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# TRIBOLOGICAL CHARACTERISTICS OF Al-Cu-TiC-Si P/M COMPOSITES

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## ABSTRACT

Aluminum-silicon composites have been used extensively in several engineering applications. The objective of the present work is to investigate the wear and friction of Al-Cu-TiC-Si composites during both dry and periodic lubricated sliding conditions. The used materials were Al-Cu-TiC-Si composites fabricated using P/M technique with silicon content in the range 0-20 wt. %. The experimental work was conducted using a pin on disk configuration, within a load range of 15-100 N and a sliding speed range 7.2-13.5 m/s, for sliding distances up to 16.1 Km. The effect of sliding speed, applied load on the wear rate, mean contact temperature and coefficient of friction were evaluated. Wear scars and debris was characterized by means of scanning electron microscopy (SEM) and X-ray analyzer. The obtained results indicate that, the wear rate depends on the level of applied load and silicon weight percentage. The wear rate and mean contact temperature changes from mild to severe at transition load, and this load increases as the silicon content increases up to 12 wt. %. In the periodic lubricated condition the wear rate, mean contact temperature, and coefficient of friction were about 1/10 which under dry condition. These aspects led to an improvement of tribological characteristics and probably shifted the transition from mild to severe wear regimes to higher critical load. The results of this study are useful for selecting materials for several engineering applications.

## KEY WORDS

Al-Composites, Powder Technology, Tribology, Wear and Friction

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## INTRODUCTION

The search for new materials with specific properties to satisfy tribological applications has boosted the interest of designers and tribologist towards metal matrix composites (MMC). Aluminum-silicon composites have been used extensively in several engineering applications due to their excellent mechanical and tribological properties. High strength-to-weight ratio, excellent corrosion resistance, good fatigue resistance, low thermal expansion characteristics and other attractive properties for tribological applications [1] characterize them. However, they have a major drawback, I .e, the tendency to score, scuff and seizer under poor lubricating condition. The design requirements of tribological elements are primarily to provide good friction properties as well high wear resistance, which proved to be difficult to achieve through traditional materials.

The wear resistance of composites has received much attention in literature but a direct comparison between published papers is often difficult due to specific differences in the wear testing procedure. Work concerning the unlubricated sliding wear behavior of such materials has examined a number of variables such as; the contact pressure, sliding velocity, temperature, the counterface type, particle volume fraction, particle size, matrix type and heat treatment. A number of mechanisms have been proposed to explain the sliding wear behavior of these composites, many of which are discussed in an excellent review of the subject [2-9].

The reinforcement type is significant in determine the behavior of composite. A more detailed study of the rule of particle type in the sliding wear behavior of composites has been presented by Roy et al. [2]. They produced composites by a P/M technique with 20 vol. % of silicon carbide, titanium carbide, boron carbide and diboride as a reinforcements. They found that titanium carbide was the lowest successful reinforcement, reducing the composites wear rate. TiC reinforced MMCs have been produced in a range of aluminum alloys using a novel casting technique presented by Shipway et al. [10]. The sliding wear behavior of the extruded composites has been studied in their work. They concluded that, TiC particle addition have been reduced the wear rates of composites and have delayed the transition load from low wear rate to higher wear rate. Zhang and Alpas[11] observed a transition from mild to severe wear in $Al_2O_3$ particulate reinforced and unreinforced Al alloys when the friction induced heating of the sliding contact surfaces exceeded at critical temperature. Martinez et al. [12] studied the wear properties of two Al-Si alloys (Al-12 %Si and Al-20%Si) alloys reinforced with 20%vol.%SiC particulate using an oscillating friction wear tester. The two Al-Si alloys displayed comparatively lower wear resistance accompanied by transfer layer formation of fragmental Si particles on their worn surfaces. Extensive combination of both Si and SiC particulate at worn surfaces of these materials was a feature of the severe wear behavior at elevated temperatures. Pathak [13] presented an account of the effect of lead addition on friction and seizure characteristics of Al-Si alloys under different condition of lubrication. It was found that the addition of lead to aluminum - silicon alloys is generally reduce interfacial friction and improve their ability to resist seizure. A lower friction coefficient and a higher seizure load are obtained for Al-Si-

Pb alloys bearing in semi dry sliding condition compared with those observed for dry conditions. Wilison and Alpas [14] studied the effect of ceramic particulate and graphite addition on the high temperature dry sliding wear resistance of two Al alloys. They observed that all the reinforced alloys were able withstand considerable thermal softening effects while remaining in mild sliding wear regime.

