.
- [6] J.A. Picas, A. Forn and E. Martín, *Surf. Coat. Technol.* **200** (2005) 1178.
- [7] D.B. Miracle, *Compos. Sci. Technol.* **65** (2005) 2526.
- [8] E. Hokaed, J. Laverinya, *J. Mater. Sci.* **92** (1999) 1.
- [9] B. Dutta, I. Samajdar and M. K. Surappa, *Mater. Sci. Technol.* **14** (1998) 36.
- [10] H. Mindivan, E.S. Kayali and H. Cimenoglu, *Wear* **265** (2008) 645.
- [11] P.N. Bindumadhavan, T.K. Chia and M. Chandrasekaran, *Mater. Sci. Eng. A* **315** (2001) 217.
- [12] Y.H. Du, P. Zhang and J. Zhang, *J. Mater. Sci. Technol.* **28** (2012) 941.