Wear behavior of squeeze cast Al-SiC$_P$ composites at room and elevated temperature

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The wear behavior of squeeze cast A-390 matrix composite, reinforced by SiC particulate is investigated. The composite specimens were fabricated using vortex stirring, followed by squeeze casting technique. The wear tests were carried out using a pin on disc technique. The experimental work extended to investigate the wear behavior at elevated temperature. The results obtained, indicate that the increase of volume fraction and/ or particle size of the reinforcement enhance the wear resistance. A small effect of particle size on wear rate was noticed when compared with the effect of volume fractions. The room temperature and elevated temperature test results showed that the specimens fabricated by squeeze casting technique have greater wear resistance than those fabricated by vortex technique. The obtained results revealed also that the transition temperature depends on composite volume fraction and fabrication technique.

نظرا للأهمية الكبيرة للمواد المركبة في التطبيقات الهندسية المختلفة ومنها مجال تصنيع محركات السيارات والمعدات الميكانيكية والتى تحتاج هذه الأجزاء إلي مقاومة كبيرة للبرى وخصوصا عند درجات الحرارة المرتفعة ولذلك يهدف هذا البحث إلي دراسة ظاهرة لبرى عند درجات حرارة مختلفة مع مقارنة هذه النتائج مع المناظرة لها في درجة حرارة الغرفة وقد آجري البحث باستخدام سبيكة الألمونيوم المستخدمة في تصنيع اسطوانات محركات السيارات وقد تم تحضير العينات بإضافة مادة التقوية وهى كربيد السيليكون إلى المعدن المنصهر بنسب وحجم حبيبات مختلفة وقد استخدم في إعداد العينات طريقة التقليب وكذلك طريقة التجمد تحت ضغط مرتفع. وقد أجريت اختباران البرى للعينات المختلفة وذلك عند درجات حرارة متغيرة. وتم عرض النتائج للشروط المختلفة المستخدمة فى أجراء الاختبارات وتم مناقشتها واستخلاص أهم التوصيات التي تم الحصول عليها

Keywords: MMC, Squeeze casting, Wear behavior

1. Introduction

Metal Matrix Composites (MMCs) have attracted considerable attention because of their physical, mechanical, and tribological properties can be tailored for a given application. Good cast ability, high corrosion resistance, and low density are some known properties of Al-Si alloys. Hypereutectic also exhibit low thermal expansion coefficients and elevated wear resistance [1]. That is why they have found applications in the manufacturing of various automotive engine components such as cylinder block liners and piston insert rings, where dry sliding wear is a predominant process [1-3].

Further improvement can be expected from the reinforcement of these alloys with ceramic particulates [3, 4].

Incorporation of ceramic particles, into a metal matrix causes a significant increase in the bulk hardness of the material, the stiffness and high temperature strength as well as wear resistance at ambient temperature [1,4,5]. Typically, 20 vol. % reinforcement can cause up 60 % increase in the indentation hardness of the material [6, 7]. The increase in composite hardness due to reinforcement tends to be linearly related to the volume fraction of reinforcement. However, the wear rates are not linearly related to the bulk hardness. The benefits of reinforcement in terms of wear resistance can be many times greater than the relative increase in hardness, but in other instances may be negligible. It is often reported that increasing the volume fraction of reinforcement leads to a decrease in sliding wear rate. This illustrated in some of the earliest work on the sliding wear of MMCs [8 - 11] for an addition of alumina particles to pure AL and AL-Si alloys. These data were obtained in sphere on disc experiments, with a hard steel sphere sliding unlubricated against the surface of an MMC disc at 100 mm s^{-1} . The unreinforcement matrix alloy wore at a rate approximately 50 times that of the optimum MMC material, which contained 20 wt. % of the largest particles (142 um). An appreciable influence of reinforcing particle size can be seen. Tests under reciprocating dry sliding conditions [11] of AL 6061 – SiCp (20 vol.%) against a 431 stainless steel counter face have also shown much lower wear rates in the composite than in the unreinforced matrix alloy, by a factor of ~ 300. The effect of reinforcement on wear resistance and mechanical properties has been the subject of increasing attention in recent years. However a few studies have been published regarding dry sliding wear at elevated temperature of aluminum-based composites [6, 12]. The influence of morphology, volume fraction, and particle size of the reinforcement and the presence of any tribolayer on the wear of composites at elevated temperature still unclear [12, 13].

2. Experimental work

2.1. Fabrication of composite specimens

The vortex technique and squeeze casting technique have been used to fabricate composite specimens based on A-390 matrix reinforced by silicon carbide particulate. The chemical composition of the matrix alloy and reinforcement particulate are shown in tables 1 and 2, respectively. The reinforcing particulates were positively charged by impregnating them in a solution containing N^+ ions for several hours, and then they were dried. This treatment is essential to enhance incorporation of the SiC particulate into the molten matrix.

In vortex technique The matrix alloy was cut to small pieces, then charged into crucible furnace of 3 kW power where it is heated to a superheat of 750°C, then the melt is stirred using mechanical stirrer. The SiC particulates were preheated at 400°C for 2 hours. The stirrer impeller was completely immersed in the molten metal with its axis coaxial with the crucible axis. As soon as a satisfactory vortex was created, the preheated particulates were gradually added in the vortex. The time needed for the addition of SiC particulate was varied between 20 and 50 minutes, according to the volume fraction of SiC particulates. When the addition of SiC particulate was completed, stirring of the mixture was continued for another 15 minutes, then the mixture was poured at 720°C into the prepared steel die. The cast was withdrawn from the mold after complete solidification, then the required specimens were taken for investigation.