Temperatures at contacting surfaces with relative sliding are important to friction and wear processes. The structure and properties of the rubbing material themselves and the characteristics of surface layers or films are strongly dependent on temperature [15]. Expressions for calculating steady state temperature generated by frictional work were presented by Lim and Ashby [16]. The influence of temperature on wear resistance was studied in a 2618 Al alloy reinforced with 15vol.%$SiC_p$in the temperature range 20-200 °C by A Martin et al. [17 ]. They observed that a transition from mild to severe wear beyond a critical temperature. The addition of the SiC particulate improved the wear resistance by a factor of two in the mild wear region, and the transition temperature, which was around 50°C higher in the composites. E.Y. El-Kady et al. [18 ] investigated the wear patterns of two Al- base composites reinforced with $Al_2O_3$ and $SiC_p$ in the operating temperature range from room temperature to 500°C. They showed that at low operating temperature up to 150°C the wear resistance of parent alloy material is higher than that of the reinforced composite material. At higher temperature, the composites material exhibits higher transition temperature than that of the parent matrix material.

It is known that the wear under lubricated conditions is caused by the fatigue fracture of surface aspirates [19,20]. Therefore, the wear behavior of aluminum alloys may be affected by material characteristics similar to their fatigue test results. Iwai et al. [21] have reported on the close relationship between wear and fatigue crack growth for aluminum alloys. They concluded that the one of the mechanisms of lubricated wear is the fatigue of the aspirates.

The objective of the present investigation was to study the effect of silicon content in presence of TiC on each of the regimes of wear. This study has been carried out by obtaining friction and wear data in situ in continuous loading experiment in a pin on disc test rig. The wear tests were performed in both dry and periodic lubricated conditions The contact surface temperatures were measured to clearing the effect of temperature on wear and friction of these composites. The worn surface and wear debris in the different wear regimes was examined.

## EXPERIMENTAL PROCEDURE

### Test Materials Processing

Aluminum composites were produced using the P/M processing techniques and extrusion. Particle size distribution of air atomized aluminum powder (99.5 % pure) used in the present investigation is given in table 1.

Table 1. Particle size distribution of aluminum powder

| Size (μm) | wt. % |
|---|---|
| + 150 | 8.5 |
| + 60 | 15.3 |
| + 45 | 25.7 |
| - 40 | 50.5 |

Electrolytic copper with grain size < 40 μm addition to titanium carbide and silicon powders were used to prepare the specimens. The mixing was carried out in a laboratory blender for four hours to give a composites of Al-4.5 wt.% Cu- 10 wt. % TiC addition to silicon ranging from 0 to 20 wt. %. The metal powder was cold compacted in a hardened steel die to a preform shape 25 mm diameter, 40 mm height and 80- 85 % theoretical density. Zinc stearate was used for die lubrication.

