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Dry sliding wear behaviour of spray formed $ZrSio_4$ reinforced Al-Si-Sn alloy

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ABSTRACT

The wear behaviour of Al-12Si alloy and Al-12Si-Sn/$ZrSiO_4$ composite prepared by spray forming technique has been investigated under dry sliding conditions at different loads and temperatures. The wear rate of spray formed composite was significantly lower than that of as cast Al-12Si alloy. Paricle size of $ZrSiO_4$ was varied from 53 to 105 µm and the amount of Sn was taken 5 and 10 %. Smaller particles of $ZrSiO_4$ were able to reduce the wear rate up to more extent as compared to that of bigger particles in the same matrix. On increasing the amount of Sn the wear rate decreases. Copyright © 2011 VBRI press.

Keywords: Spray forming; wear; metal matrix composite; rapid solidification.

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Introduction

Spray forming is a method of casting metal components with homogeneous microstructure [**1**] via the deposition of semi-solid sprayed droplets on a substrate [**2, 3**]. The resulting part exhibits a rapidly solidified microstructure with very refined grain sizes and greatly reduced levels of segregation [**4**]. The ability of the process to eliminate harmful segregation effects makes it a very attractive alternative processing route for those difficult to work alloy systems [**5**] which cannot be fabricated in the as-cast condition [**6,7**]. $ZrSiO_4$ possesses a very low thermal expansion coefficient compared to most of the other ceramic oxides. Therefore, a change in temperature would not give rise to very high thermal stresses within $ZrSiO_4$ particles. $ZrSiO_4$ reinforced composite shows better wear resistance than alumina reinforced composite due to its superior particle-matrix bonding. It has high hardness, high modulus of elasticity, high temperature resistance and excellent thermal stability [**8**].

Wang et al. [**9**] have compared the sliding wear behavior of a hypereutectic Al-Si alloy prepared by spray-deposition and conventional casting methods and it has been found that the spray-deposition technique produces a finer matrix structure and provides better wear resistance as compared to the conventional cast one. Mondal et al. [**10**] have studied the high stress abrasive wear behavior of aluminium hard particle composites and it has been noted that the abrasive wear rate of alloy reduced considerably due to addition of SiC particle and the wear rate of composite decreases linearly with increase in SiC content. Kaur et al. [**11**] have studied the effect of the addition of zircon sand on microstructure of spray deposited Al-Si alloy. Zircon sand was found to be uniformly distributed as well as having good particle/matrix interfacial bonding in the alloy matrix.

The present study emphasizes on the preparation of ceramic particulate reinforced aluminium metal matrix composite via spray deposition technique. The reinforcement chosen for the study is $ZrSiO_4$. Wear tests of the synthesized composite was done and the worn surfaces and debris characterized under SEM to understand the wear mechanism.

Experimental

A spray forming set up is given elsewhere [**12**] which mainly consist of the following units:

(i) Melting and atomization unit
(ii) Spray deposition unit

The melting and atomization units consist of a resistance heating furnace with a graphite crucible placed inside it, which is charged with the metal to be spray deposited. This crucible is connected with a metal delivery tube at its bottom surface, which passes through the central hole of convergent divergent nozzle [**13**]. $ZrSiO_4$ particles were injected through two injectors having 5 mm diameter, in the spray closer to the atomization zone of the melt. The deposition unit consists of a copper substrate. Nozzle to substrate distance of 380 mm was invariably used in all the experimental runs.

About 1 kg of Al–Si alloy of commercial purity (**Table 1**) was heated to a temperature of 1073K in the crucible kept over the nozzle. A stopper rod at the entrance of delivery tube prevents the melt flow through it prior to its atomization. Nitrogen gas (commercially available having 99% N_2) at the pressure of 1.0 MPa was supplied for atomization prior to melt flowing through the delivery tube. Atomization of melt resulted in a spray of wide range of micron size droplets. These droplets were allowed to deposit over a copper substrate. Preform was taken out of the substrate after deposition [**14**].

Table 1. Chemical composition of Al-Si alloy

Si	Fe	Cu	Mn	Mg	Zn	Ti	Ni	Pb	Sn	Al
12	0.37	1.23	0.41	0.94	0.21	0.025	0.94	0.029	0.01	balance

The composition of commercially available $ZrSiO_4$ used in the present work is reported in **Table 2**.