In squeeze cast technique, a special die set of 50 mm inside diameter, 100 mm outside diameter and 125 mm height provided with a punch of 50 mm diameter. The die set was manufactured from tool steel material. The die walls were coated by graphite to inhibit sticking of ingot to the walls. The reinforcing particulate and small pieces of the matrix alloy were charged into the die. The die was heated using an electric furnace, until the matrix was melted and superheated. The temperature of molten metal was held at 720°C for 30 minutes to achieve a uniform temperature distribution in the matrix. A gradually increasing pressure was applied to the aggregate through the punch. The maximum applied pressure of 100 MPa was maintained constant till complete solidification, then it is released. The ingot inside the die was ejected using high-pressure press. The obtained cast was cut to the required shape and dimensions.

The volume fractions were calculated through applying the following formula:

$$\upsilon_f = (\upsilon_r / \upsilon_s - \upsilon_r)100.$$

Where, υ_f is the volume fraction, υ_r is the volume of reinforcing particulates, and υ_s is the volume of fabricated composite specimen which contain reinforcing particulates. The present pilot experimental work proved that, only 50 mm from the total height of the fabricated specimen contain reinforcing particulates.

Table 1
Chemical composition of matrix alloy A-390

Element	Si	Fe	Cu	Mg	Mn	Ni	Zn	Ti	A1
Percent	16.47	0.36	4.29	0.62	0.132	0.149	0.019	0.017	Bal.

Table 2
Chemical composition of SiC particulate

Element	SiC	SiO_2	C	AL_2O_3	Si	Fe_2O_3
Percent	98.0	0.75	0.4	0.2	0.6	0.05

2.2. Experimental conditions

The experimental work was carried out to investigate the wear loss of composite specimens fabricated by the two different methods: vortex casting method and squeeze casting method. The fractions of reinforcements was varied to include 8, 12 and 20 vol.%. Typical experiments were conducted by varying the particle size to include: 28 µm, 52 µm, and 93 µm.

Wear experiments were conducted at different temperatures covering the range from 50 °C to 300 °C with steps of 25 °C.

A pin on disc apparatus was specially designed for this purpose. The apparatus is equipped with a controlled electrical furnace around the high carbon steel disc and tested specimen to enable constant temperature for the elevated temperature. The high carbon steel disc and the tested specimen were heated for one hour before conducting the test. Chemical analysis of the disc material was conducted before and after wear test to evaluate the transfer of material from test piece to the disc during test. The chemical composition before test is given in table 3. Test specimens of 8 mm diameter and 30 mm length were machined from the cast composite ingots. The end of test specimens was finished using surface grinding machine. Grinding conditions were adjusted to obtain similar surface topography in all specimens.

The machined specimens were heat treated as follows: solution treated at 530 °C for one and half hour, water quenched, naturally aged at room temperature for 20 hours and then artificially aged at 175 °C for 8 hours.

All wear tests were conducted at constant operating pressure of 0.2 and constant operating speed of 2 m/sec. Dry tests were used to accelerate wear.

3. Results and discussions

3.1. Distribution of reinforcing particulate in metal matrix composite

To investigate the distribution of the reinforcing particulate in the metal matrix composite specimens fabricated by vortex technique and squeeze casting technique, the microstructure in both the transverse and longitudinal sections were observed using an optical microscope. The macrographs in the transverse section of specimen containing 20 vol.% fractions were shown in fig. 1. The macrostructure exhibits a relatively homogenous particulate distribution with random orientation. The particle distribution is more homogenous at the center than at the edge. The macrographs on longitudinal plane, (fig. 2) also indicate a reasonable particle distribution. The shown dark spots in the macrograph indicate porosity positions which is confirmed by observations at high magnification. High agglomeration was noticed for specimens of high volume fraction as shown in the micrograph of fig. 3.

The micrographs of composite specimens fabricated by squeeze casting technique is shown in fig 4. The distribution of reinforcing particles. is much more uniform in the matrix, with absence of porosity as compared

Table 3
Chemical composition and mechanical properties of the disc material

Element	C	Si	Mn	S	P	U.T.S	H.V.
Percent	0.6	0.9	0.85	0.03	0.025	720 N/mm^2	220

Fig. 1-a. Macrograph in the transverse plane for vortex specimen X-50.

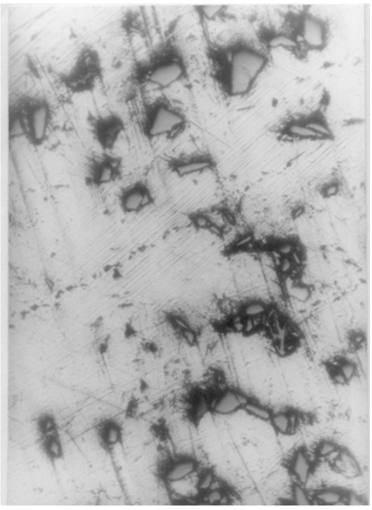


Fig. 1-b. Macrograph in the longitudinal plane for vortex specimen X-50.

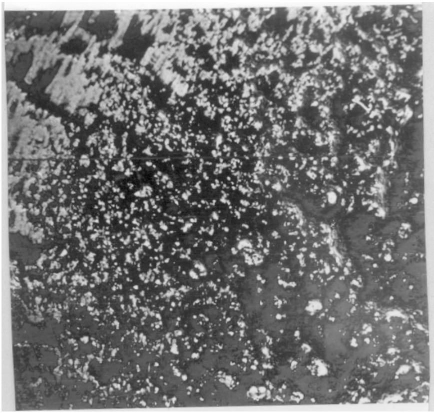


Fig. 2-a. Macrograph in the longitudinal plane for vortex specimen X-50.