Metal powder extrusion is one of the more recent compacting methods. Experimental set up consisted of the extrusion assembly surround by a band heater capable of heating the assembly up to 550 °C During extrusion the container and the die were graphite lubricated. The cold compacted specimen was heated to 500 °C for 2 hrs in hydrogen atmosphere. Then, inserted into the container. As soon as the ram was placed over the container and pressure was applied .The used die was of reduction ratio 4:1 having extrusion angle 45° The extruded products were heated to 510 °C for one hour, quenched in water and then aged for 16 hrs at 150 °C

**Wear Tests**

Dry and periodic sliding wear tests were carried out using a pin on disk wear test apparatus. A schematic illustration of the apparatus is shown in Fig.1. The tests consisted of holding a cylindrical pin 8 mm diameter against a rotating steel disc (50 HRC). Tests were conducted in air at room temperature (28 °C) .The influence of applied load was studied at different loads ranging from 15 N to 100 N and constant sliding speed of 9.6 $ms^{-1}$ .The effect of sliding speed ranging from to 7.2 to 13.5$ms^{-1}$ on the wear rate has been investigated at constant applied load 15 N. Tests were also conducted in the presence of oil lubricant. In this series of experiments, calibrated system for providing SAE 30 lubricating oil to the bearing zone. This system provides three drops of lubricating oil every one minute. The specimen was initially running - in for 10 minutes at load 5 N. On the other hand, after the running-in period, the frictional force was calculated by recording the deflection of the tested pin holder using strain gauge and half bridge instrumentation. The coefficient of friction was calculated with reference to sliding time. The wear rates of pin specimens were calculated from the difference in their weight measured before and after each test and divided by the sliding distance. The sliding distances were calculated by multiplying the sliding time with the sliding speed. Mean contact temperatures of the pin specimen, were measured using commercially available type (Chromel-alumel) thermocouple probes of 1 mm outer diameter. The mean contact temperature of the pin specimen was measured using a previously developed method [15] by inserting the probe through a hole drilled at 1.5 mm distance from the contact surface. Before starting a new wear test, both the disk and the pin were cleaned and ground with 600 grad emery paper for each wear run being exactly identical. After periodic lubrication test condition the surfaces of pin specimens were subsequently cleaned using acetone to remove any oils or grease and dried using electrical air dryer.

To investigate the wear patterns the worn surfaces and the collected debris have been analyzed by using the scanning electron microscope (SEM), optical microscope and an X - ray analyzer.

## RESULTS AND DISCUSSION

### Applied Load - Wear Rate Relationship

The variations in wear rate as a function of applied load for different wt. percent Si are shown in Fig.2. Each point on the respective graph represents one wear test under dry condition. From figure it is clear that, all composites show three distinct stages; low, mild and sever wear rates. However, the numerical values of wear rates and loads are completely different. The wear rate of 0 wt. % Si at applied load of 20 N was 37 $x 10^{-4}$ gm/Km where as the wear rate of the composite of 12 wt .% Si at the same load was 22 x $10^{-4}$ gm/Km. It should be noted that, the resultant increase in wear rate from the beginning of low wear rate regime to the beginning of mild -wear rate regime in each particular composites was almost the same. However, the load at which the transition occurs is 2.5 times higher for the 12 wt. %Si composite. A similar behavior has been observed in the other composites. Also, it has been reported that "a critical load" for non-destructive wear exists; below this load, the wear rate is mild and steady and a severe wear rate occurs above this "critical load" [23]. The transition load in the case of 0 wt. % Si was found to occurs at 25N while that of 4,8,12,16 and 20 wt. % Si composites were at 30,30,50,40 and 35 N respectively. However, the wear rate in all cases at the corresponding transition load is the same, and it was 50 x $10^{-4}$ gm/km. The wear rates of 8,12,16 and 20 wt. %Si composites increased in two distinct regions. These two regions have been referees to as the "low load" region and the" high load" region, which are separated by high, wear rate. The wear rates that observed in the low load region did not show much variation with varying silicon composition. Wear rate in this region is interpreted as reflecting the fracture of oxide layer at the wear interface, especially since the load levels involved are insufficient to cause deep penetration and deformation in metal below the oxide. Also, as was shown by Razavizadeh and Eyre [22], the temperature levels reached at interface are not high enough to cause the extent of oxidation necessary for the observed amount of debris.

