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Research Article

Production and Tribological Characteristics of Heat Treated AA2024-Fly Ash Composite

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Abstract

Of the many different types of particulate reinforcements tried out in the recent times for producing composite, fly ash is the cheapest and abundantly available waste by product from the combustion plants. Keeping in mind the environmental hazards of fly ash it has been used for producing composites besides for brick and cement manufacturing. Generally the physical and chemical nature of fly ash varies depending upon source. In the present investigation, precipitator type fly ash having particle size below 45 µm is collected from JSW steels, Bellary, Karnataka, India at atmospheric temperature and composite were produced by reinforcing it in the wrought aluminium alloy AA2024.The motorized stir casting setup has been employed to fabricate the composite samples containing 2.5, 5, 7.5, 10 and 15 % by weight of fly ash. Solutionizing is carried out on AA2024+10 composite at a temperature of 350,450 and 530^oC for same duration of 90 minutes followed by quenching in air (37^oC) and water media (25^oC). Artificial aging is carried out at 175^oC for 60 minutes.The non-heat treated and heat treated AA2024+10% fly ash composite samples were tested for dry sliding wear behaviour in pin-on-disc machine. For each specimen the wear test is conducted at constant speed of 200 rpm (0.628 m/sec velocity) and by applying different normal loads like 10, 25 and 35 N in the laboratory conditions. For determining the wear mechanism of composite, the worn surfaces were examined using Inverted metallurgical microscope. Experimental results indicated a good improvement in the wear characteristics due to heat treatment. Artificially aged specimens in specific showed superior wear performance than the other.

Keywords: *stir casting, fly ash composite, pin-on-disc machine, dry sliding wear, heat treatment*

1. Introduction

Among many types of matrix materials for composites aluminium and its alloys are the most favorite material for producing metal matrix material. Aluminium-alloy-based composites are very attractive on account of their processing flexibility, wide range, low density, high wear resistance, high thermal conductivity, heat-treatment capability, improved elastic modulus and strength, stiffness and dimensional stability.

To overcome the environmental hazards of fly ash and to take advantage of its low cost, low density and abundant availability as waste by product from the combustion plants it can be used as another reinforcement to widen the engineering applications of particulate composites.

Aluminum–fly ash composites have potential applications as covers, pans, shrouds, casings, pulleys, manifolds, valve covers, brake rotors, and engine blocks in automotive, small engine and the electromechanical industry sectors (T.P.D. Rajan *et al* 2007).

Incorporation of fly ash particles in aluminium metal/alloy will definitely promote the use of this low-cost waste by-product and, at the same time, has the potential for conserving energy intensive aluminium and thereby, reducing the cost of aluminium products.

The objective of present investigation is to study the wear performance of aluminium-fly ash composite. The results of this research can act as reference for exploring the new wear resistive applications.

The properties of aluminium/composite can be significantly improved by heat treatment process. In the past two decades many researchers have worked in this direction, the summary of their work has been presented below.

(D. Z. Wang *et al* 1994) have studied the effect of ageing on wear performance of SiC_w/Al composite. Their results show that solution ageing treatment explicitly affects the wear of composite and when suitably over aged the wear resistance could be superior. Also it's pointed out

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that there is no direct relation between hardness and wear resistance. (A.B. Gurcan and T.N. Baker 1995) produced AA6061 + 20 vol.% Saffil, AA6061 +20 vol.% SiC_p, AA6061 + 11 vol.% Saffil+ 20% SiC_p and AA6061 + 60 vol.% SiC_p composites. The composites were given a T6 heat treatment of 520°C for two hours, water quenched to room temperature, followed by ageing at 160°C for 18 hours and water quenched. It was found that after testing for wear against SiC grit, AA6061 + Saffil showed little advantage over the monolithic alloy, but the other three composites had a significant improvement in wear resistance. The hybrid and the AA6061 + 60% Sic showed the best performance. (W.Q. Song *et al* 1995) have studied the effect of thermal ageing on the wear performance of age hardened 2014 Al/SiC and 6061 Al/SiC composites. The composite were aged between 50°C and 250°C.The experimental results indicated a relatively low hardness and abrasive wear resistance of materials when under aged (between ~ 50-150°C). Raising the ageing temperature to ~ 200°C increased the hardness and abrasion resistance of the composites to the peak-aged condition. At 250°C (over-aged) there was reduction in hardness and wear resistance of composites. In (M. J. Tan *et al* 1995) work, the high temperature age hardening behaviour of a silicon carbide particulate-reinforced aluminium-lithium alloy is presented and compared with that of a similarly thermo mechanically treated matrix material. The results indicated that the peak hardness and time are function of both ageing temperature and material. (B. Dutta and M.K.Surappa 1995) studied the age hardening behaviour of Al-Cu-SiC_p composite and their results show that the cast and extruded Al-3.2Cu-5 vol.% SiC_p composites exhibiting accelerated hardening during natural ageing and high temperature ageing. (A. Martin *et al* 1996) have carried out high temperature wear test on 2618 Al alloy and 2618 Al alloy reinforced with 15 vol.% SiC_p composites. The extruded composite bars were solution heat treated at 530°C for 1 hour, water quenched and cold stretched up to 2% .Afterwards they were artificially aged at 190°C for 10 hours to reach peak aged condition (T651).Specimens of both alloy and composite in the naturally aged (solution heat treated, water quenched and aged at ambient temperature) and peak-aged condition were tested for wear characteristics. The results indicate that both materials have shown transition from mild to severe wear as the temperature is increased from 20 to 200°C. (K. H. W. Seah *et al* 1996) have studied the mechanical properties of as cast and heat treated composite of ZA-27 zinc-aluminium alloy with SiC particles as reinforcements. The composite specimens were tested after being heat treated at 320°C for 1, 2, 3 and 4 hours, respectively. Their mechanical properties were compared with those of as-cast. The results have shown that the mechanical properties like ductility and impact strength have significantly improved due to heat treatment but at the same time cause reductions in ultimate tensile strength and hardness. The same group of researchers further studied effect of artificial ageing on the hardness of cast ZA-27/graphite particulate composites. Here the ageing temperatures were 75°C, 100°C and 125°C for ageing durations of 6, 12 and 18 hours respectively. The results show that for any particular graphite content and ageing temperature, hardness seems to increase monotonically with ageing time, although it probably tends towards an asymptotic value. (G. Straffelini *et al* 1997) tested for dry sliding wear behaviour of specimens of 6061aluminium alloy reinforced by 20 vol.% Al_2O_3 particles after some specimens were heat treated to the T6 condition (530°C for 1 hour, water quenching, ageing at 175°C for 16 h). Other specimens were forged at 440 °C (in a closed die lubricated with graphite with an initial reduction of 70% followed by a second reduction of 50%) prior to the T6 treatment. Finally, some specimens were over aged at 220°C for 0.5 hour. Results indicate that the as-received extruded composite has low matrix hardness and displays the lowest wear rate. The other materials, aged at the T6 condition, forged and T6-aged or treated and over aged at 220°C, display higher wear rates which increase as their hardness is increased. (M.Gupta *et al* 1997) produced composite having 2% wt Cu-Al (bal.) as matrix with α-SiC particulates and subjected to ageing. Specimens taken from the as-processed rods were solutionized for 1 hour at 450°C, quenched in cold water and aged isothermally at 160°C for various intervals of time. The results of ageing studies conducted on ceramic and SiC reinforced composite samples reveal greater as quenched and peak hardness of the Al-Cu/SiC samples when compared with that of the Al-Cu/ceramic composite samples, and accelerated ageing kinetics exhibited by the Al-Cu/SiC samples when compared with the Al-Cu/ceramic composite samples. (Z.M. El-Baradie *et al* 1998) have developed SiC-7020 aluminium composite to study the aging behaviour of the unreinforced and reinforced materials for both natural and artificial aging at 170°C.The outcome of research shows that the incorporation of 5 and 10 vol.% of SiCp can be improved considerably by natural or artificial aging. (Rong Chen *et al* 2000) used A356 aluminum alloy matrix composites reinforced by 15 vol.% of SiC_p to study the fretting wear. Composite specimens were tested in T6 heat treatment, it was solidified at temperature 530-540°C for 6 hours and quenched in 80°C water, then aged at a temperature of 200°C for 5 hours in air. Their results show that T6 heat treatment of composites offers better fretting wear resistance compared with that without heat treatment, including low coefficient of friction, small net fretting wear and heap volumes. (O.P. Modi 2001) has studied the influence of heat treatment two-body abrasion of a cast Al–Cu (2014 Al) alloy-Al_2O_3 particle composite. Samples of the composite and matrix alloy were subjected to T-6 type heat treatment which involved solutionizing at 495°C followed by artificial ageing at 190°C. The soaking time in both cases was maintained at 9 hours. The results of this investigation show that heat treatment improved the wear resistance of the as-cast alloy and composite. (L. Ceschini *et al* 2001) have studied the effect of T6 thermal treatment and recycling on the tribological behaviour of an AlSiMg–SiCp composite. The researchers concluded that the T6 aged composites showed delaminative wear, caused by crack formation and propagation. (Z.M. El-Baradie *et al*