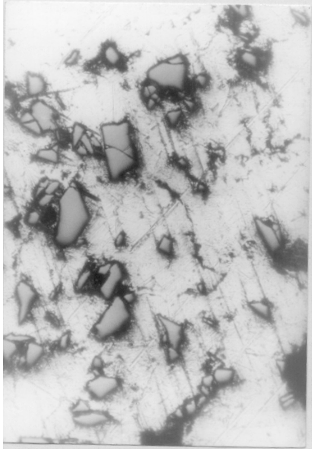


Fig. 2-b. Macrograph in the longitudinal plane for vortex specimen X-50.

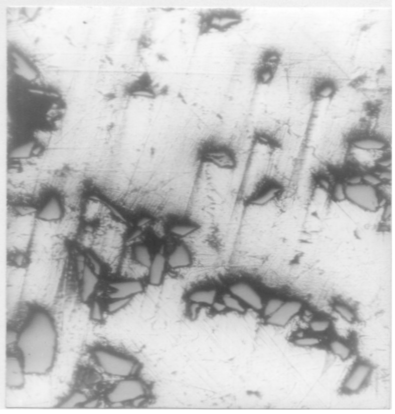


Fig. 3. Microstructure of the vortex specimen X-200.

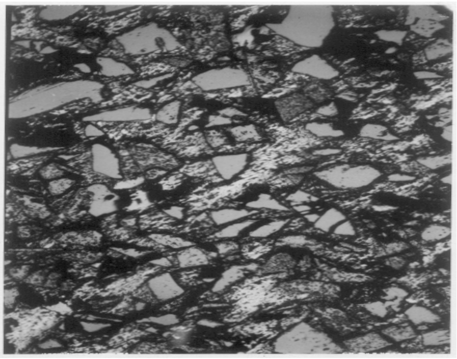


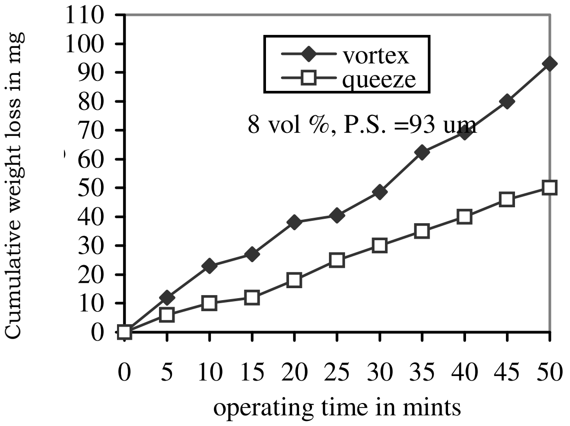
Fig. 4. Microstructure of the vortex specimen. 20 Vol. % Sic X-200.

to the case of composite prepared by vortex casting. This emphasis the role of squeezes casting technique in inhibiting porosity and agglomeration phenomena. Absence of dark areas around the reinforcing particulate indicates a good interface between reinforcing particulate and matrix.

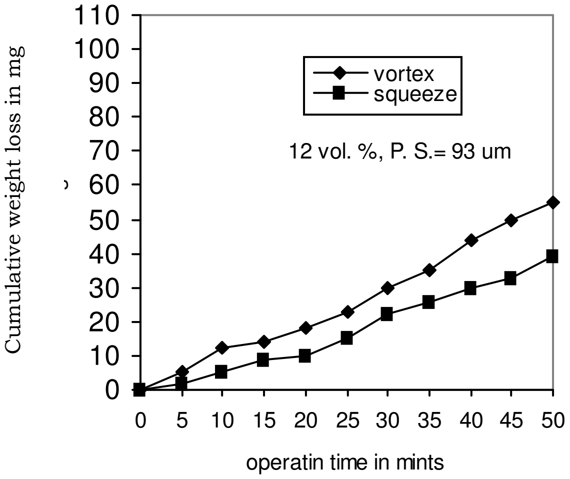
3.2. Effect of v_f and particle size on room temperature wear resistance

Fig. 5-a, 5-b, and 5-c represents the cumulative weight loss in mg versus wear test time in minutes for specimens of different SiC volume fraction of 8%, 12%, 20% volume, respectively. The tests were conducted on similar specimens prepared by vortex technique and squeeze casting technique. In all specimens, particle size was kept constant at 93 µm. The results indicate that squeeze cast composite specimens showed greater wear resistance than that fabricated by vortex technique. A similar trend was noticed for tests conducted on specimens reinforced by particle size of 51 µm and 28 µm, as shown in figs. 6-a, 6-b, 6-c and 7-a, 7-b, and 7-c.

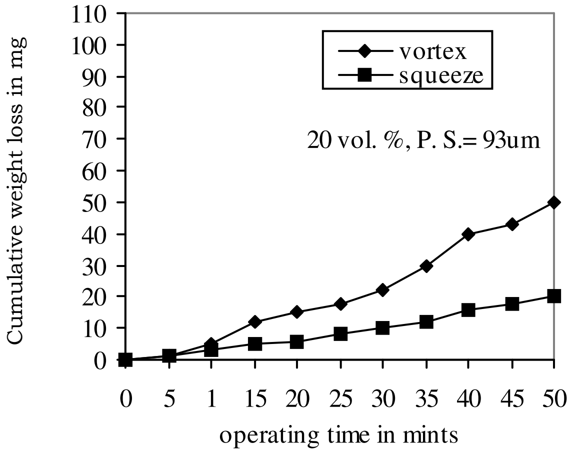
The bar chart of fig. 8 shows the cumulative weight loss in mg versus volume fraction for constant operating time of 50 minutes and different particle sizes of 93 µm, 51 µm and 28 µm. These results show that, the increase of SiC volume fraction improves the wear resistance of the composite. These results are attributed to the fact that the increase of volume fraction increases the number of hard particles that share in carrying the applied load. Hence the force transmitted to the grain boundary and matrix interface are reduced. Fig. 9, represent bar chart presentation of cumulative weight loss in mg versus particle size for different volume fractions of 8, 12 and 20 vol. %. The results correspond to tests conducted at constant operating time of 50 minutes on specimens fabricated by vortex technique and squeeze technique. In the investigated range, these results revealed that, the particle size has a small effect on weight loss for composite specimens contain low volume fractions of 8 vol. % and 12 vol.% as shown in figs. 9-a, b. The large particles of 93 µm and 51 µm very effectively resist penetration and cutting into the surface and this is attributed to, high values of hardness, and good bonding with the matrix and small particle/ matrix interface



(a) Volume fraction of 8 vol. %.