A better understanding of wear behavior can be gained by studying the thermal conditions under which the surfaces are rubbed together. Fig.3 illustrates the mean contact temperature of the specimens plotted against the applied load. The measured temperature represents an average temperature of pin subsurface at about 1.5 mm below the contact surface. It can be seen that the mean contact temperature increases as the applied load increases. The fracture and removal of the oxide debris particles primarily control wear. As supporting evidence, in the low load region, deformation in subsurface regions was not observed. The effect of increasing the applied load below the transition point is to accelerate the fracture of the oxide and thus cause increased wear rate. As the surface oxide is removed, the fresh metal exposed is further oxidized. From Fig.2 and Fig.3, it is clear that, at the severe load high wear rate occurs. This was characterized by the formation of metallic debris particles present along with the fine oxide debris. For 0 and 4wt.%Si composites, large- sized debris particles rolling through the interface cause plastic deformation in the surface layers of these composite. Fig.4 shows the plastic flow region in the surface layer for 0 wt.%Si. Severe wear produces considerable deformation and fragmentation in the subsurface and the contacting surface, and the surface has deep groves (Fig.5).

During the wear test, cracking and sapling of the surface of wear pin occurs to form debris. In the case of low and mild wear rates, the debris produced was predominantly fine equaled particles. If conditions are such that severe wear caused, the debris changes to metallic flakes similar in shape to large chips produced during machining. From the forgoing, the wear mechanisms of both the 0 wt.% Si and the other composites can be classified to three mechanisms, namely oxidation induced delaminating, high strained induced delaminating, and subsurface delaminating "microgrooving"[23]. It is evident that the addition of silicon to matrix alloy has no effect on the mechanism of the wear the influence seems to are primarily on transitions load and wear rates.

Fig.6 shows the variations in friction coefficient as a function of the applied load under dry condition. The friction coefficient slightly varied and took almost the same variation for all composites. The composites with 12 wt.%Si showed a lowest friction coefficient compared with the other composite at every applied loads. On the other hand, the composite containing 20 wt.%Si showed a highest friction coefficient.

As stated in the introduction, the wear under lubricated condition as known to be related to fatigue phenomenon [19,20]. Fig.7 shows photographs of macroscopic and SEM observations of worn surface under periodic lubrication. In comparison, the wear under lubricated condition may be produced considerably by fatigue failure of the contact surfaces.

The wear rates are plotted as a function of applied load for 12 and 16 wt.%Si under lubricated condition in Fig.8. It can be seen that, the wear rates of the two composites are almost the same at low applied loads up to 40 N. On the other hand, the wear rates in this region under lubricated condition were about 1/10 those under dry condition. The wear rate of 16 wt.%Si was greater than that of 12 wt.%Si, but the difference become larger with increasing applied load. For example the wear rate of 16 wt.%Si was 1.23 times that of 12 wt.%Si at applied load 100 N and almost

the same at applied load 35 N. In the present investigation, the range of the applied loads under lubricated condition was close with the mild wear regime.

Fig.9 shows plots of mean contact temperature and coefficient of friction as a function of applied load for 12 wt.%Si under dry and lubricated conditions at 9.6 $ms^{-1}$ as a sliding speed. It can be seen that, the mean contact temperature under lubricated condition was about 1/3.6 that under dry condition at applied load 15 N and 1/5 at applied load 45 N. It can also be seen that, under lubricated condition mean contact temperature slightly increased and took almost the same trend of coefficient of friction with an increase of applied load. This is because, at low loads, a thick, continuous oil film separates the matting surfaces and thus the e mutual material contact is eliminated. However, as the load increase, the oil film thickness between the matting surfaces is reduced to the height of the surface roughness and asperity contact through the oil film a possibility. Under high loads, the lubricant film can become sufficiently thin to permit direct contact between the matting surfaces under that condition, the adhesion component of friction implies shearing in or very close to the interface. Thus, the force needed to shear asperity junction of Al-Si base alloys will be high [13]. From Fig.9 it is clear that under lubricated condition, wear rate, the coefficient of friction and mean contact temperature generally decreased and no severe wear regime occurred under the range of the used applied loads in the present wear testes.

