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Wear of semi-solid rheocast SiC$_p$/Al metal matrix composites

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Abstract: Rheocasting of plates in Al alloy 359 reinforced with SiC at 11%, 27% and 50% (volume fractions) exhibits the capability of the council for scientific and industrial research−rheocasting system(CSIR-RCS) in rheo-processing and high pressure die casting of SiC metal matrix composites. The metal matrix consisting of nearly spherical proeutectic α(Al) globules was produced. Spheroidization of fibrous eutectic silicon took place upon heat treatment of the as-cast metal matrix composites(MMCs). Hardness increases as the volume fractions of SiC increases. Wear rates of the MMCs in the F and T6 heat treatment conditions were assessed with a metallographic preparation machine. It is found that the 11% SiC MMC wear rate is higher on SiC abrasives compared with the 50% SiC MMC wear rate due to wear of the aluminum matrix. This trend is reversed on diamond abrasives due to pull-out of the irregular shaped composite particles. The 50% SiC MMC suffers from composite particle fracture porosity after high pressure die casting (HPDC).

Key words: CSIR–RCS; HPDC; SiC; F condition; T6 condition; wear rate; hardness; porosity

1 Introduction

Metal matrix composites (MMCs) are natural materials of choice for wear sensitive applications. Attractiveness for making MMC components comes from the ratio of the material’s strength to mass although at the expense of ductility. Machining of such components becomes very difficult on account of the material’s wear resistance. Therefore, the ability to cast MMCs into near-net shape components will realize savings.

MMCs are being successfully cast with different gravity as well as high pressure die casting (HPDC) techniques[1]. In all these processes porosity originating from dissolved gasses at a high liquid metal pouring temperatures is of great concern.Processing temperatures of liquid metal in semi-solid metal (SSM) casting are much lower, resulting in reduced or even eliminated porosity. Attention has mainly been given to semi-solid casting of aluminum MMCs by the thixocasting route[2–7] but less so to the rheocasting route[8–10].

The aim of this work is to assess the capability of the CSIR–RCS through SiC with various volume fractions reinforced aluminum metal matrix composite and also to investigate consequent wear properties in the as-cast (F) and T6 heat treatment conditions on different abrasive media.

2 Experimental

Plates of SiC particles with various volume fractions were produced by rheo-processing and subsequently high pressure die casting (HPDC). Fig.1 shows the whole casting with dimensions of 100 mm×55 mm×6 mm including the plate component: the runner and the biscuit. Variation of volume fraction of SiC was achieved through settling stratification of Duralcan F3S.20S MMC in a 20 kg tilting furnace without any form of melt agitation. The composition of the Duralcan F3S.20S alloy, a hypo-eutectic Al-Si alloy, was 9.3% Si, 0.55% Mg, 0.11% Fe, 0.1% Ti, 0.01% Cu and the balance Al. The starting alloy contained 21.4% SiC with a median particle size of 12.8 μm.

The sequence followed for casting was: liquid metal was poured from the tilting furnace into the stainless steel processing cup (about 400 g), which was then manually transferred to a single coil version of the CSIR–RCS (induction stirring with simultaneous forced air cooling[11]) where processing started when the cup entered the coil. A thermocouple measures the semi-solid temperature of the material in the cup, and when the temperature measured by thermocouple reached the preset SSM temperature (587 °C), the processing

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Fig.1 Example of rheocast plates that includes runner and biscuit

stopped. The cup was then ejected from the coil and transferred to the HPDC machine (LK DCC130) and injected into the die. The piston followed the set computer to control injection velocity profile that is kept constant for the SiC castings with different volume fraction. The liquid metal pouring temperature (640 ˚C) was kept constant, but necessary changes were made to the semi-solid processing temperature to compensate for the rheology changes from the increases of the volume fraction of SiC to ensure good die filling during HPDC.

The first, fifth and last (tenth) castings were selected for investigation. Cylindrical specimens were wire cut from the runner area. Each casting yielded two specimens, one for the F condition and the other for heat treatment to the T6 condition. Heat treatment parameters for the T6 condition were: solution treatment at 540 ˚C for 6 h and quenching in room temperature water; artificial aging at 170 ˚C for 10 h. Equal area specimens, for each heat treatment condition, were mounted in bakelite for wear rate and bulk hardness testing.