2001) have studied the properties of as-cast and heat treated Zn–12Al composite alloy consisting of glass reinforcement. In this work specimens from reinforced and unreinforced material were subjected to a heat treatment which consisted of solution treatment at 380°C for 12 hours followed by iced water quenching. The specimens, reinforced and unreinforced, were then immediately aged at 95°C for 2 and 4 hours. (Grigoris E. Kiourtsidis and Stefanos M. Skolianos 2002) have studied the wear behavior of artificially aged AA2024/SiCp composites. In the investigation all composites and plain alloy pin specimens were T6 heat treated. First they were homogenized at 495°C for 6 hours and quenched in iced water at 3–4°C. Then one series of pin specimens was artificially aged at 177°C for 14 hours (peak aged) and another one was over aged at 177°C for 100 hours. The results indicated that wear rate in peak aged as well as in over aged composites is remarkably reduced in comparison with the respective as-cast composites. (N.E. Bekheet *et al* 2002) investigated the effect of aging on fatigue and hardness of 2024 Al alloy/SiC composites. The aging process essentially involved a solution treatment of the sample for 2 hours at 500°C, then quenching in cold water followed by aging at four different conditions. These conditions were: Aging at room temperature (natural aging), artificial aging at 170°C and applying 10 or 30% cold deformation after solution treatment, followed by natural aging and artificial aging. All specimens were immediately refrigerated until testing to prevent room-temperature aging. Their results show that the peak hardness of composites is slightly higher than that for 2024 Al alloy and the addition of SiCp and or artificial aging greatly improves the fatigue limit of the composite. (A. Daoud and W. Reif 2002) studied influence of Al_2O_3 particulate on the aging response of A356 Al-based composites. Specimens were first solution treated at 540°C for 8 hours, water quenched at 60°C and isothermal aging for various times at 155°C. After the solution treatment and/or the aging treatment, the specimens were stored at all times in a freezer (when not in use) to preclude any natural aging. The researchers concluded that the hardness of composite is higher than that of the matrix in the solution treated condition and it increases during heat treatment. (J.M. Gómez de Salazar and M.I. Barrena 2004) have studied the influence of heat treatments on the wear behaviour of an $AA6092/SiC_{25p}$ composite. In this work To investigate the age-hardening behaviour of these materials, the samples were heat treated at 560 ± 0.5°C and 530±0.5°C for 3 h, quenched in ice water and ageing treated at 175 ± 0.5°C.The results of this work show that The highest wear resistance is obtained for T6 thermal treatment condition (heat treated at 560 ± 0.5°C for 3 hours, quenched in ice water and ageing treated at 175 ± 0.5°C for 7 hours). (S. Sawla and S. Das 2004) Combined effect of reinforcement and heat treatment on the two body abrasive wear of aluminum alloy and aluminum particle composites. Their results show that in case of heat-treated alloy and composites, the wear constant (K) decreases monotonically with load. (M. Warmuzek *et al* 2004) studied the influence of the heat treatment on the precipitation of the intermetallic phases in commercial AlMn1FeSi alloy and they have concluded that The changes in the chemical composition (relative concentrations of the transition metals Fe, Mn and Si) of the α-AlFeMnSi phase occurring during the heat treatment were related to the activation of the short circuit diffusion of the transition metals Fe and Mn along the interface α-Al/Al_6FeMn/α-AlFeMnSi. (Grigoris E. Kiourtsidis *et al* 2004) studied aging response of aluminium alloy 2024/silicon carbide particles (SiCp) composites. In their work the specimens were solution heat treated at 495°C ± 2K for 6 hours and artificially aged at 177°C for periods of 2 and up to 200 hours. The results of this work show that hardness in over aged condition reduced with increase in content of reinforcement and aging kinetics has changed as a function of content of reinforcement. (Cevdet Meric *et al* 2006) have studied the effect of aging on wear behaviour of AlMgSi1 alloy. The results of this investigation show that natural aged specimen observed maximum wear resistance. The precipitation hardening is performed under the certain conditions like, solutionizing at 520 ± 5°C for 1 hour; quenching in water at room temperature; aging at 150, 160, 170, 180 and room temperature; and cooling in air. (K. Mahadevan *et al* 2006) have heat-treated the AA6061-SiCp composite to observe changes in hardness. The specimens were solutionized at a temperature of 530°C over a range of time period and subsequently artificially aged in a muffle furnace. Temperatures were accurate to within ±2°C and quench delays in all cases were within 20 sec. The tests conducted as per design of experiments were helpful in developing a mathematical model in terms of heat treatment parameters. The results of this work indicate that the second-order interaction of the heat-treatment parameters has the maximum influence on hardness. (Mahagundappa M. Benal and H.K. Shivanand 2007) carried out investigations to know the effect of content of reinforcements and aging durations on wear characteristics of AA6061 based hybrid composites. In their work the as cast specimens were subjected to the different heat-treatment conditions like, solution treatment for 12 hours at a temperature of 530°C; quenching in water at a temperature of 80°C; stabilizing at room temperature for 3 hours and ageing at 175°C for different intervals of time ranging from 1 to 7 hours in an interval of 2 hours. Their results show that in each test the wear rates of the hybrid composites were found to decrease with increase in ageing durations. (Rajesh Sharma *et al* 2007) have studied the influence of solutionizing temperature during artificial age hardening treatment (T6) of cast Al-(8, 12,16%)Si–0.3%Mg on abrasive wear behaviour. In this research all the alloys were solutionized at 450°C, 480°C, 510°C, and 550°C for 8 hours followed by water quenching (30°C) and aging hardening at 170°C for 12 hours. Their results show that increase in solution temperature improved the wear resistance. Hypereutectic alloy showed better wear resistance than the eutectic and hypoeutectic alloys under identical conditions. Also for alloys it is observed that the increase in solutionizing temperature improved distribution of silicon grains. (K.B. Shah *et al* 2007) have studied the influence of aging temperature during artificial age hardening treatment (T6) of cast Al–(4, 12,20%)Si–0.3% Mg on abrasive wear behaviour. The research reports that silicon content and aging temperature significantly affect the wear resistance. Increase in aging temperature improves the wear resistance. Hypereutectic alloy showed better wear resistance than the eutectic alloy under identical conditions. In the heat treatment cast alloys were given age hardening treatment having sequence of solutionizing, quenching and artificial aging. All the alloys were solutionized at 510^{o}C for 8 hours followed by water quenching (30^{o}C) and aging hardening at 150, 170, 190, 210 and 230^{o}C for 12 hours. (Shafaat Ahmed *et al* 2007) considered Al–4.5% Cu–3.4% Fe in situ composite in as-cast condition, solution treatment, aging and hot rolling and studied the wear behaviour. Their results indicate that the as-cast in situ composite exhibited the highest wear rate. The wear rate of the (cast + solution treated + aged) composite was about 4.5 times and that of the (rolled + solution treated + aged) composite about 9.5 times lower than the wear rate of the as-cast composite. Hot-rolling + solution treatment + ageing of the MMC was found to yield the lowest wear rate among all processing conditions. (S. Das *et al* 2008) have examined the synergic effect of SiC particle reinforcement and heat treatment on the two body abrasive wear behavior of an Al–Si alloy (BS: LM13) under varying loads and abrasive sizes. The alloy and composites were solution treated at 495^{o}C for 8 hours, quenched in water and aged