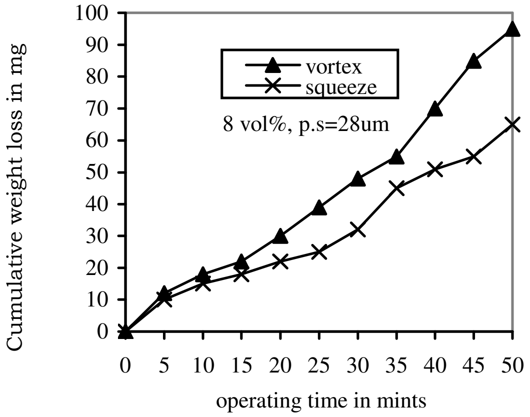


(b) Volume fraction of 12 vol. %.

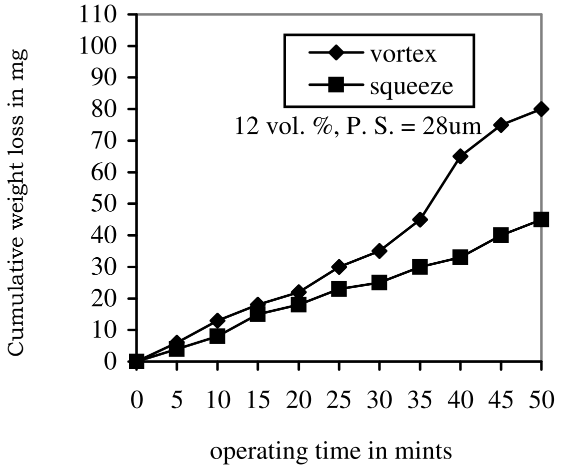


(c) Volume fraction of 20 vol. %.

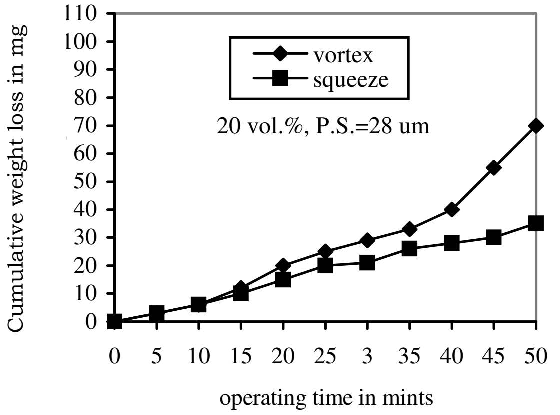
Fig. 5. Cumulative weight loss versus operating time in minutes for different volume factions and constant particle size of 93 µm.



(a) Volume fraction of 8 vol. %.

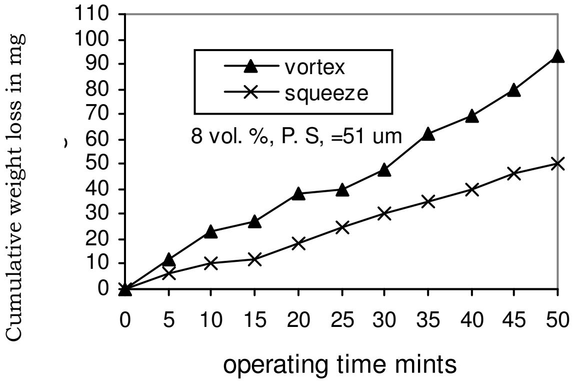


(b) Volume fraction of 12 vol. %.

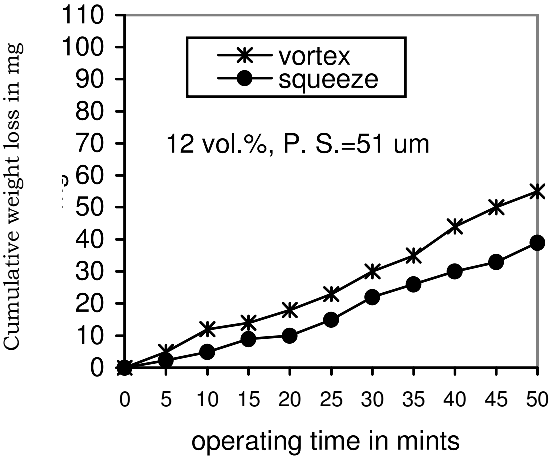


(c) Volume fraction of 20 vol. %.

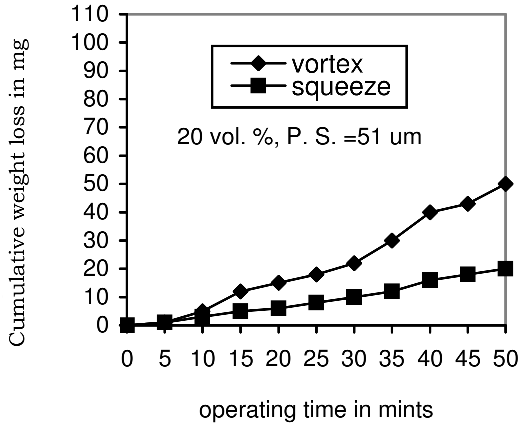
Fig. 6. Cumulative weight loss versus operating time in minutes for different volume factions and constant particle size of 28 μm.



(a) Volume fraction of 8 vol. %.