An optical microscope (Leica DMI5000 M) equipped with a camera (Leica DFC480) and imaging software (Image–Pro MC v6.0) revealed the F and T6 condition microstructures of the mounted and polished samples. Image analysis software (ImageJ 1.38x) revealed the volume fraction of SiC per casting. Table 1 gives the set parameters on an automated metallographic preparation machine (ATM SAPHIR 550) used to characterize wear resistance. A new SiC grinding paper was used for each sample tested. Diamond impregnated discs were repeatedly used for the different samples as the other media. A balance (Sartorius extend) was used to measure mass loss to the forth decimal. The bulk hardness was measured (Future–Tech LC–200R).

Table 1 Parameters used on automated metallographic preparation machine

Wear medium	Grit	Time/s	Pressure/N	Speed/ $(r \cdot min^{-1})$
SiC	80	120	35	300
	240	120	35	300
Diamond	80	30	35	300
	220	30	35	300

3 Results and discussion

Rheocast SiC MMC castings were successfully produced by the combination of the CSIR–RCS and HPDC machine. The die filled properly with each cast to produce a full casting including the runner and the biscuit. It can be seen from Fig.2 that the settling stratification experiment is successful by increasing the volume fraction of SiC particles from the first to the last casting. The first casting was found to contain 11% SiC particles, the middle casting 27% SiC particles and the last casting 50% SiC particles.

All the microstructures in Fig.2 are defined by three constituents. The globular white phase is proeutectic α-Al that is nearly spherical and about 75 μm in diameter. From a practical point of view, the relative size of the globules should not distract from the fact that successful castings were achieved. The light gray phase is the last liquid to solidify and forms the eutectic phase. Fig.3 shows the silicon in the eutectic that has a fibrous appearance in the F condition. The dark gray phase is SiC particles in different irregular angled shapes and sizes. SiC particles have segregated to the eutectic liquid. There is also evidence of that small SiC particles entrapped in the proeutectic α. These small particles may have behaved like a nucleation agent or grain refiner, but judging from the density of particles included in a particular globule, it seems more likely that inclusion happened in suspension during rheo-processing. The absence of distinguishable proeutectic globules in the

50% SiC MMC (Fig.2(c)) probably resulted from restricted movement of the solidifying globules in the liquid phase during rheo-processing.

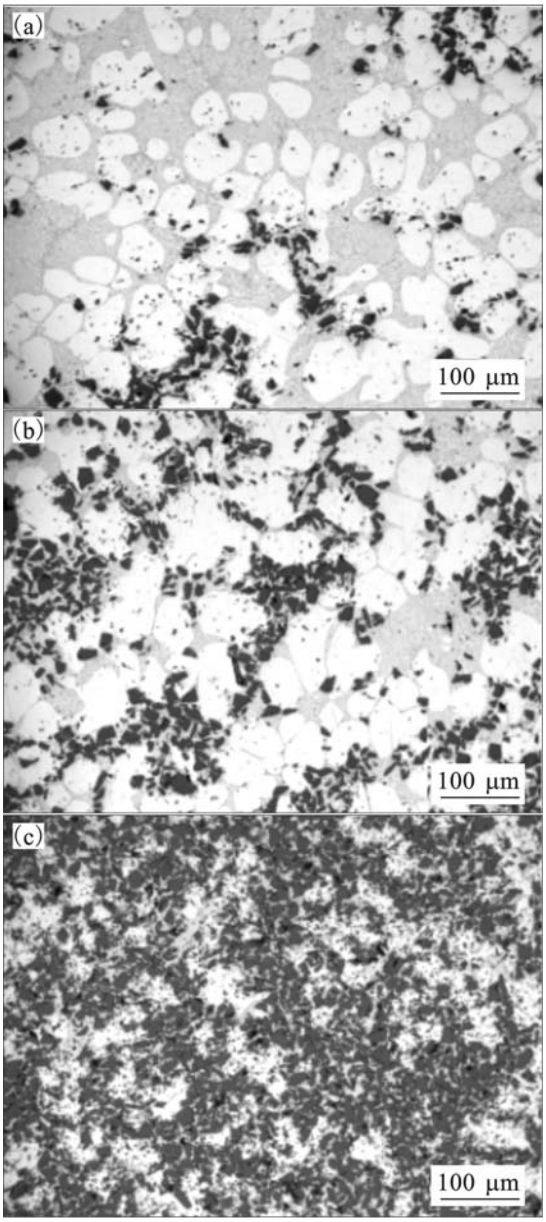

Fig.2 Optical micrographs of 11% (a), 27% (b) and 50% (c) SiC metal matrix composite castings in F condition