at 175^{o}C for 6 hours and cooled in air. The results show that the hardness and strength of composite is more after heat treatment. But in case of alloy, the hardness and strength are noted to be more when they are aged for 6 hours. (Ali Kalkanlı and Sencer Yılmaz 2008) heat treated AA7075/SiC$_p$ composites according to ASM T6 heat treatment procedures. The heat treated samples were solutionized at 480^{o}C for 55–65 min. The solutionized metal matrix composite specimens were then quenched in water. Finally, precipitation heat treatment was carried out for 24 hours at 120^{o}C.The results show that peak hardness values were obtained following T6 heat treatment. Composites were solution heat treated at 480^{o}C for 55-65 min and precipitation heat treated at 120^{o}C for 24 hours. From 4 to 24 hours the hardness values increased gradually. The peak hardness values are 20-25% higher than the as-cast hardness values. (K. Mahadevan *et al* 2008) studied the influence of precipitation hardening parameters on the fatigue strength of AA 6061-SiCp composite. Their results show that Solutionizing time has more influence than the other two parameters, viz., aging temperature and aging time on the fatigue strength of the composite. (Sharmilee Pal *et al* 2008) studied the aging behaviour of Al–Cu–Mg alloy–SiC composites. The age-hardening kinetics of composites subjected to solution treatment at 495^{o}C for 0.5 hour or at 504^{o}C for 4 hours followed by aging at 191^{o}C, have been studied in particular. The aging kinetics indicated that the peak-age hardness values are higher, and the time taken for peak aging is an hour longer on solutionizing at 504^{o}C for 4 hours, due to greater solute dissolution and the composites have taken longer time to peak-age than the alloy. (Hakan Aydın *et al* 2009) studied the tensile properties of friction stir welded joints of 2024 aluminum alloys in different heat-treated-state. Their investigation showed that the peak tensile properties are being obtained in the T6 (100^{o}C -10 hours) joint. (A. Mandal *et al* 2009) conducted dry sliding wear test on T6 treated A356–TiB_2 in-situ composites. The results of their work show that the wear rate of the composites is a strong function of TiB_2 content rather than overall hardness of the composite. (C.S. Ramesh *et al* 2009) studied the influence of heat treatment on slurry erosive wear resistance of Al6061 alloy. The results of this work show that with increase in aging duration for all quenching media (air, water and ice) studied there is a reduction in slurry erosive wear rate. However, ice as quenching media offers higher erosive wear resistance compared to water, air and non-heat treated alloy. For heat treatment Al6061 alloy were studied by subjecting to solutionizing at temperature of 530^{o}C for a duration of 2 hours, followed by quenching in air, water and ice media. Both natural and artificial aging at 175^{o}C was performed on quenched samples from 4 to 10 hours duration in steps of 2 hours. (Ashutosh Sharma and Sanjeev Das 2009) have studied the age hardening behavior of Al–4.5%Cu alloy composite reinforced with zircon sand particulates for different quenching media viz, water, oil, and salt brine solution (7 wt%).The results of ageing demonstrate that the micro hardness of age hardenable Al-Cu based alloy composites depend on the quenching medium in which they are heat treated. Salt brine quenching is faster as compared to water and oil, even if higher strength is obtained but cannot be used for complex shapes and thin sections where oil quenching is the alternative due to minimum distortion and cracking problems. S.M.R. (Mousavi Abarghouie and S.M. Seyed Reihani 2010) studied the aging behavior of a 2024 Al alloy-SiCp composite and they reported that The peak hardness of the composite sample took place at shorter times than that of the unreinforced alloy for the samples solution treated for 2 and 3 hours, but took place at longer times for the samples solution treated for 1 hours. It is felt that the suitable solution treating time was about 2 hours for both the composite and the unreinforced alloy that led to the fastest aging kinetics and the maximum hardness. At the solution treating time shorter than 2 hours due to incomplete dissolution of precipitates, the aging kinetics decelerated and the hardness values decreased. (H.R. Lashgari *et al* 2010) developed A356–10%B4C cast composites to study the effect of heat treatment on the microstructure, tensile properties and dry sliding wear. The heat treatment (T6) consisted of solutionizing treatment for 5 hours at 540^{o}C, followed by quenching in hot water and then aged at 170^{o}C for 8 hours. The results of this study show that higher strength, hardness and wear properties of heat treated metal matrix composites was observed in comparison with un heat treated state. (Emma Sjölander and Salem Seifeddine 2010) studied the heat treatment effect of Al–Si–Cu–Mg casting alloys. Their results show that artificial ageing of Al–Si–Mg alloys anywhere in the temperature range 170–210^{o}C gives the same peak yield strength, while Cu-containing alloys show a decrease in peak yield strength with increasing ageing temperature. S.M.R. (V.S. Aigbodion and S.B. Hassan 2010) studied the precipitation process in case of Al–Cu–Mg/bagasse ash composites. The results indicated a smaller amount of Guinier–Preston (GP) zones, faster precipitation kinetic of the intermediate phases (θ^{11} and θ^{1}) and absence of the peak related to the formation of the θ phase. (G.H. Zahid *et al* 2011) have produced aluminium/Al_2O_3 composite and studied for the effect of ageing. Their results show that the highest strength in composite was achieved after 4 h at 200^{o}C. (M. Sameezadeh *et al* 2011) studied effect of reinforcement and the heat treatment on hardness and wear performance of AA 2024-MoSi2 nano composites. They reported that for all samples, the hardness of solution and aged condition (T6) was higher than as hot-pressed (HP) condition. The wear resistance of all samples in T6 condition was higher than HP condition and increased with increasing $MoSi_2$ content. (A. Malekan *et al* 2011) considered Al–15%Mg_2Si composite to study the effect of solution temperature on microstructure and tensile properties. composite specimens were subjected to solutionizing at different temperatures of 300^{o}C, 350^{o}C, 400^{o}C, 450^{o}C, 500^{o}C, 550^{o}C and 580^{o}C for holding time of 4 hours followed by quenching. The results of this study reveal that upon temperature increment the morphology of both primary and secondary Mg_2Si particles was changed with the latter being more significant. According to the tensile results, solution treatment in the range of 500–550^{o}C can greatly enhance the properties of the Al–Mg_2Si composite. (H.J. Liu and X.L. Feng 2013) have investigated the effect of post-processing heat treatment on the microstructure and micro hardness of water-submerged friction stir processed 2219-T6 aluminum alloy. The results show that the post-processing aging treated samples showed coarsened equilibrium precipitates and no re-precipitation, which led to the further decrease of the micro hardness. (Rıdvan Yamanoglu *et al* 2013) investigated the effect of effect of heat treatment on the tribological properties of Al–Cu–Mg/nano SiC composites and they came to conclusion that addition of SiC to the alloy increases the hardness of the material but does not change the wear mechanism. An increase in the hardness causes a decrease in the wear rate. The specimen aged for 6 hours at 225^{o}C has the lowest wear rate for both (steel and alumina) counter faces. (Ahmed M. El-Sabbagh *et al* 2013) studied the effect of rolling and heat treatment on the tensile behaviour of wrought Al-SiCp composites and results have shown that almost 240 and 390% improvement in ultimate tensile strength (UTS) for 6061 and 7108 composite was obtained, respectively. The improvement in strength was remarkable for composites rolled to 0.4 mm. Annealing improved the elongation% at break of the 10–15% Vol. composite more than 3 times. UTS of rolled composite was enhanced by T6 treatment at 176^{o}C and 120^{o}C for 6061 and 7108 composites.

