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SIMULATION OF THE STIR CASTING PROCESS

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ABSTRACT: Non homogeneous particle distribution is one of the greatest problems in casting Metal Matrix Composites (MMC's). To optimize some of the parameters for uniform particle distribution for batch compocasting the present simulation studies were conducted. The simulation involves visualisation experiments. In the visualisation experiments liquid and semi solid aluminium are replaced by other fluids with similar characteristics. SiC reinforcement particulate similar to that used in aluminium MMC's was used in the simulation fluid mixtures. Scaled-up stirring experiments were carried out in a transparent crucible with the percentage of reinforcement material being varied. Optimum conditions for photographing flow patterns were established. The dependence of the photography conditions (shutter speed, aperture control, lighting), particles dispersion and settling times and vortex height on stirrer geometry and speed was found. Results are discussed in terms of their applicability to MMC production.

KEYWORDS: MMC’s, batch compocasting, Al-SiC, simulation.

1 INTRODUCTION

MMCs are a range of advanced materials providing properties heithertofore not achieved by conventional materials. These properties include increased strength, higher elastic modulus, higher service temperature, improve wear resistance, decreased part weight, low thermal shock, high electrical and thermal conductivity, and low co-efficient of thermal expansion compared to conventional metals and alloys [1, 2]. The excellent mechanical properties of these materials and the relatively low production cost make them very attractive for a variety of applications in automotive and aerospace industries. There are several fabrication techniques available in manufacturing the MMC materials. According to the type of reinforcement, the fabrication techniques can vary considerably. These techniques include stir casting (called compocasting) [3-8], liquid metal infiltration [9], squeeze casting [10], and spray codeposition [11]. Compocasting involves the addition of particulate reinforcement into Semi Solid Metal (SSM) by means of agitation. The advantage of compocasting lies in a lower processing temperature [12], leading to a longer die life and high production cycle time [13]. Reduced fluidity can be achieved in SSM by means of shearing [14]. The greater resultant fluidity of the SSM also reduces solidification shrinkage, making the fabrication of structural components with tight tolerance possible [15]. The production can be carried out by conventional foundry methods [16]. Disadvantages that may occur if process parameters are not adequately controlled include the fact that non-homogeneous particle distribution results in sedimentation and segregation [17].

Although compocasting is generally accepted as a commercial route for the production of MMC’s [18], there are however technical challenges associated with producing a homogeneous, high density composite. Effectiveness with which mechanical stirring can incorporate and distribute the particles throughout the melt depends on the constituent materials, the stirrer geometry and position, the speed of stirring, and the mixture temperature. Research has been conducted in an effort to optimise the mechanical properties of MMC’s [3, 5, 7, 10, 19-23]. Little of this work however is concerned with investigation of time required for particulate distribution. Unfortunately, in normal practice the effect of the stirring action on the flow patterns cannot be observed as they take place in a non-transparent molten metal within a furnace. As such, and because of the fact that direct measurements of metal flow characteristics can be expensive, time consuming and dangerous, the current research focuses on methods of simulating fluid and particle flow during stirring.

Very little work has been conducted to date with simulation materials for the compocasting process. Exceptions to this include the work of Kocaefe et al. [24], Hashim et al. [25] and Rohatgi et al. [26]. The work of Kocaefe et al. used a water-SiC mixture, but related only to a specific set of processing conditions. Hashim et al. on the other hand, in an effort to simulate SSM viscosities used glycerol with small polystyrene particles to highlight the flow pattern. Experimental results from Rohatgi et al. indicated the homogeneity of SiC distributions during stirring in water-SiC mixtures. Other important parameters, such as uniform dispersion and settling time for different viscosity simulation fluids within a conventional cylindrical crucible, have not been investigated. This work examines in details these situations with a variety of processing conditions. Results from such simulations can, for example, indicate the time frames required to obtain a uniform distribution of particulate within the molten or SSM.

2 EXPERIMENTAL

Water and transparent glycerol/water solutions were used to provide fluids of a varying viscosity. Viscosities similar to those of SSM of 300, 500, 800 and 1000 mPas were produced from glycerol/water solutions [27]. Water provided a viscosity of 1 mPas, similar to that of liquid aluminium [28]. Two levels of 13 μm sized SiC particles, 0.1% or 10%, were added to these fluids. The lower level allowed internal flow patterns to be observed whereas the upper level, simulating a typical quantity of SiC in a MMC, showed external flow patterns and allowed measurement of