Table 2. Chemical composition of $ZrSiO_4$.

Component	$ZrSiO_4$	TiO_2	Fe_2O_3	Volatiles
Wt. %	98.10	0.27	0.12	1.51

A series of reinforcement was selected in such a way to see the effect of particulate size variation and immiscible additive element Sn on the composite performance. The series prepared is given in **Table 3**.

Wear testing

Dry sliding wear tests were carried out with a pin-on-disc type machine. It consisted of a hardened EN-24 steel disc (surface roughness = 0.4-0.5 μm) of diameter 12 cm with Rockwell hardness of 57 HRC and a specimen holder. The specimen was in the form of pins with 6 mm diameter. The wear surfaces were first ground and then polished through diamond paste prior to wear testing. The sliding velocity was fixed at 1.6 m/s. The experiment has been designed with variable loads of 3, 4 and 5 kg respectively. Wear characteristics have been studied at two different temperatures 40 and 80 ^{0}C. The worn samples were characterized through SEM (JEOL JXA 840A).

Table 3. Spray formed alloys used in the present study.

Series	Composition
A	Al-12Si
B	Al-12Si-5Sn/10 $ZrSiO_4$ particle size 53-74μm
C	Al-12Si-5Sn/10 $ZrSiO_4$ particle size 88-105μm
D	Al-12Si-10Sn/10 $ZrSiO_4$ particle size88-105μm

Results and discussion

Effect of sliding distance

The wear rate against sliding distance was studied at different loads of 3, 4 and 5 kg for as cast and spray formed alloys 'A' to 'D' (**Table 3**) at a temperature of 40 ^{0}C as shown in **Fig. 1-5**.

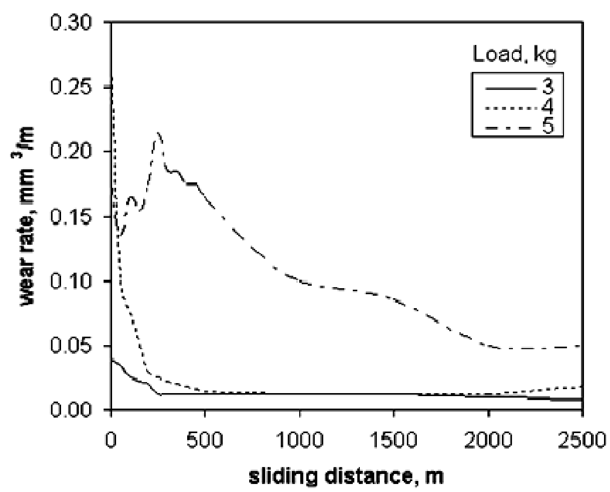

Fig. 1. Variation of wear rate with sliding distance at different loads for as cast alloy 'A' at a temperature of 40 ^{0}C.

Similar trends were observed at a temperature of 80 ^{0}C. The results show two different regimes in the trend of wear rate. The curves signify that the wear rate initially is very low, rising steeply with wear distance, and then gradually decaying at longer wear distance. This behaviour is analogous to the wear rate obtained from respective material at various applied loads. It has been found that initial wear rate up to 300 m is much higher from that of constant or steady wear rate.

Gupta et al. [**15**] reported the similar results for dry sliding wear characteristics of 0.13% carbon steels. For both as cast alloy 'A' (**Fig. 1**) and spray formed alloy 'A' (**Fig. 2**) a steady state is approachable after 300 m sliding distance for all applied loads except higher load of 5 kg.

However, for reinforced composite the stabilized wear rate is attained for all applied loads as shown in **Fig. 3-5**. These results are analogous to dry sliding block-on-ring wear test of squeeze cast A390 reinforced with 20% SiC at 5 Kg applied load and 3.3 m/s sliding speed reported by Ma et al. [**16**] Wear rate was also found to be higher at higher applied loads. Similar observations also have been reported by Chaudhury et al. [**17**] in the Al–2Mg–TiO_2 system for spray and stir cast composites.