2. Experimental

2.1. Materials

2.1.1 Fly ash Reinforcement

The precipitator type fly ash is used as reinforcement for the present investigation which is a gray colored fine powder with most of the particles size falling below 45 μm. The particle size distribution is as shown in Fig.1 The fly ash samples were subjected to chemical analysis as per IS: 1727-1967 RA 2004 and the detailed chemical composition is as shown in Table-1. The bulk density of fly ash is 1.1902 gm/cc.

Table 1 Chemical composition of fly ash

Oxide	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	LOI*
% Wt	26.73	24.94	18.1	7.43	2.075	2.81	0.0648	0.0493	2.62

*LOI=Loss On Ignition

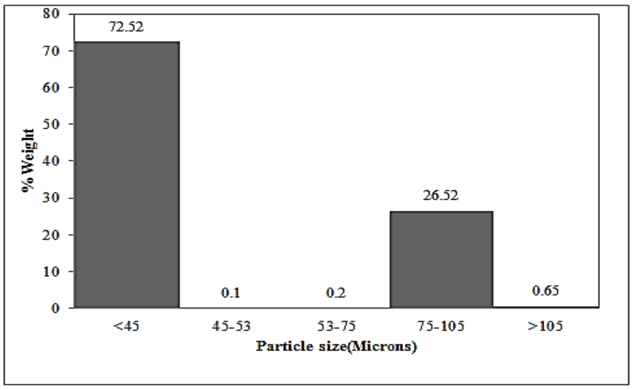


Fig.1 Graph showing the fly ash particle size distribution

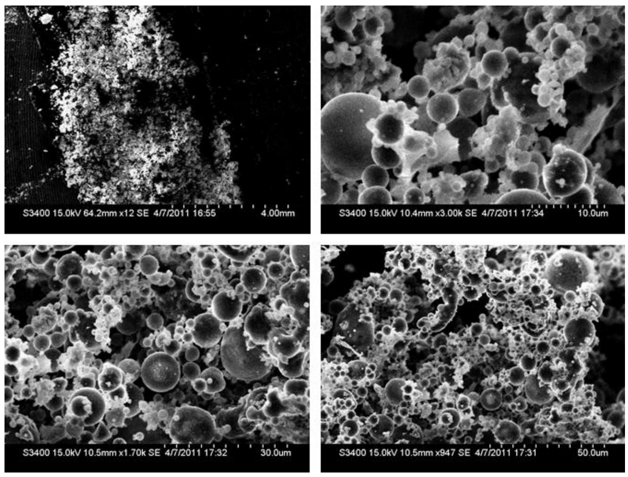


Fig.2 SEM photographs of fly ash showing spherical particles

2.1.2 Aluminium alloy Matrix

The aluminium alloy selected for the matrix material is

AA2024 whose chemical composition is as shown in Table-2.The density of as received alloy was 2.77 gm/cc. The alloy ingots were supplied by Manufacturing Metallurgy & Management Training Institute, Materials Research Centre, Bangalore, Karnataka, India.

Table 2 Chemical composition of wrought AA2024 alloy

Element	Si	Mg	Cu	Mn	Fe	Ni	Ti	Zn	Pb	Sn	Al
% Wt	0.5	0.066	4.51	0.13	0.663	0.075	0.013	0.118	0.029	0.021	Rest

2.2. Casting of composites

About 3000 grams of blocks of AA2024 was melted in a graphite crucible by electric resistance furnace of 5 kW rating. The melt temperature was raised to 850°C and the scum powder in small quantities is added to the melt to remove the slag or flux. The total melt is then degassed by adding dry hexa chloroethane tablet weighing 10 grams (C_2Cl_6, 0.3 % by weight). The fly ash particles were preheated to 400°C for 1 hour to remove the moisture before adding into the melt. After degassing, preheated fly ash particles with different % by weight were added to the vortex formed in the melt by stirring. A mild steel stirrer with vertical axis was used. The rpm of the stirrer was maintained at 350-400 and stirring is continued for about 10 minutes to allow for proper mixing of the fly ash in the melt. During stirring small pieces of magnesium (0.5 % by weight) were added to molten metal to improve the wettability of fly ash particles with the melt. The melt temperature was maintained at 800-850°C during the addition of the particles. The pouring temperature was kept at 850°C and the time of pouring was 5 minutes. The melt was poured in the grey cast iron molds which were preheated to 300°C.The aluminium-fly ash composites were produced by varying amount of fly ash from 2.5 to 15 % by weight. The cast aluminium-fly ash composite specimens were obtained after solidification in air for about 2 hours. To ascertain the uniform distribution of fly ash particles the casted specimens were cut and were observed in scanning electron microscope. The details of stir casting are shown in Fig.3. The photographs Fig.4 clearly indicate a fairly uniform distribution of fly ash particles in the matrix material.

(a) (b) (c)

Fig.3 (a) Stir casting set up (b) Stirring process(c) Pouring of melt in moulds

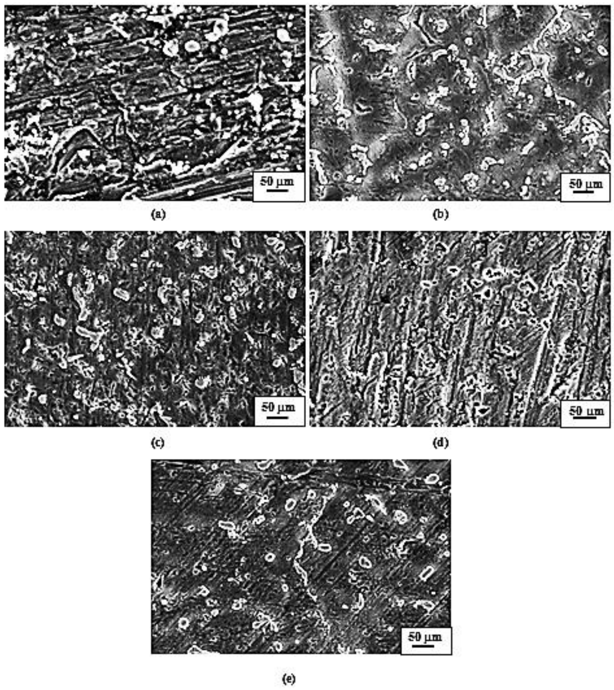


Fig.4 SEM photographs showing distribution of fly ash particles in the matrix(a)2.5%(b)5%(c)7.5%(d)10%(e)15%

2.3 Hardness test

The as cast alloy and composite specimens were sectioned and the surface was polished to mirror finish by emery paper and hardness was determined using the Brinnel

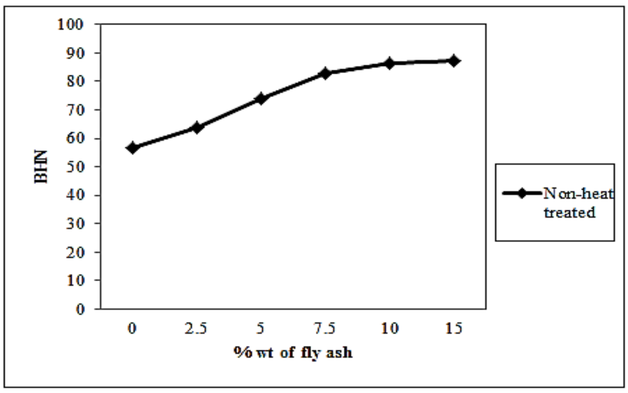


Fig.5 Variation of hardness with increase in content of fly ash in alloy matrix

Table 3 Hardness of different composite specimens and alloy

Specimen	BHN
	Non-Heat treated
AA2024	56.8
AA2024+2.5	63.6
AA2024+5	73.9
AA2024+7.5	83
AA2024+10	86.4
AA2024+15	87.3

hardness tester with an applied load of 250 kg using a 5 mm steel ball indenter. The load was applied on the surface and held for 5 sec for indentation. The Table-3 shows the values of BHN for different specimen sections. As seen from the Fig.5 hardness of aluminium fly ash composites increase with increase in amount of fly ash in the aluminium alloy matrix (Y.M.Shivaprakash *et al* 2011)

2.4 Tensile test

The Tensile test was carried out by the computerized Universal Testing Machine having data acquisition system. The online plot of variation of Load (kN) with the Cross Head travel (mm) is obtained through the data acquisition system. The tensile test was carried as per ASTM-E8M. Table-4 gives the values of tensile strength for different composite and alloy. It can be observed from Fig 6 that with percentage increase in fly ash, tensile strength increases with loss in ductility (Y.M.Shivaprakash *et al* 2011).