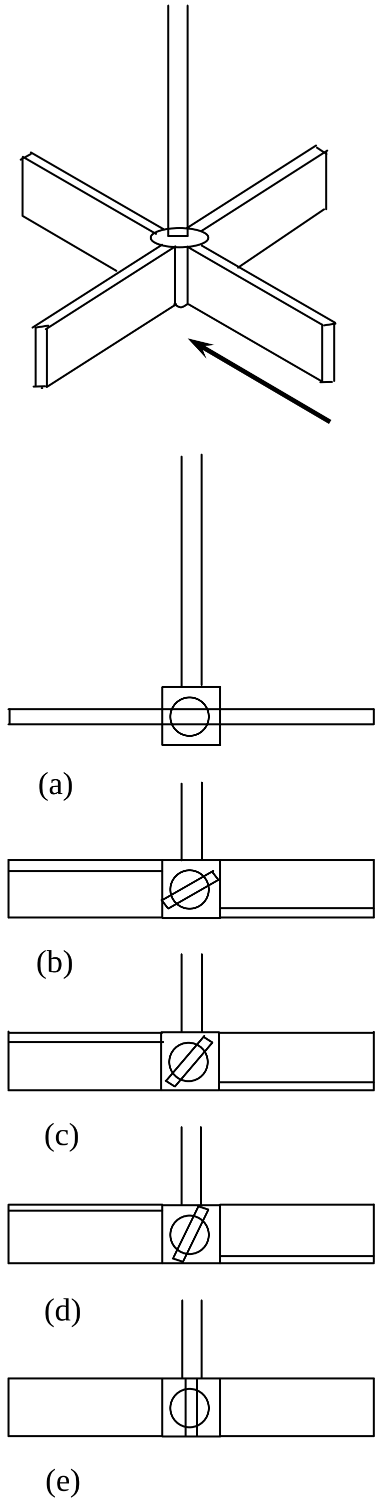

Figure 1: Four blades stirrer, showing different blade configurations (a) 0° (b) 30° (c) 45° (d) 60° and (e) 90°.

dispersion rates. A 400 ml quantity of each of these solutions was prepared in a 10.5 cm diameter Pyrex beaker. This resulted in a solution height of 6.5 cm. Agitation was provided by three different stirrer types. Three and four bladed stirrers with blades normal to the axis of rotation as well as a fixed bladed turbine stirrer were used. Flat blades could be rotated about their longitudinal axis (Figure 1). A speed controlled DC motor enabled accurate control of the stirring speed. Height of the stirrer from the bottom of the beaker, H, was adjustable. A schematic of the experimental set up is shown in Figure 2. The scale shown in this drawing related directly to a laboratory scale production facilities for MMC's.

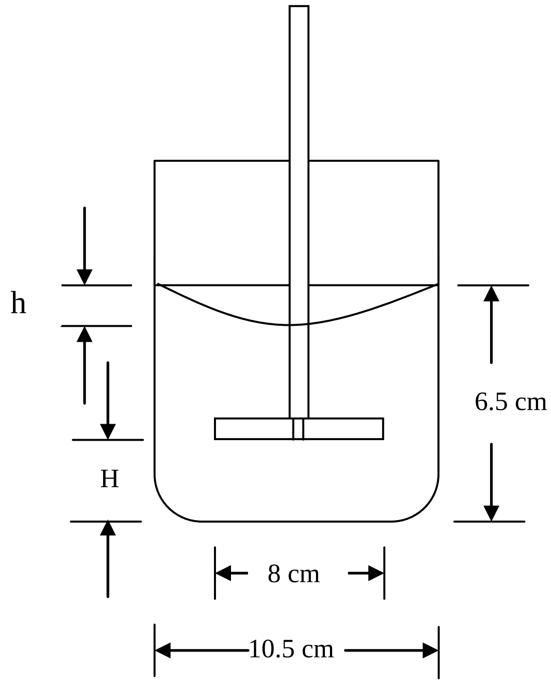

Figure 2: Schematic of the experimental set up.

A camera was mounted along the same horizontal plane as the beaker. Shutter speed, aperture, and lighting settings were adjusted to optimise the picture quality. During these tests, shutter speeds were varied from 1/15-1/2000 s while the aperture was automatically controlled. Conversely, the aperture was varied from F5.5-38 while the shutter speed was automatically adjusted.

Steady state flow patterns were set up in the fluids with stirring speeds of 50, 100, 150, 200, 250 and 300 rpm. With the SiC particles initially resting at the bottom of the beaker, time required from shearing commencement, for a uniform dispersion of particles were recorded. When shearing was stopped, settling times for uniformly dispersed particles in the different fluids were measured. Uniform dispersion and settling were completely judged by visual examination. The effects of different stirrer heights on different solutions were also observed. In addition, vortex height, h (Fig.1), was recorded for water and glycerol/ water with different stirrer types and stirring speeds.