The change of the eutectic microstructure upon heat treatment from the F condition to the T6 condition is clearly visible in Fig.4. The fibrous silicon is completely spheroidized[12] in both the 11% SiC MMC and the 50% SiC MMC (including the 27% SiC MMC that is not shown). It is relatively difficult to distinguish the spheroidized silicon in the eutectic from the small SiC particles also in the eutectic in the 50 % SiC MMC. Once again a large number of small SiC particles are visible in the proeutectic α(Al) globules.

The matrix of the Duralcan MMC is a heat treatable Al-Si-Mg alloy. Precipitation strengthening by Mg_2Si precipitates was achieved through solution heat treatment, quenching and subsequent artificial aging. This process increase strengths above the original F condition properties[12]. In the current work hardness is the only measure of such an increase in strength. Table 2 indicates the hardness of each SiC MMC with different volume fraction in the F condition while Table 3 indicates the

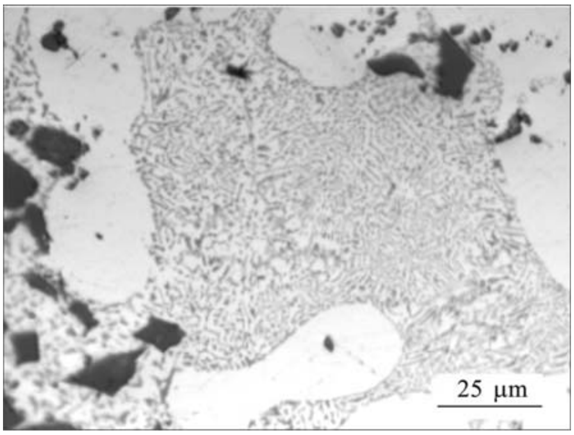

Fig.3 Optical micrograph of eutectic region in 11% SiC metal matrix composite in F condition

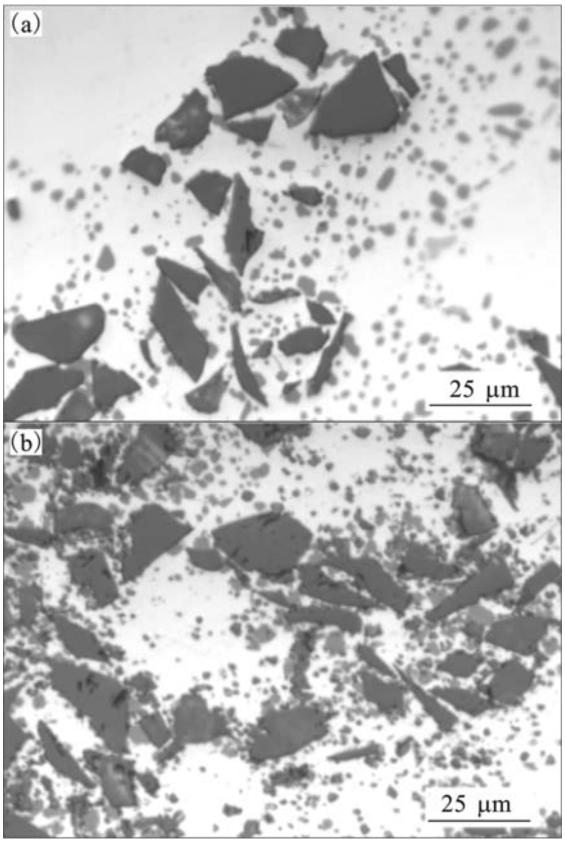

Fig.4 Optical micrographs of 11% (a) and 50% (b) SiC metal matrix composite in T6 condition

hardness of those in T6 condition.