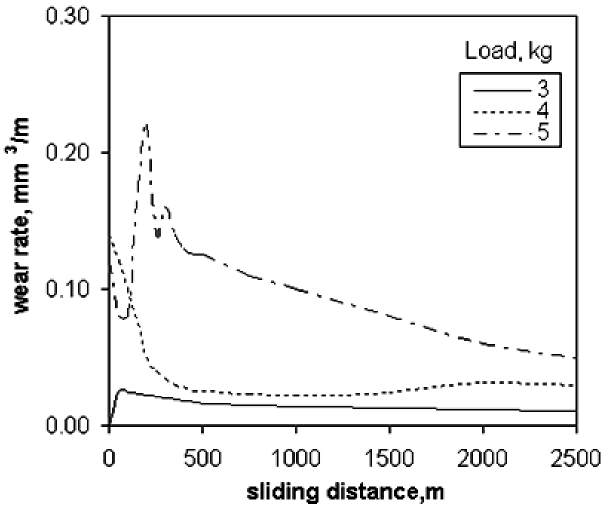

Fig. 2. Variation of wear rate with sliding distance at different loads for alloy ‘A’ at a temperature of 40 ^{0}C.

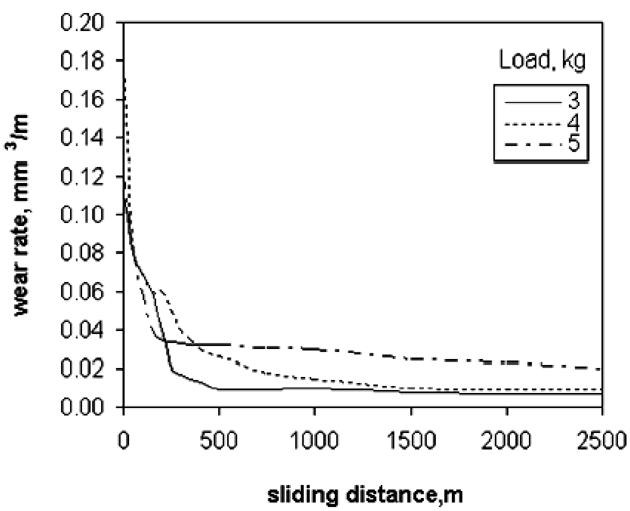

Fig. 3. Variation of wear rate with sliding distance at different loads for alloy ‘B’ at a temperature of 40 ^{0}C.

Fig. 3 and **4** show the wear rate for alloys ‘B’ and ‘C’ having $ZrSiO_4$ particle size 53-74 and 88-105 μm, respectively. This has been found that the lower particle size of $ZrSiO_4$ are able to reduce the wear rate more as compare to that of the bigger size. On comparing the wear rate at each load it has been found that the wear resistance offered by spray processed composite is higher than that of the as cast Al-Si alloy as shown in **Fig. 1** and **2**. Wear resistance is also higher for $ZrSiO_4$ reinforced Al-Si composite as compared to that of its parent alloy.

Moreover, wear rate in alloy ‘D’ having 10% Sn (**Fig. 5**) is lower than that of alloy ‘C’ having 5% Sn (**Fig. 4**). It depicts that on increasing the amount of Sn the wear rate decreased for same particle size of $ZrSiO_4$ reinforced composite. Sn is a soft metal and generally used in babbit alloys as a solid lubricant in plain bearings. The Sn metal solidifies along the grain boundaries of aluminium [**18**]. This Sn provide an interface between the pin and wheel while sliding. As the pin wears the harder particulate is exposed, with the matrix eroding somewhat to provide a path for lubricant to flow between the rubbing surfaces. It provides an anti-frictional surface to reduce wear. Further, microstructural analysis of the wear surfaces and wear debris is necessary to understand the wear mechanism.