**Sliding Speed-Wear Rate Relationship**

The wear rates versus sliding speeds for different wt. percent Si under dry condition are shown in Fig.10. All the presented composites have similar trend at all speed range. Fig.10 shows two distinct stages; wear rate-decreasing stage and wear rate-increasing stage. In the first stage, the wear rate decreases with the increasing sliding speed up to 9.6 $m/s^{-1}$. These results are not in agreement with the experimental data reported in the literatures [24,25,26]. Sato and Mehrabian [24] observed that the wear rate of aluminum composite tented to increase with increasing sliding speed. Wange and Rack [25] reported that blow 1.2 $ms^{-1}$ where the main operative mechanism is microcracking, $SiC_w$ reinforcement did not improve the wear resistance.

However, the present results agree with the observations of Wang et al.[25]. They observed that the transition load was dependent on the sliding speed. For first stage, the higher wear rate attributed to higher friction coefficient and third body abrasion at low speed (where friction is enhanced). Furthermore, sliding speed increased the initial and steady state wear rates for all composites decreased as sliding speed increases [26]. The wear mechanism principally controlled by third body behavior, i.e. third body abrasion, has been shown to be dependent on the sliding speed.

Measurements of mean contact temperature as a function of sliding speed for all composites have been plotted in Fig.11. The curves are typical for measurements made after an initial run-in period of rapid temperature rise. Mean contact temperature measurements were averaged over the equilibrium portion of each test to obtain steady state temperature, which have been represented in the temperature curves. Temperature measurements for a test at 15 N are shown in Fig.12 at different sliding speeds. The figure shows that as sliding speed increases, the mean contact temperature increases for all composites. The consequences of this temperature rise are the decrease in the flow stress of composites; the formation of different oxide layers on the surface which change the surface traction and increase the wear rate.

## CONCLUSIONS

1- Increases in the silicon content extent to load range where fine equaled particles are produced.
2- A transition from mild to severe wear occurs owing to the destabilization of the protective layer caused by subsurface flow.
3- The transition from severe to seizure wear is related to contact temperature.
4- For the tested composites, with periodic oil lubrication, contact temperature, coefficient of friction and wear rate were about 1/10 under dry condition.
5- The coefficient of friction was found to be insensitive to variation in silicon content and applied load for the tested composites.
6- The composite with 12 wt % Si shows the lower wear rate compared with all the tested composites. This composite is recommended for high load and high sliding speed applications.

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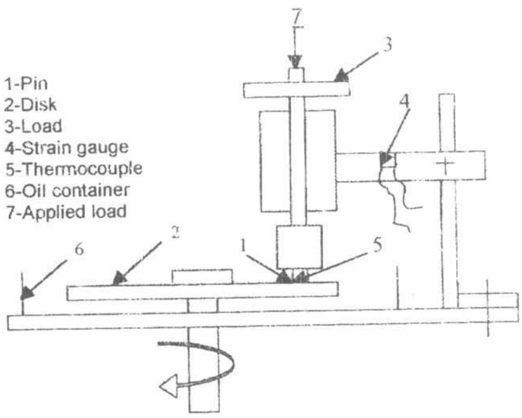