Table 2 Wear resistance and hardness of SiC MMC in F condition

Medium	Grit	w(SiC)/%	Mass wear rate/ $(\mathrm{mg\cdot min^{-1}})$	Hardness (HRB)
SiC	80	11	262	42
		27	72	54
		50	51	67
	240	11	65	42
		27	37	54
		50	8	67
Diamond	80	11	796	42
		27	972	54
		50	988	67
	220	11	234	42
		27	190	54
		50	250	67

Table 3 Wear resistance and hardness of SiC MMC in T6 condition

Medium	Grit	w(SiC)/%	Mass wear rate/ $(\mathrm{mg\cdot min^{-1}})$	Hardness (HRB)
SiC	80	11	192	73
		27	75	83
		50	57	93
	240	11	65	73
		27	19	83
		50	14	93
Diamond	80	11	761	73
		27	851	83
		50	1 036	93
	220	11	236	73
		27	261	83
		50	297	93

Comparing the hardness of each SiC MMC with different volume fraction in the F condition, it is noticed that as the volume fraction of SiC increases, the hardness increases. It is expected that SiC is much harder than the aluminum matrix as is indicated by the high hardness of the 50% SiC MMC. The MMCs in the T6 condition follows the same trend.

Precipitation strengthening was achieved successfully as is evident by the increase of almost 50% in hardness in all cases of SiC MMCs going from the F condition to the T6 condition.

Table 2 gives account of wear rates of SiC with different volume fractions MMCs on different media in the F condition while Table 3 gives account of wear rates in the T6 condition for the same parameters. In general, not only are wear rates higher on diamond than those on SiC but also are the coarser grits in a specific abrasive medium.

On any of the SiC media and in any heat treatment condition the 11% SiC MMC wears faster than the 50% SiC MMC. The SiC abrasive is expected to primarily wear the aluminum matrix down since it is softer than the SiC reinforcing particles.

Close inspection of both Table 2 and Table 3 reveals that on any of the diamond media the 11% SiC MMC wears slower than the 50% MMC. The reason is clear although this trend is unexpected. The diamond particles on the diamond impregnated discs donot blunt or dislocate as the SiC abrasive particles do on the grinding paper. It means that the harder SiC particles in the SiC MMCs with higher volume fraction are pulled out more frequently from the matrix; therefore, they has a higher wear rate. Proving the proposed wear mechanisms will be the subject of a follow-on investigation.

Finally addressing porosity, it is observed from this investigation that casting of composites with high volume fraction is prone to porosity. The main causes are shrinkage porosity and gas porosity. However, in this case Fig.5 shows composite particle breakage porosity encountered in the 50% SiC MMC and to a lesser extent in the 27% SiC MMC. Because the casting injection pressures in HPDC are high, it means that inter-particle contact pressures during forced rheological flow of the cast material will be excessive resulting in local fracture and abrasion of composite particles especially when they are irregularly shaped.

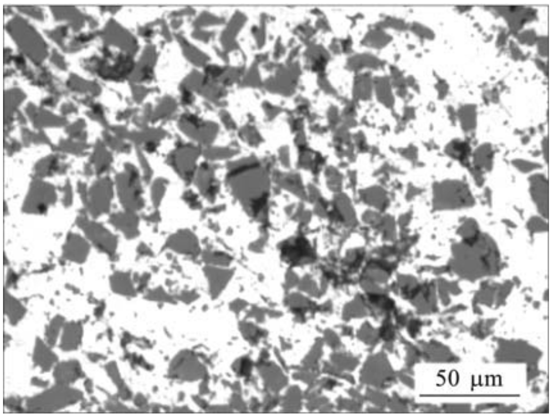

Fig.5 Optical micrograph showing composite particle breakage porosity (black areas around some SiC particles) found in 50% SiC metal matrix composite casting

4 Conclusions

1) The CSIR–RCS with HPDC can successfully shape rheocast metal matrix composites over a wide range of SiC particle volume fractions with nearly spherical proeutectic α globules.

2) SiC particles are associated with the eutectic that is the last liquid to solidify.

3) Spheroidization of the as-cast eutectic silicon takes place after solution heat treatment.

4) Hardness increases as the increasing of the volume fraction of SiC in the F and T6 condition.

5) Wear rates in the F and T6 conditions on SiC abrasive mediums decrease as the increasing of the volume fraction of SiC particles due to primary wear of the aluminum matrix.

6) Wear rates in the F and T6 conditions, on diamond abrasive mediums, increase as the increasing of the volume fraction of SiC particles due to pull-out of composite particles.

7) Porosity develops at high volume fraction of SiC due to reinforcing particulate fracture.

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