3 RESULTS

Camera shutter speeds at least greater than 1/60 s were required to capture the flow pattern in the stirring speed range investigated (50-300 rpm). Faster shutter speeds up to 1/2000 s did not affect captured image quality. Aperture control with automatic shutter speed settings did not produce good photographs due to the low shutter speeds recorded for the aperture range investigated (<1/60 s). Integral camera flash, with a white background to the Pyrex beaker, proved the best lighting solution. With this set-up internal flow pattern were captured in 0.1% SiC fluids and external flow of the fluid could be observed in the 10% SiC fluid mixtures.

At 50 rpm no dispersion of the particles occurred irrespective of blade angle or fluid. Uniform particulate dispersion times for a 10% SiC water mixture, for different stirring speeds above 50 rpm are listed in Table 1. From Table 1 it is observed that at 100 rpm and with 0 and 30 degree blade angles no uniform dispersion resulted, but with 45 and 60 degree blade angles there was full particulate dispersion. It is further observed for all stirring speeds that dispersion rates increase with increasing blade angle. The turbine blade also produces dispersion times similar to the best found for the flat bladed stirrers.

Table 1: Uniform dispersion time for 10% SiC particles for different stirrer types and stirring speeds in water of viscosity 1 mPas. Stirrer height was 20 mm from the base of the beaker.

Stirring speed (rpm)	Blade angle (Degrees)	Uniform dispersion time (s)		
		3 blade stirrer	4 blade stirrer	Turbine blade stirrer
100	0	N/A	N/A	180
	30	N/A	N/A	
	45	300	180	
	60	180	180	
	90	180	120	
150	0	120	120	27
	30	90	25	
	45	30	29	
	60	25	12	
	90	28	27	
200	0	120	29	17
	30	60	17	
	45	20	16	
	60	19	16	
	90	25	16	
250	0	60	16	16
	30	30	16	
	45	16	16	
	60	15	16	
	90	14	18	
300	0	60	15	15
	30	19	15	
	45	15	15	
	60	13	15	
	90	13	15	

Below 150 rpm no dispersion occurred for the higher viscosity glycerol/water mixtures. Uniform particulate dispersion times for a 10% SiC glycerol/water mix (with 300 mPas viscosity), for the different stirring speeds are shown in Table 2. At 200, 250 and 300 rpm the range of dispersion time for 3, 4 and turbine bladed stirrers are 1920-2700, 1680-1980 and 900-1320 seconds respectively. Though there was a tendency for reduced dispersion time with higher blade angle, it was found that for most cases the 60 degree angle produced the lowest dispersion times. The turbine stirrer again produced the lowest dispersion time. Very similar results were observed for the higher viscosity (300, 500, 800 and 1000 mPas) glycerol/water mixtures tested.

Uniform dispersion times for 10% SiC particles in glycerol/water solution for different stirrer types and heights, H, are listed in Table 3. Due to high vortex formation in water at higher stirring speeds and the lack of dispersion in the glycerol/water mixture at lower speeds, a stirring speed of 150 rpm was used in water and 200 rpm in the glycerol/water mixture. With increase in the height of the stirrer in the melt, the dispersion times increase. Indeed, for stirrer heights of 30 mm and above in the glycerol/water mixtures, the particles are not dispersed into the solution. From Table 1, 2 and 3, a general result observed is the strong tendency for the turbine to produce a faster dispersion time than the other stirrer types. A less pronounced tendency for the 4 blade stirrer to produce shorter stirrer times than the 3 bladed stirrer is also observed.

Table 2: Uniform dispersion time for 10% SiC particles for different stirrer types and stirring speeds in glycerol/water solution of viscosity 300mPas. Stirrer height was 20 mm from the base of the beaker.

Stirring speed (rpm)	Blade angle (Degree)	Uniform dispersion time (s)		
		3 blade stirrer	4 blade stirrer	Turbine blade stirrer
200	0	2700	2520	2340
	30	2520	2460	
	45	2400	2400	
	60	2100	1920	
	90	2640	2460	
250	0	1980	1800	1680
	30	1800	1800	
	45	1800	1740	
	60	1740	1680	
	90	1920	1800	
300	0	1320	1200	900
	30	1200	1140	
	45	1080	1080	
	60	900	900	
	90	1200	1200	

Table 3: Uniform dispersion time in different solution for 10 % SiC particles for different stirrer types and height for 45 degree blade angle.