(b) Volume fraction of 12 vol. %



(c) Volume fraction of 20 vol. %.

Fig. 7. Cumulative weight loss versus operating time in minutes for different volume fractions and constant particle size of 51μm.

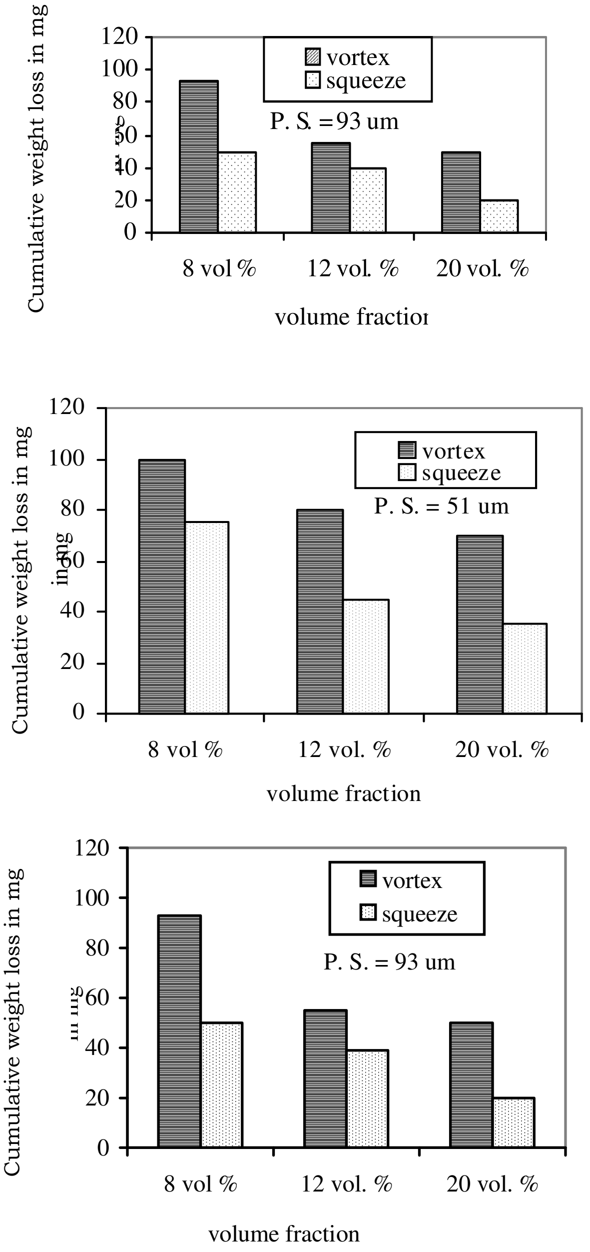
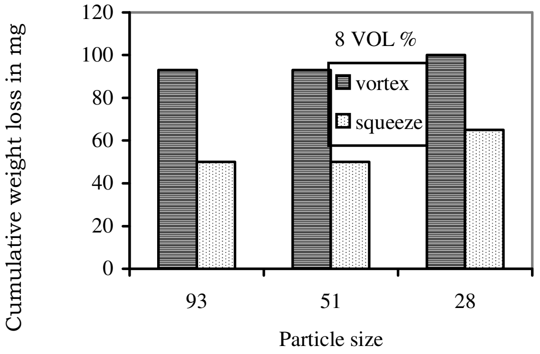


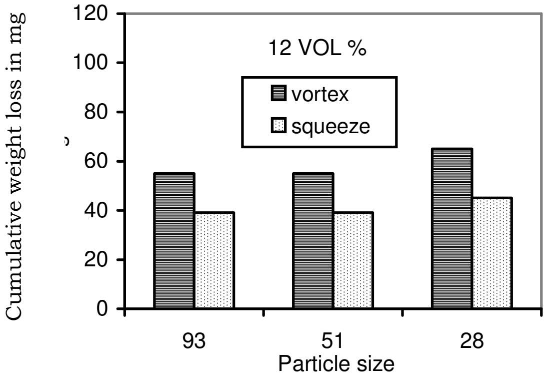
Fig. 8. Bar chart relationship between cumulative weight loss versus volume fractions for constant operating time of 50 minutes.

stress. For composites containing small particle size of 28 µm, the SiCp strengthens the aluminum matrix, thus limiting the deformation, also it resists the penetration and shearing action of the hard asperities or particles pin into the composites and thus improves in comparison with the matrix alloy. On other hand, in comparison with large particles of SiC, small particles can conform with the deformation of the matrix to a certain extent, and are more easily extracted along with the matrix, from the specimen.

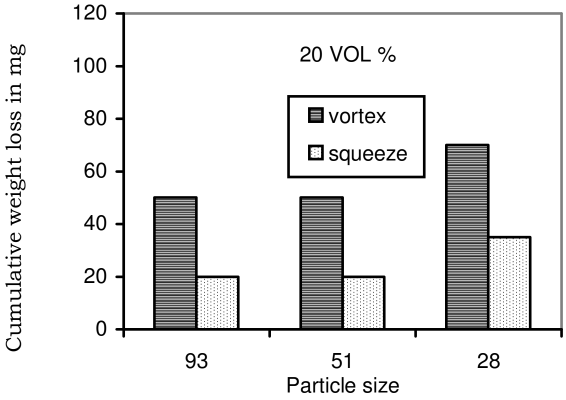
The good wear properties of the high volume fraction composites based on large particles shown in fig. 9-c, are mainly attributed to the excellent wear resistance provided the large size SiC particles. Where the wear behavior of the composites based on large particles can be described by the



(a) Volume fraction 8 vol. %.



(b) Volume fraction 12 vol. %.



(c) Volume fraction 20 vol. %.