Table 4 Tensile strength of different composite specimens and alloy in non-heat treated condition

Specimen	Tensile strength MPa
AA2024	147.17
AA2024+2.5	150.66
AA2024+5	154.38
AA2024+7.5	157.59
AA2024+10	163.11
AA2024+15	164.23

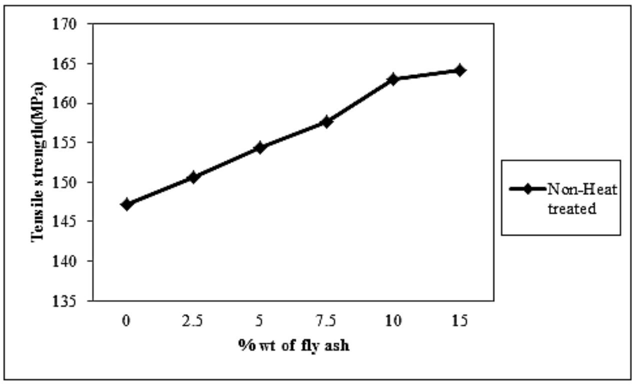


Fig.6 Variation of tensile strength with increase in content of fly ash in alloy matrix

2.5 Heat treatment of AA2024+10% wt. fly ash composite

Heat treatment is conducted by using an electrical resistance furnace equipped with programmable temperature controller with an accuracy of ±2^{o}C for both solutionizing and aging. Solutionizing is carried out at a temperature of 350,450 and 530^{o}C for same duration of 90 minutes followed by quenching in air (37^{o}C) and water media (25^{o}C). Artificial aging is carried out at 175^{o}C for 60 minutes.

Table 5 Hardness of AA2024+10 composite in different heat treatment conditions

Heated temperature (°C)	Air cooling at 37^{o}C (BHN)	Water quenching at 25^{o}C (BHN)
350	92.2	94.4
450	95.7	98.3
530	98.6	101.7

2.5 Density variation due to heat treatment

The density of the composite specimens was determined experimentally by the Archimedes principle. The small pieces cut from the specimens were weighed first in air and then water and density values were calculated using the following expression:

$$\rho = \frac{\text{Weight in air}}{\text{weight in air-weight in water}} \text{ X } \rho_{water}$$

The hardness values are tabulated in Table-6. Fig.7 shows the variation of density with the increase of content of fly ash. It can be seen that the density keeps reducing as the content of fly ash is increased. Also it is noted that the heat treatment brings about a small decrease in the density of the composite which is almost same for air cooling at 37^{o}C and water cooling at 25^{o}C.

Table 6 Density of different composite specimens and alloy

Type of specimen	Density (Non-Heat treated) (gm/cc)	Density (Heat treated) (gm/cc)
AA2024	2.752	2.751
AA2024+2.5	2.723	2.718
AA2024+5	2.715	2.71
AA2024+7.5	2.706	2.7
AA2024+10	2.693	2.685
AA2024+15	2.671	2.652

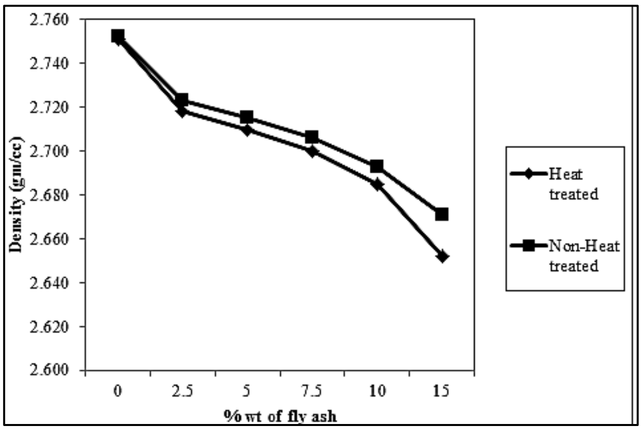


Fig.7 Comparison of density variation in heat treated and non-heat treated conditions

2.3 Wear test

To evaluate the sliding wear behaviour of aluminium alloy and composite specimens, experiments were conducted in Pin-on-Disc type wear and friction monitor [DUCOM, India make; Model: TR-201CL] supplied with data acquisition system as shown in Fig.8 This tribometer is specifically suitable for fundamental wear and friction characterization.

The wear tests were conducted as per ASTM G-99 standards in air under the laboratory condition having a relative humidity of 80 to 85% and temperature ranging between 25 to 29^{o}C.The duration of single test was 6 hours. The test specimen contact surface and disc surface were polished with silicon carbide emery paper of 600 grit for smooth contact between them prior to the conduction of each test. The specimens were cleaned with ethanol solution before and after each test. After each 1hour during the test the specimen mass was measured to know the mass loss by using a high precision electronic weighing machine (Infra digital balance, Model: IN2011) having a resolution of 0.001mg. Also the track of disc and specimen surface was regularly cleaned by soft cotton cloth to avoid the entrapment of wear debris.

The test specimen used was a cylindrical pin (8 mm diameter and 27 mm length) that was held with its axis perpendicular to the surface of the disc, and one end of pin slid against the disc in a dry friction condition, under a constant axial load applied with a dead weight. For testing specimens of each type a track diameter of 60, 70 and 80 mm were selected. The applied normal load was 10, 25 and 35 N with variable speed of 200, 300 and 400 rpm. In total 8 sets of test specimens were tested for dry sliding wear. Each set contained 9 pieces of specimens of a particular type of composition. After each test duration of 6 hours the micrograph of worn surface was taken by using an Inverted metallurgical microscope (IM 7000 series).

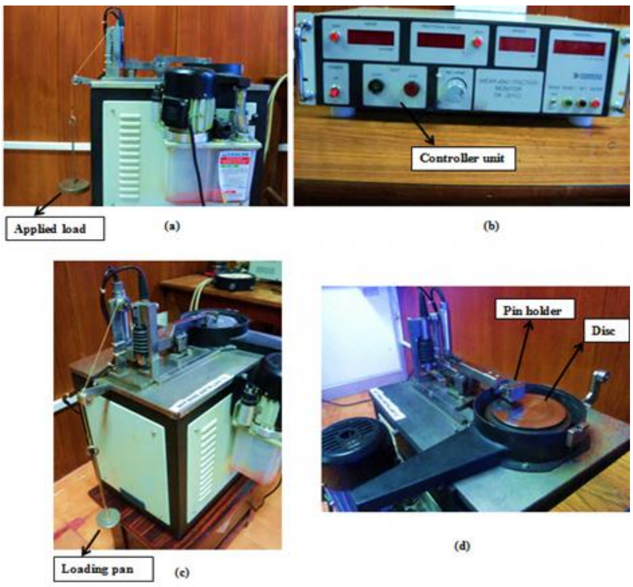


Fig.8 Pin-on-Disc type wear and friction monitor

3. Results and Discussion

In the previous study (Shivaprakash.Y.M *et al* 2013) it is found that the optimal filler content of fly ash to be between 10 to 15% by weight. Assuming the minimum side of filler as 10% an attempt has been made to increase the wear resistance of AA2024+10 composite by heat treatment. The wear rate of this composite is less at lower sliding velocity (0.628 m/sec or 200 rpm).Hence the wear test is conducted at this velocity/speed in pin-on-disc machine on heat treated specimens. Based on the test various graphs have been plotted to arrive at the conclusions on wear behaviour.

Wear rate is less at lower load but it increases as the load is increased for all heating temperatures. Also wear rate keeps decreasing for 35 N normal load and at all temperatures as the sliding distance is increased. But for lower(10 N) and medium(25 N) load the wear rate curve has shown an increasing and decreasing trend with respect to increase in sliding distance[Fig 9]. From Fig 10, we observe that wear rate even in water quenched specimens was more at higher load similar to the one observed previously. The wear rate at all the loads kept initially increasing at lower sliding distance but it gradually decreased as the sliding distance is increased to higher side.