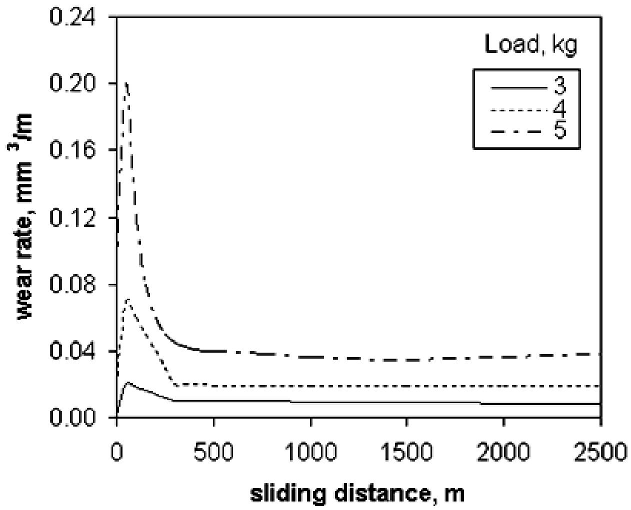

Fig. 4. Variation of wear rate with sliding distance at different loads for alloy ‘C’ at a temperature of 40 ^{0}C.

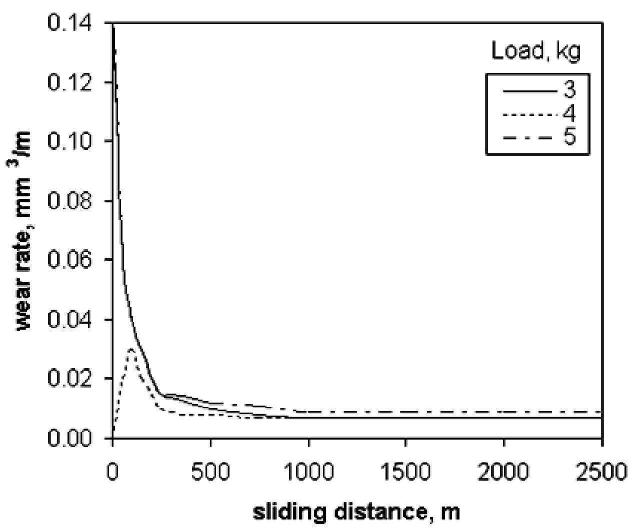

Fig. 5. Variation of wear rate with sliding distance at different loads for alloy ‘D’ at a temperature of 40 ^{0}C.

Effect of various parameters on wear

The average wear rate has been determined for each load, temp and alloys after the steady state is approached i.e. after 300 m sliding run as shown in **Fig. 6-8** for 3, 4 and 5 kg wear load, respectively. The wear rate of as cast alloy

'A' is also shown in the same figures. Alloys 'C' and 'D' represent the effect of Sn composition variation whereas alloys 'B' and 'C' represent the effect of $ZrSiO_4$ particle size on wear rate. At 40 ^{0}C, it has been found that spray formed composites have lower wear rate as compared to that of as cast alloy 'A' [**19**] for 3 and 5 kg wear load. However, the results shown at 4 kg load are different which might be due to the change in the wear mechanism of both alloys and composites. At higher temperature of 80 °C and lower load cast alloy shows better wear resistance as compared to that of composites.

From all the alloys, alloy 'D' has offered the best wear characteristics due to the higher content of Sn in the Al-Si alloy which caters lubrication effect. Moreover, the alloy 'B' offers greater wear resistance than that of the alloy 'C' which is due to the decrease in particle size of $ZrSiO_4$. Therefore, it is necessary to know the operative wear mechanism for these samples under these conditions. The wear mechanism can be understood with microstructural analysis of the worn pin and collected debris.

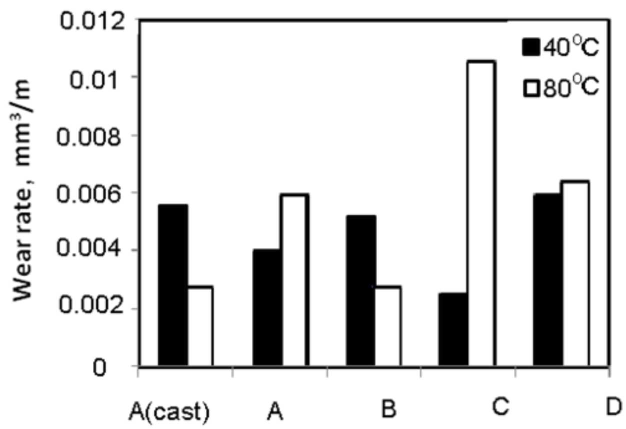

Fig. 6. Wear rate for different alloys at two different temperatures for 3 kg wear load.