Fig. 9. Bar chart relationship between cumulative weight loss versus particle size.

particulate decoherence model [7]. The lower wear resistance of the high volume fraction composites based on small particle size of 28 um shown in fig. 9-c, is attributed to the increase separation of reinforcing particles from the matrix, which increases the number of cutting points scratching both the composite pin and steel disc surfaces. Because of different wear mechanisms, the wear resistance of composite containing large particles is higher than that of those containing small ones, although the bulk hardness of the former group is slightly lower than that of the latter [2, 5].

3.3. Effect of casting technique on wear resistance

The results of vortex specimens were compared with that fabricated by squeeze technique for different volume fraction and particle size as shown in figs. 5 to 9. The cumulative weight loss versus the operating time for the matrix alloy A-390 specimens fabricated by vortex and squeeze technique are shown in fig. 10.

The obtained results indicate that the wear resistance of the squeeze casting specimens is relatively higher than that of specimens fabricated by vortex technique under the same reinforcing conditions. Squeeze casting improves the casting properties namely inhibiting the porosity, enhancing good interface between reinforcement particulate and matrix, enhancing uniform distribution of particles as shown in microscopic graph fig. 4 and finally refining the matrix grains as shown in the micrographs of figs. 11-a, b. Specimens prepared by vortex technique experience considerable porosity, cavities and agglomeration of grains which reduce the properties of the casting. This is significantly noticed from the micrograph of fig. 3 for grain size of 51 μm.

3.4. Elevated temperature results

The wear resistance of the metal matrix alloy A-390 and composite specimens were studied in the range of temperature from 50 °C to 300 °C with a step of 25 °C. The temperature was controlled using a thermocouple with an accuracy of ±1°C. All test conditions were as stated in room temperature tests.

The effect of elevated temperature on the wear rate of sliding specimen is shown in fig. 12 for specimens of different SiC volume fraction of 8 vol. %, 12 vol. % and 20 vol.% and constant particle size of 51 μm. The wear rate was calculated using the formula:

$$w = \Delta m / 2.7 \times v \times t \times W \ .$$

Where: w is the wear rate in mm^3/N.m, Δm is the weight loss in gm in time t, v is the sliding velocity in m/sec, t is the operating time in sec, and W is the normal load in N.

From fig. 12 it is noticed that, the wear rate of both matrix specimens and composite specimen increases with the increase of test temperature. The trend of results for matrix alloy indicates negligible change of wear rate from room temperature till 150 °C for specimens fabricated by vortex technique. This range increased to 175 °C for specimens fabricated by squeeze technique as shown in fig. 12-a. In case of composite specimens containing 8 vol. % SiC a transition from negligible to considerable wear occurs at temperatures of 175 °C and 200 °C in case of vortex and squeeze techniques as shown in fig. 12-b. For specimens of 12 vol. % SiC the noticed transition temperatures are 200 °C and 250 °C for vortex and squeeze cast specimens, respectively, as shown in fig. 12-c.

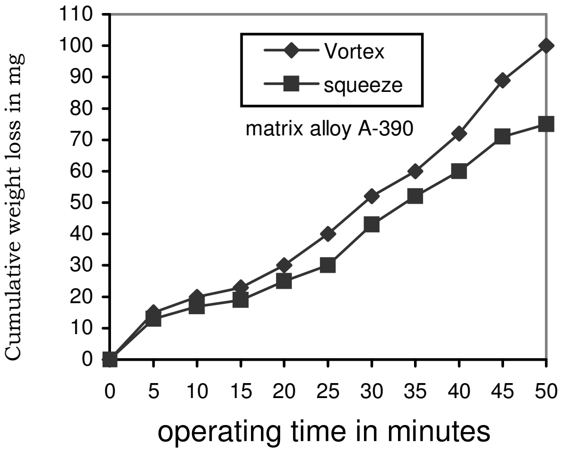


Fig.10. Cumulative weight loss versus operating time for matrix alloy A-390.

Fig. 11-a. Squeeze casting matrix X-200.