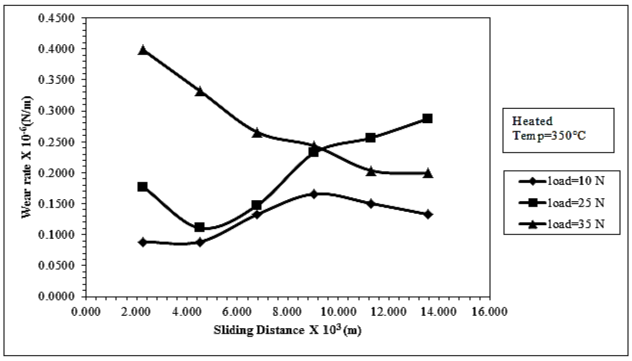
The volumetric wear rate kept reducing as the heating temperature is increased for air cooled and water quenched specimens but at the same time it kept increasing as the normal load is increased[Fig 11(a)] for air cooled specimens and for 450^{o}C in case of water quenching. But interestingly an opposite trend of variation is seen for lowest (350^{o}C) and highest (530^{o}C) temperature for water quenching [Fig 11(b)].

Specific wear rate is found to be decreasing for increase in load at all heated temperature. For 35 N at 350^{o}C and 450^{o}C the specific wear rate kept decreasing as the sliding distance is increased. At lower sliding distance the specific wear rate increased but it decreased and remained almost constant for higher sliding distances [Fig 12]. Almost similar variation pattern is observed [Fig 13] even for the specimens subjected to water quenching at 25^{o}C.

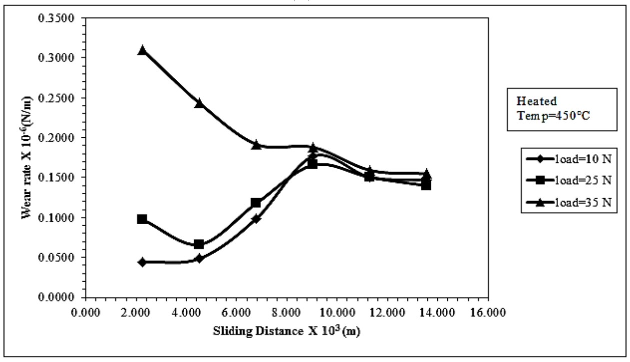
Co-efficient of friction was higher for water quench as compared to air cooling for 350, 450 and 530^{o}C. It remained almost constant for increase in sliding distance for air cooled specimens at all the temperatures. Eventually it increased successively by small amounts for water quenched specimens with respect to increase in sliding distance [Fig 14].

A comparison of variation of wear rate with respect to increase in normal load for non-heat treated and heat treated conditions is made in Fig 15. It can be seen that the wear rate is least in case of water quench conditions as compared to air cooled and non-heat treated conditions for all the temperatures. Wear rate in all the cases increases as the normal load is increased from 10 N to 35 N.

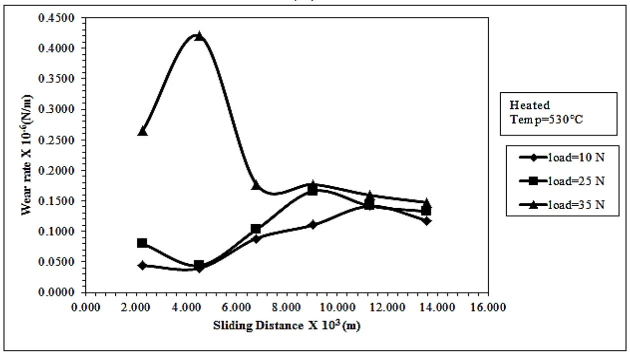
The specific wear rate increases for increase in load and decreases for increase in temperature for a specific load for air cooled and water quenched conditions. Also it kept increasing for increase in load for non-heat treated conditions. Fig 16 also depicts that specific wear rate is lowest for water quenched condition as compared to air cooling and non-heat treated conditions at all the loads and temperatures except at 10 N, 530°C and 25 N, 350°C.



(a)

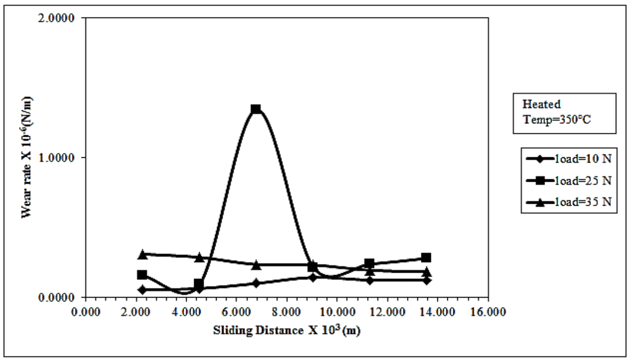


(b)

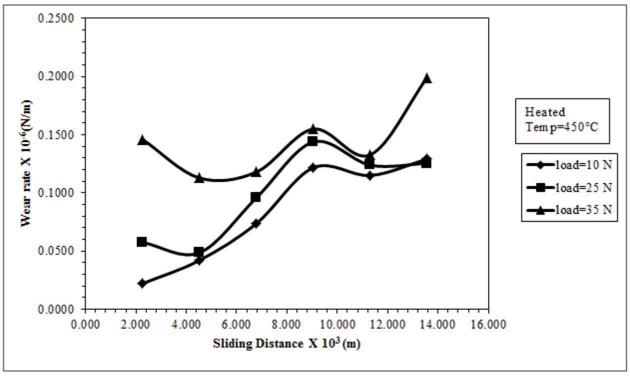


(c)

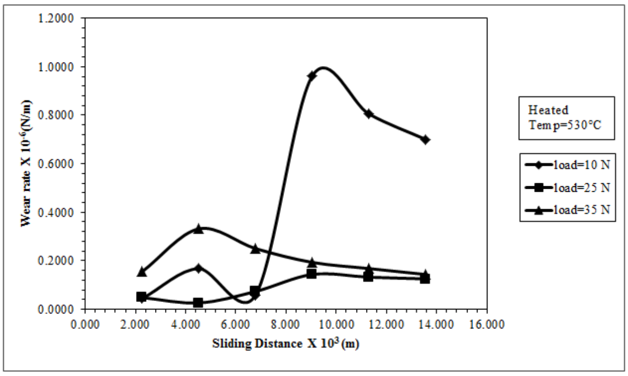
Fig.9 Variation of wear rate with sliding distance for different temperatures in air cooled condition



(a)

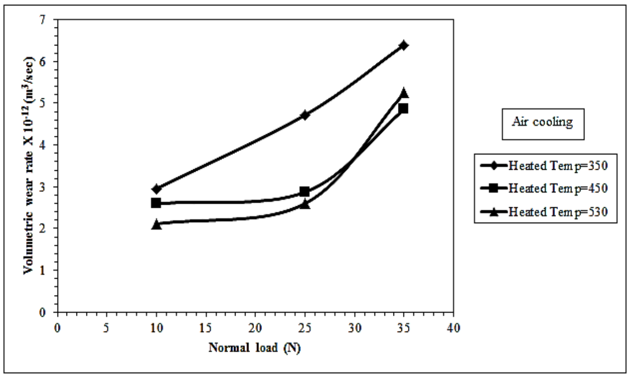


(b)

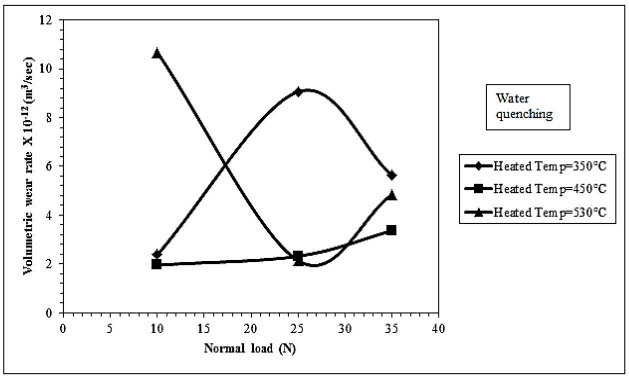


(c)