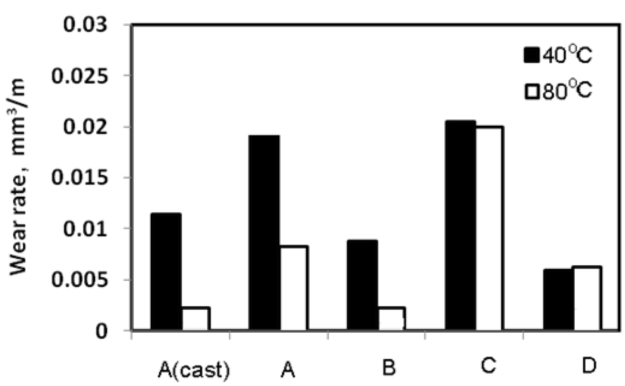

Fig. 7. Wear rate for different alloys at two different temperatures for 4 kg wear load.

Analysis of worn pin and debris

Fig. 9-12 show surface morphology of the worn surface and debris at 4 kg load under various conditions to understand the wear mechanism. It has been found that in **Fig. 9-10** the wear grooves run parallel to the sliding direction. Worn surface of the as cast Al-Si at 80 ºC (**Fig. 9a**) shows the microcutting marks along the sliding direction by which the material has been removed from the surface. Moreover, the crack propagation and debris formation in the chunk amount is clearly visible on the track which is shown in **Fig. 9**(**b**). The worn surface of spray formed Al-Si alloy has shown the repititive plughing of the material inside the grooves as shown in Fig.10a. Size of debris is small in spray formed Al-Si alloy as compared to that of as cast Al-Si alloy as shown in **Fig. 10**(**b**).

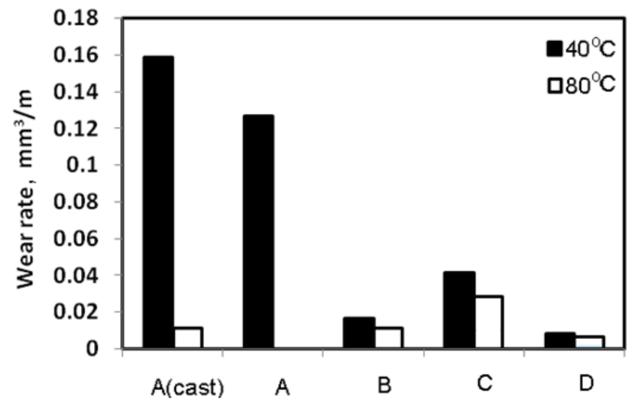

Fig. 8. Wear rate for different alloys at two different temperatures for 5 kg wear load.

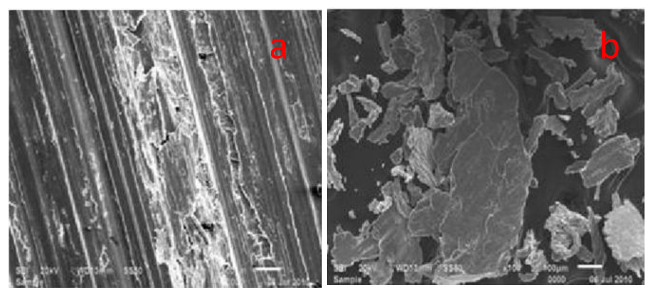

Fig. 9. (**a**) SEM micrograph of worn surface of as cast alloy 'A' at 80 ^{0}C for 4 kg wear load and (**b**) debris of as cast alloy 'A' at 80 ^{0}C for 4 kg wear load.

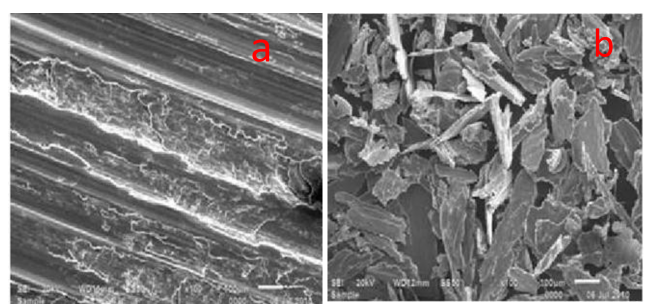

Fig. 10. (**a**)SEM micrograph of worn surface of alloy 'A' at 80 ^{0}C for 4 kg wear load. (**b**) SEM micrograph of debris of alloy 'A' at 80 ^{0}C for 4 kg wear load.