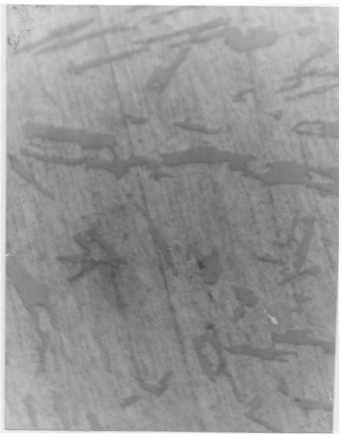
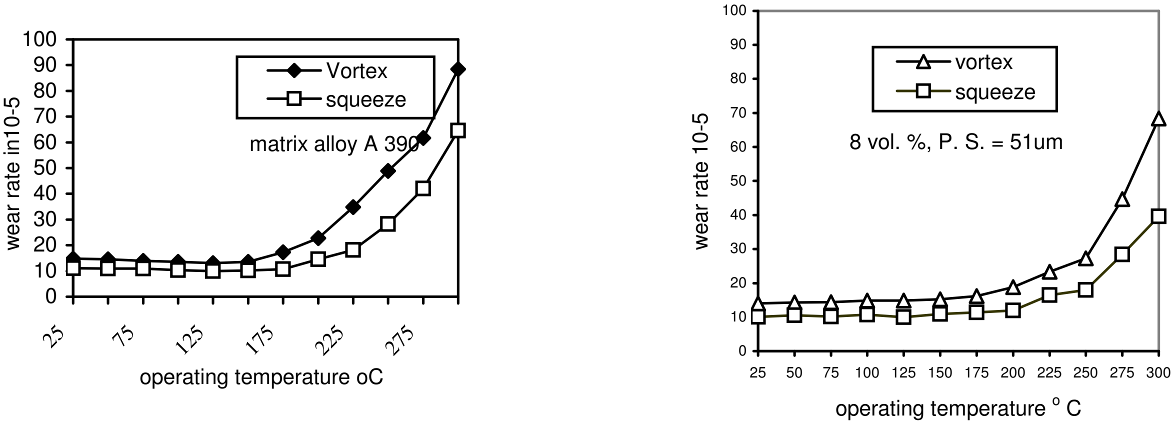
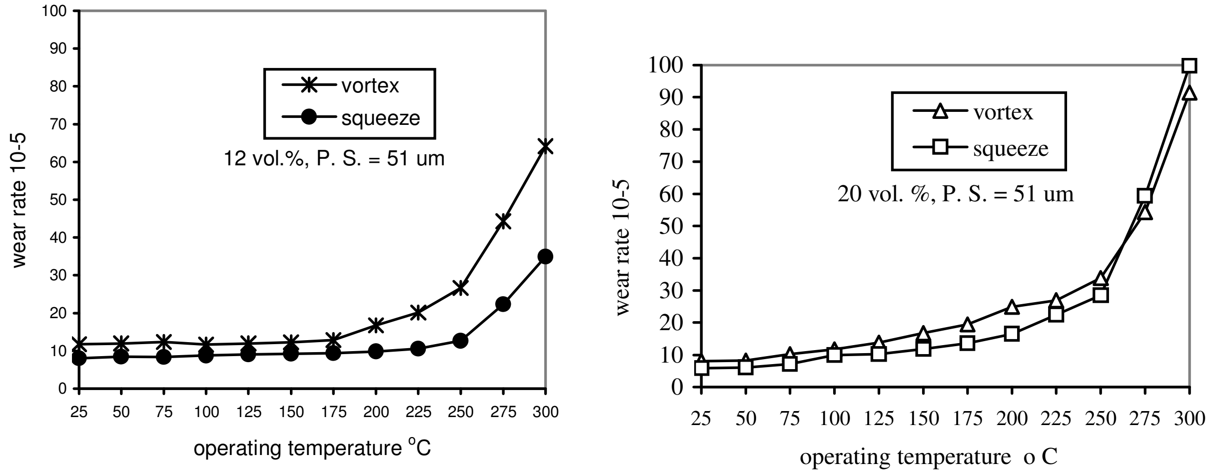


Fig. 11-b. Matrix as cast X-200.



(a) Wear rate in mm³ /Nm versus operating temperature in ⁰ C for matrix alloy.

(b) Wear rate mm³ /Nm versus operating temperature for volume fraction of 8-vol. %.



(c) Wear rate mm³ /Nm versus operating temperature for volume fraction of 12-vol. %.

(d) Wear rate mm³ /Nm versus operating temperature for volume fraction of 20-vol. %.

Fig. 12. Wear rate in mm³ /Nm versus operating temperature for different volume fractions and constant particle size of 51.

Specimens containing 20 vol. % SiC experienced greater wear rate as shown in fig. 12-d. This is attributed to, the increase of separated reinforcement particulates from the specimen surface. The separated particulates work as cutting agent, which scratch the high carbon steel disc and specimen matrix. A remarkable effect was noticed after those mentioned transition temperatures. The wear mechanism before transition temperature is oxidation wear, where the oxide layer at the surface of composite specimen breaks under the effect of sliding contact and produces fine particles as shown in macrograph of worn surface of steel disc fig. 13, which reducing the frictional force, generated heat hence reduces wear loss. Above the transition temperature the matrix is softened and the strength of particles/matrix interfaces is reduced, hence the separated particles increases and wear rate increases. The higher transition temperature of squeeze cast specimens is attributed to a strong matrix and particle/matrix interface strength. This also increases particle/matrix stiffness, and this limits the contact during wear test between the steel disc surface and composite reinforcement particulate, protecting the matrix from direct contact with the sliding surface. Hence the reinforcement by squeeze casting technique enhances wear resistance at all operating conditions than in case of vortex techniques. The obtained experimental relation-ship between the wear rate and operating time indicates superior wear resistance of the composite from the beginning of the test: composites are able to withstand significantly harsh operating conditions before showing signs of sever wear as compared to un-reinforced matrix alloy.

4. Microstructure of worn surfaces

The micrographs of worn surface of composite specimens fabricated by vortex and squeeze technique are shown in fig. 13-a, b respectively. The micrographs show parallel scratches due to the abrasive action between the steel disc and separated reinforcement particulate with the matrix surface. Rounded cavities were observed in some places due to the tear out of the particulate. A higher numbers of rounded cavities is noticed in specimens fabricated by vortex technique than that fabricated by squeeze casting technique. This is attributed to the high interface strength between particulate and matrix in squeeze fabricated specimens than that in vortex fabricated specimens as shown in fig. 14.

Fine and bright particles embedded within the matrix and steel disc results from the breakdown of the oxide layer as shown in micrograph of Fig. 15. For steel disc sliding against squeeze cast specimens and vortex specimens, the worn surfaces do not show any sign of welded microchip or fragments with the matrix surface or with the steel disc, indicating absence of diffusion wear as shown in fig. 15-a, b. The worn surface macrographs at different temperatures, indicate no change in wear behavior at low temperature. Small welded fragmented chips were observed at high operating temperature for both matrix specimens and some composite specimens fabricated by vortex technique, as shown in fig. 16. The diffraction charts shown in Figs. 17-a, b represent the analysis of squeeze cast specimen and vortex cast specimens after wear test at 250 °C

X-Ray Diffraction (XRD) records indicate that, no change of X-ray diffraction for composite specimens tested at room and low operating temperature. A remarkable change of X-ray trace was noticed at high operating temperature and low volume fraction of 8 vol. %, where the Fe element was increased. This means that Fe fragments has been separated from the steel disc to the composite specimen during wear test.