Fig.10 Variation of wear rate with sliding distance different temperature for water quenching condition

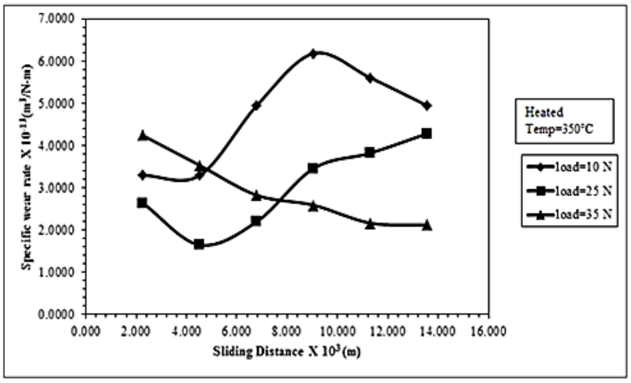


(a)

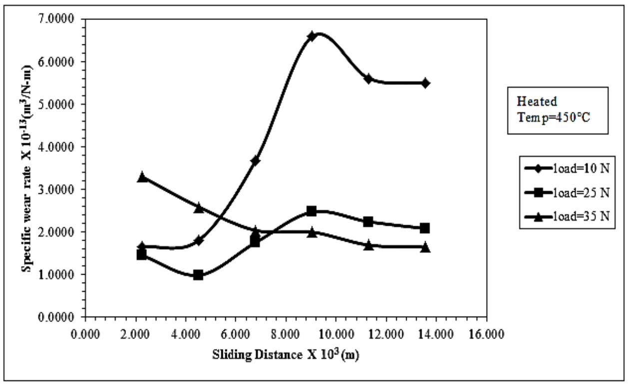


(b)

Fig.11 Variation of volumetric wear rate with normal load



(a)



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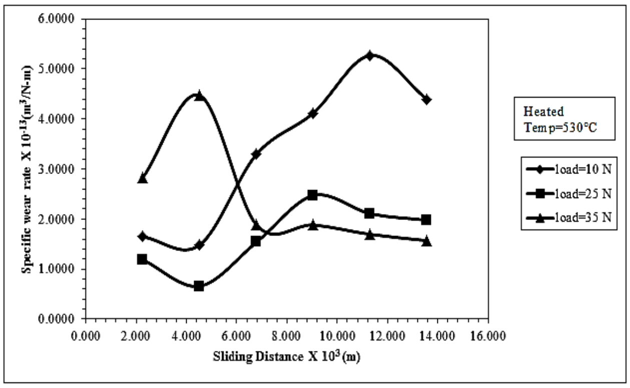
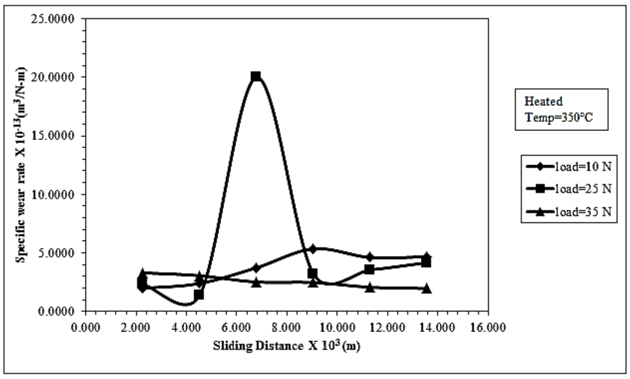
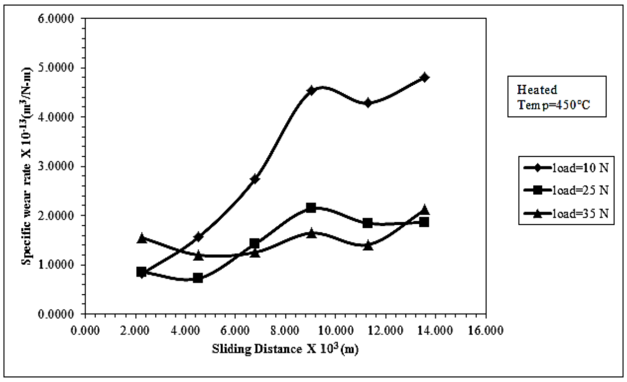


(c)

Fig.12 Variation of specific wear rate with sliding velocity at different temperature for air cooling



(a)



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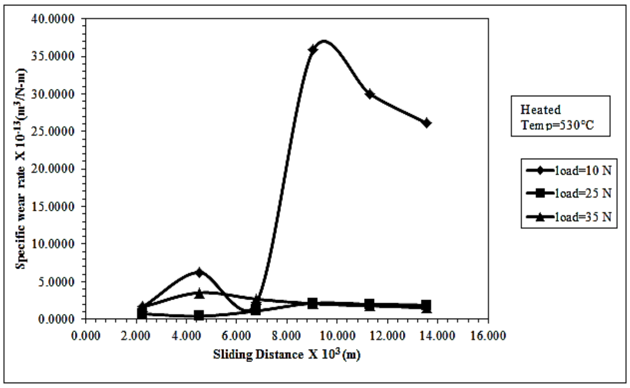
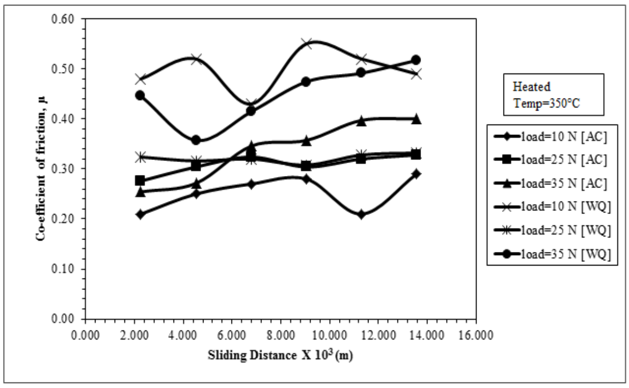
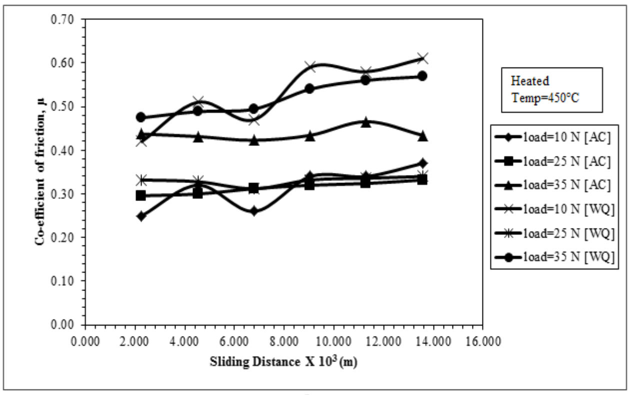


(c)

Fig.13 Variation of specific wear rate with sliding distance at different temperatures in water quench condition



(a)



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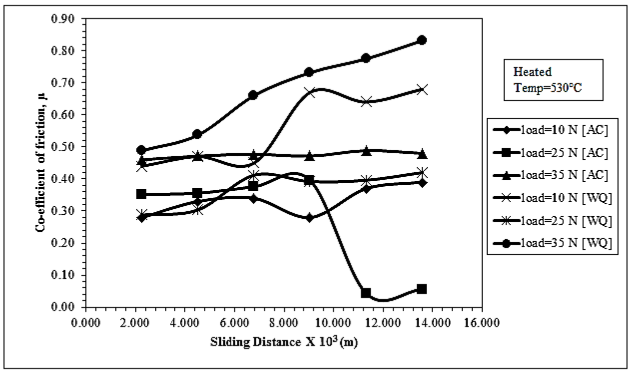


(c)

Fig.14 Variation of co-efficient of friction with sliding distance at different temperature