At 40 ^{0}C a different surface morphology is observed in the alloy 'D' (**Fig. 11a**) as compared to that of the as cast and spray formed alloy 'A'. It is observed that wear grooves are fine with few dimples on the worn surface. The morphology of the collected wear debris (**Fig. 11b**) shows the oxidative wear mechanism and the size of the wear debris is greatly reduced in comparison to that of the as cast and spray formed alloy 'A'.

At 80 ºC, the width of the grooves (**Fig. 12a**) and wear debris morphology (**Fig. 12b**) is similar to that of the worn surface at 40 ^{0}C except the more amount of shining of the Sn-phase.

It has been found that the worn pin morphology of $ZrSiO_4$ composite at the surface is shallow as compared to that of the as cast and spray formed alloy 'A'. This indicates that the wear in $ZrSiO_4$ composite should be less than that of both alloys which is again justified from **Fig. 6-8**.

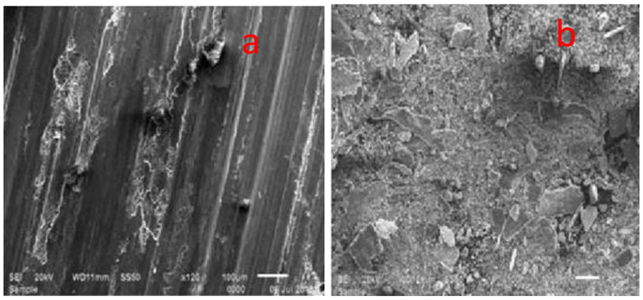

Fig. 11. (**a**) SEM micrograph of worn surface of alloy 'D' at 40 ^{0}C for 4 kg wear load.(**b**): SEM micrograph of debris of alloy 'D' at 40 ^{0}C for 4 kg wear load.

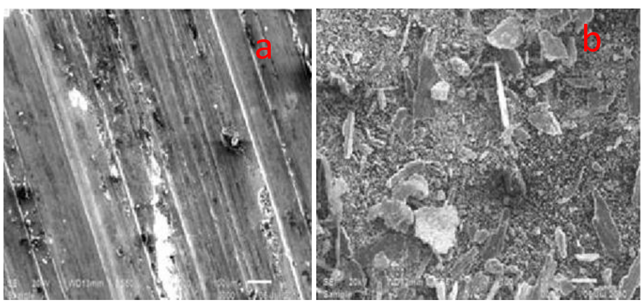

Fig. 12. (**a**) SEM micrograph of worn surface of alloy 'D' at 80 ^{0}C for 4 kg wear load. (**b**) SEM micrograph of debris of alloy 'D' at 80 ^{0}C for 4 kg wear load.

One of the key features observed for alloy 'A' (both as cast and spray formed) is that the debris shows metallic character. The size of these debries is bigger and moreover, some of them are twisted which indicates that these debries also come out as a chunk particle and these remain at the track. These debries are rolled further when trapped beneath the pin during subsequent movement. However, in case of $ZrSiO_4$ composites a mixed morphology of debries is seen which comprises of long and splat debries alongwith fine one and the twisted features are absent. This variation in debries also indicates the presence of different wear machanism in both cases.

Conclusion

1. Wear rate was found to increase very rapidly with sliding distance in the initial stage and then decreases gradually. Beyond a distance of 300 m wear rate becomes almost constant.
2. Smaller particles of $ZrSiO_4$ are able to reduce the wear rate up to more extent as compared to that of the bigger particles in the same matrix.
3. On increasing the amount of Sn in the spray formed alloys the wear rate decreases.
4. In general spray formed alloys are imposing more wear resistance, except for 4 kg wear load, as compared to that of the as cast Al-Si alloy for 3 and 5 kg wear load.

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