5. Conclusions

It is concluded from the present investigation that:

1. The squeeze cast composites manifest higher wear resistance as compared to vortex cast composites.
2. A small effect of particle size on wear rate was noticed when compared with effect of volume fraction. Maximum wear resistance is obtained by adding volume fraction of about 12 %.

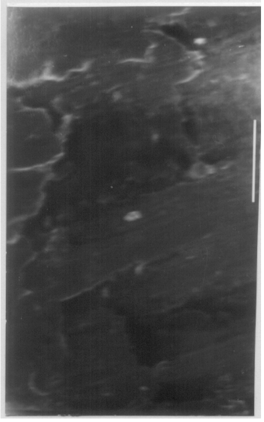


Fig. 13-a. Worn surface of the steel disk against sliding of 8 vol. % squeezed composite specimen X-250.

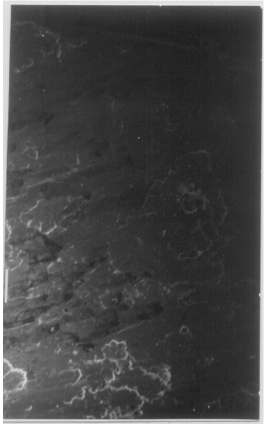


Fig. 13-b. Worn surface of the steel disk against sliding of 8 vol. % squeezed composite specimen X-250.

Fig. 14-a. Micrograph of worn surface of composite vortex specimen at 150 °C X-250.

Fig. 14-b. Micrograph of worn surface of composite squeeze specimen at 150 °C X-250.

Fig. 15-a. Micrograph of worn surface of composite vortex specimen at 250 °C X-250.

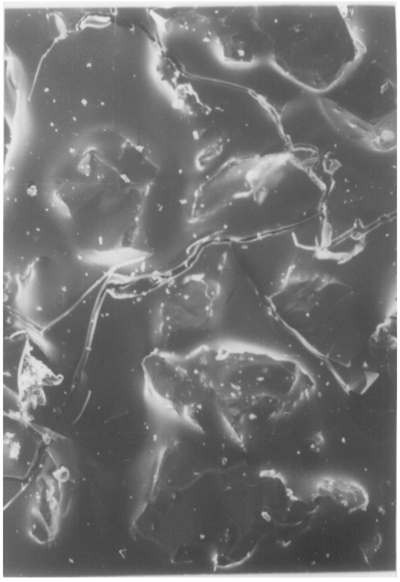


Fig. 15-b. Micrograph of worn surface of squeeze composite vortex specimen X-250.

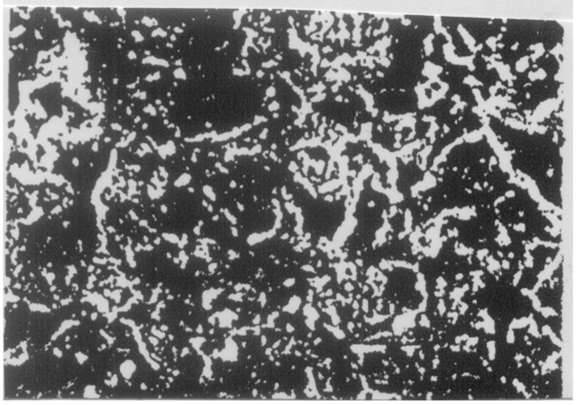


Fig. 16-a. Micrograph of worn surface of matrix alloy specimen at 300 °C X-300.

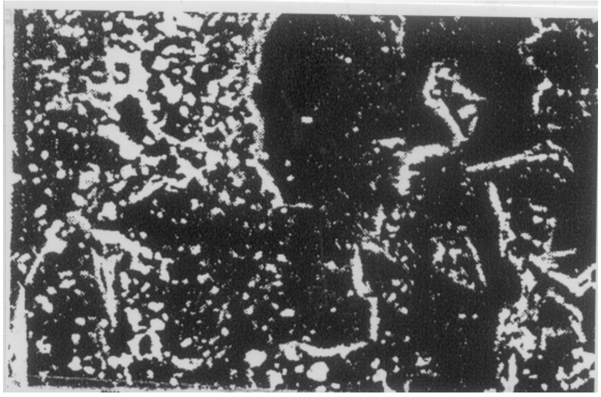


Fig. 16-b. Micrograph of worn surface of surface of composte vortex specimen at 300 °C X-300.

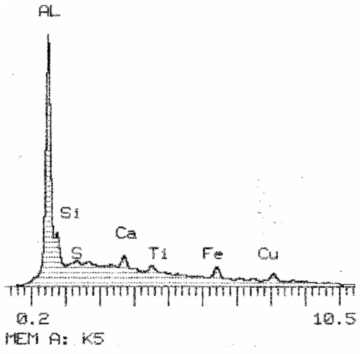


Fig. 17-a. XBD squeeze specimen at 250 °C for 8 vol. % and particle size of 28 μ m.

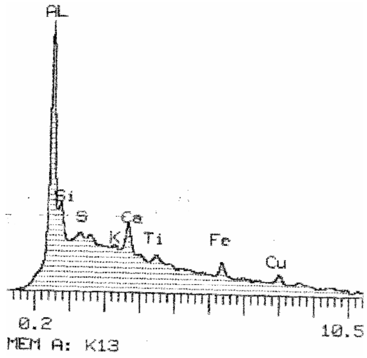


Fig. 17-b. XBD squeeze specimen at 250 °C for 8 vol. % and particle size of 28 μ m.

3. Squeeze casting enhances interfacial bonding and consequently minimizes wear debris formation by retarding the initiation of subsurface cracking associated with this wear mechanism.
4. Wear at elevated temperatures is influenced by the volume fraction of reinforcement, and preparation of composite. Mild to severe wear transition temperatures of 250 °C, 200 °C and 150 °C were reported for squeeze composite, vortex cast composite and matrix material respectively.

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