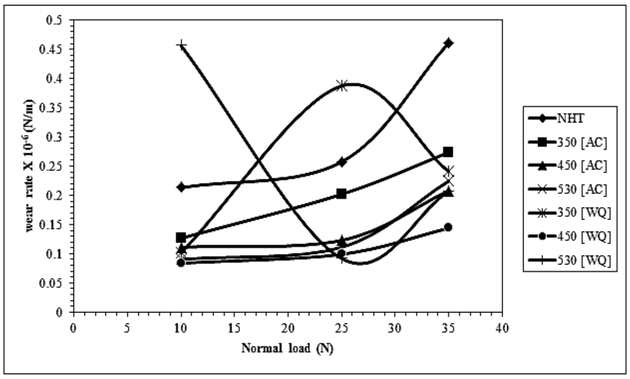
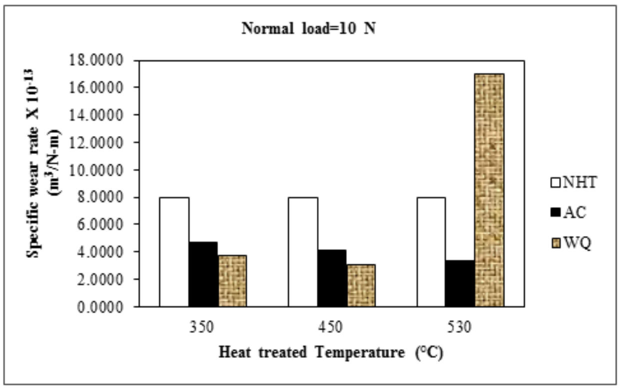
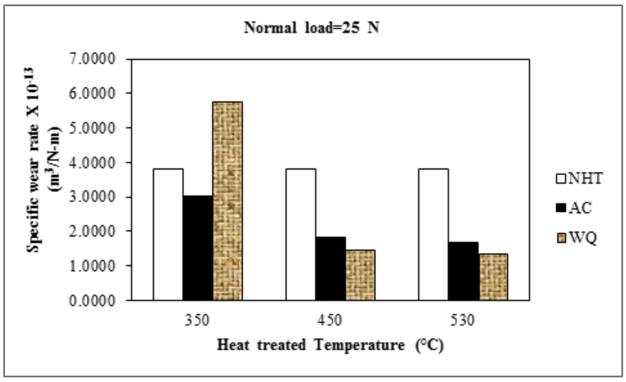


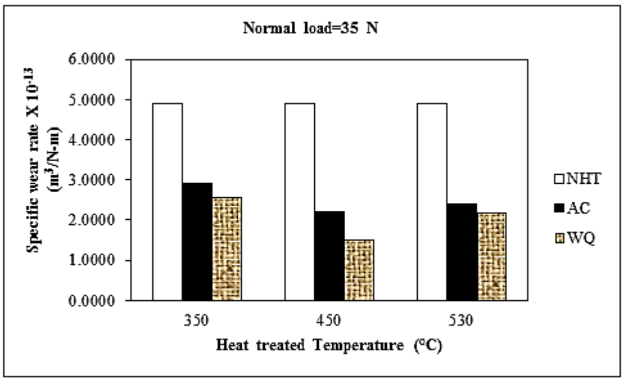
Fig.15 Variation of wear rate with normal load under different temperature



(a)



(b)



(c)

Fig.16 Variation of specific wear rate with different temperature and cooling media

The micrographs of the worn surfaces were taken at 200X magnification in an inverted metallurgical microscope. Some typical micrographs are as shown in Fig 17-18.The worn surfaces of AA2024+10 composite subjected to air cooling and to different loads and temperatures have been shown in Fig.17(a),(b) and (c).By comparing these we observe that at 350°C,10 N load large number of surface cavities have formed due to removal of hard surface particles. Cavities have grown and aligned in the direction of sliding. Even the extension is seen in the direction perpendicular to sliding. The grooves at 350°C, 10 N were finer. As the load and temperature are increased to 25 N and 450°C respectively a slight change in surface appearance is observed [Fig.17 (b)] with reduction in cavity size and slight increase in groove size. It appears that hard particles probably have come out of surface and have entrapped in the grooves aligned in the direction of sliding. As the load and temperature are further increased the groove size have still grown but with very minimal surface damage [Fig.17(c)].

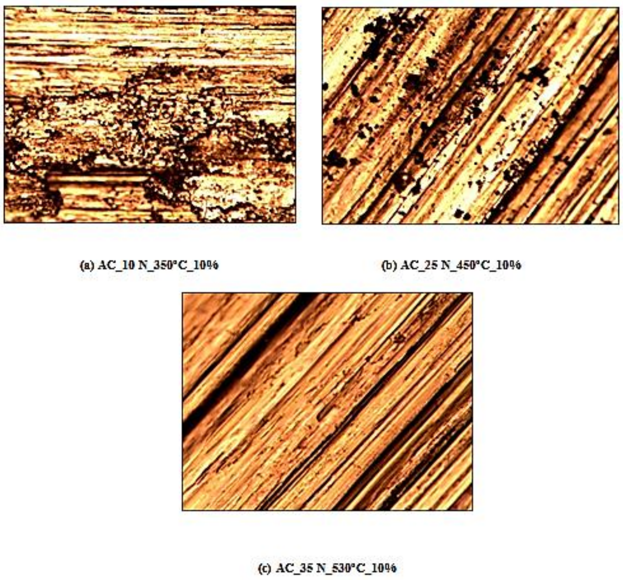


Fig 17 Micrographs showing worn surface composite with 10% fly ash subjected to air cooling for different temperature (350,450 & 530°C) and 35 N load

The micrographs of worn surface of water quenched specimens are shown in Fig.18 (a), (b) and (c). The cavities or pores are very minimal for water quenched specimens at 10 N, 350^{o}C as compared to air cooling under similar conditions but the grooves are much finer [Fig. 18(a)]. A slight surface damage is seen with very small cavities having fly ash particles embedded in them [Fig. 18(b)]. Also this Fig shows a slight growth of grooves with entrapped hard particles in some of the grooves. At higher load and temperature the widening of grooves is seen [Fig. 18(c)] with very minimal damage of surface and wear tracks. The damage of surface in some of the above situations is mostly because of localized stresses induced around the cavities and grooves.

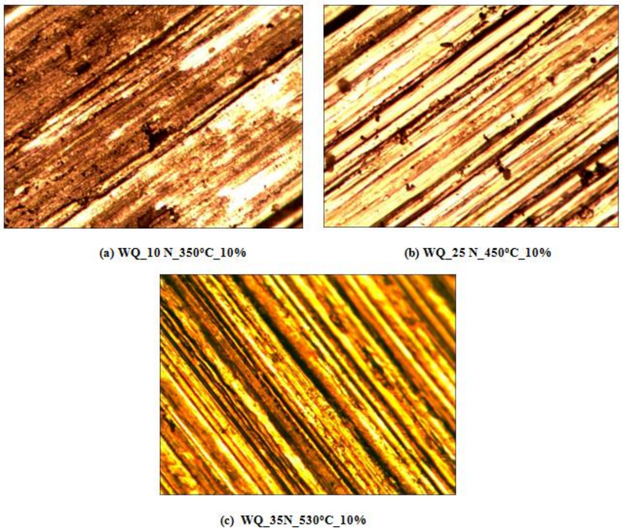


Fig 18 Micrographs showing worn surface composite with 10% fly ash subjected to water quenching for different temperature (350,450 & 530^{o}C) and 35 N load

Conclusions

- The AA2024 based fly ash reinforced composite were successfully produced with fairly uniform distribution of fly ash particles in the matrix.
- Hardness and tensile strength of composite increases with increase in the content of fly ash.
- AA2024+10 composite specimens were heat treated with cooling media as air and water. A slight decrease in density of heat treated composites is found as compared to non-heat treated composite.
- Heat treated AA2024+10 composite show superior wear characteristics as compared to non-heat treated category, specifically the wear performance was better for water quenched specimens as compared to air cooled and non-heat treated ones.

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