Solution	Stirring speed (rpm)	Stirrer Height (mm)	Uniform Dispersion time (s)		
			3 Blade Stirrer	4 Blade Stirrer	Turbine Blade stirrer
Water, viscosity 1mPas	150	10	30	25	24
		20	30	29	27
		30	50	45	40
		40	120	90	60
		50	180	120	70
Glycerol, viscosity 300mPas	200	10	1500	1500	1320
		20	2400	2400	1740
		30	N/A	N/A	N/A
		40	N/A	N/A	N/A
		50	N/A	N/A	N/A

In all cases, particulate settling times measured were independent of stirrer types and stirring speed. Approximately 90% of all particles settled within 60 seconds in water and complete settling was recorded after 180 seconds. The time at which particulate settling occurred in the glycerol/water mixtures was evident from the emergence a clear layer, absent of SiC particles, at the top of the mixture. For all glycerol/water mixtures the uniform dispersion of SiC remained for one hour, and complete particulate settling only occurred after 20 hours.

Table 4 compares the vortex depth of different viscosities solutions, stirrer types, and stirring speeds. It is clearly evident from this table that at higher stirring speed in water the vortex height increases. Much greater vortex height is also observed in the water mixtures compared with the glycerol/water mixtures. No vortex was present in glycerol/water mixtures for stirring speeds below 150 rpm. Air entrapment was also observed in all fluids at speeds above 250 rpm, though this was surprisingly more evident in the higher viscosity fluids.

Table 4: Comparison of the vortex height for different stirring speeds and stirrer types in solutions of viscosities 1, 300, 500, 800 and 1000 mPas.

Solutions	Stirring speeds (rpm)	Vortex Depth (mm)		
		3 blade stirrer (45 degree blade angle)	4 blade stirrer (45 degree blade angle)	Turbine blade stirrer
Water Viscosity 1mPas	100	4	5	6
	150	12	13	14
	200	22	25	30
	250	35	40	45
	300	40	50	55
Glycerol Viscosity 300 mPas	100	No Vortex	No Vortex	No Vortex
	150	No Vortex	No Vortex	1
	200	2	1	5
	250	5	5	7
	300	7	6	10
Glycerol Viscosity 500 mPas	100	No Vortex	No Vortex	No Vortex
	150	No Vortex	No Vortex	No Vortex
	200	1	No Vortex	1
	250	2	3	3
	300	4	5	6
Glycerol Viscosity 800 mPas	100	No Vortex		No Vortex
	150	No Vortex		No Vortex
	200	No Vortex		No Vortex
	250	1	1	1
	300	2	3	4
Glycerol Viscosity 1000 mPas	100	No Vortex	No Vortex	No Vortex
	150	No Vortex	No Vortex	No Vortex
	200	No Vortex	No Vortex	No Vortex
	250	2	1	1
	300	2	2	3

4 DISCUSSION

From the results presented it is apparent that the stirring speed and blade angle have a significant effect on particle distribution in the water mixture. These effects are dampened by the higher viscosity glycerol/water mixtures. In this regard, even the relatively low viscosity glycerol/water mixture (300 mPas) has a significant effect.

The height of the stirrer is also seen to have an important effect for the distribution time of the SiC. This is particularly true for the higher viscosity glycerol/water solutions. Particulate settling time are in general longer than dispersion time though they are of similar order of magnitude. Settling time, in contrast to dispersion time, show no variation with stirring speed but are strongly dependent on fluid viscosity. From the results with the liquid aluminium simulation fluid (water) it was seen that settling occurs within seconds of stopping shear within the fluid. In the context of compocasting MMC materials, solidification would then have to be immediate in order to retain the uniform SiC distribution. A slight increase in viscosity however allows for much longer time before processing. Such a viscosity increase can be obtained from lowering temperature to that within an alloy's semi-solid range. A disadvantage of higher viscosities however is their increased lack of fluidity. A compromise is then required in the casting temperature. It is seen from the results above that at a viscosity of 300 mPas would be sufficient to increase the time available for SSM processing.

Excessive vortex height was shown to result in air entrapment, however brute force has also been shown to provide the best method for incorporating particles in SSM [29]. For batch casting then, the stirrer should only produce strong currents in the bottom region of the SSM to encourage particle entrapment and discourage air entrapment. Air entrapment leads to internal voids and oxides within the casting which deteriorate the mechanical properties. Non-reactive argon or nitrogen gas atmospheres mitigate the problems of oxide formation. However these gases may also form pores when present within the SSM during solidification. In contrast to the constant viscosity simulation fluids used in this work the viscosity of SSM changes during processing. Lower fractions solid, higher shear rates, or longer shearing periods result in lower viscosity in the SSM which would help prevent retention of these gases [14].

5 CONCLUSION

1. Higher blade angles and lower viscosity result in reduced particulate dispersion time.
2. A minimum stirring speed of 100 rpm for water and 200 rpm for glycerol/water-SiC mixtures is required for uniform dispersion to occur.
3. A viscosity increase from 1 mPas (for liquid metal) to 300 mPas has a tremendous effect on the SiC dispersion and settling time. However a further increase from 300 mPas to 1000 mPas has negligible effect on this time.

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