Fig. 1.Schematic diagram of test rig

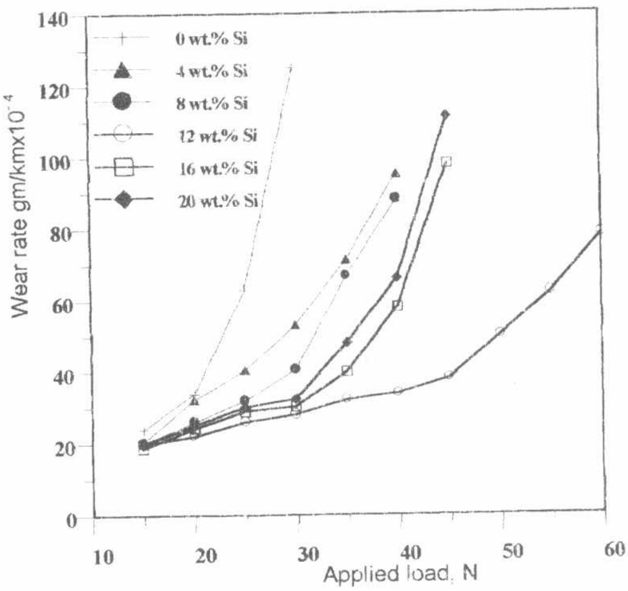



Fig.2.Wear rate Vs. Applied load under dry condition.
(sliding speed 9.6 m/s)

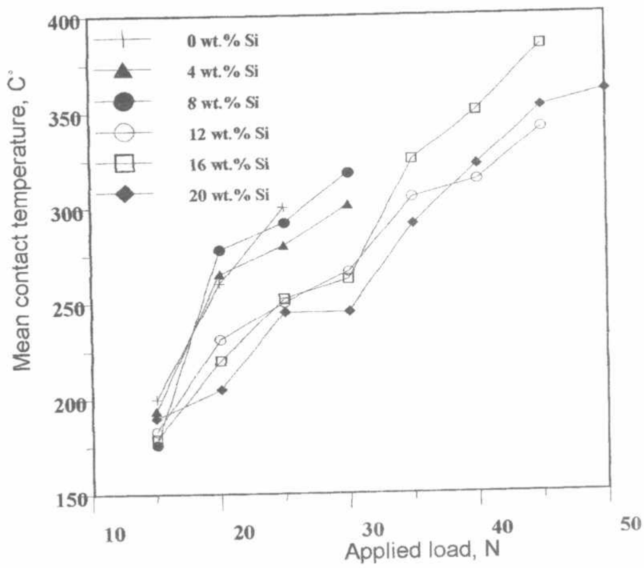
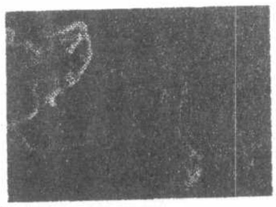



Fig.3.Mean contact temperature Vs.applied load under dry condition. (sliding speed 9.6 m/s)

X200



X2000

Fig.4.SEM micrograph of 0 wt.% worn surface under dry condition (p=25N, v=9.6 m/s)

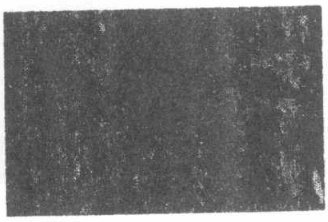


Fig.5.Optical micrograph of 0 wt.% worn surface under dry condition (p=45N, v=9.6 m/s) , X 200

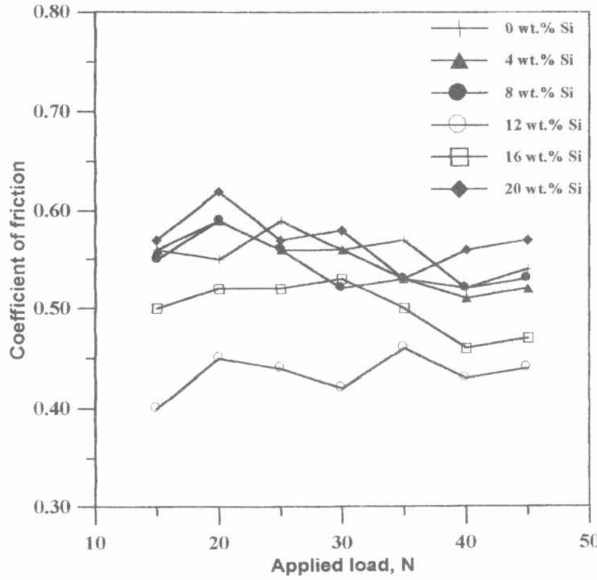
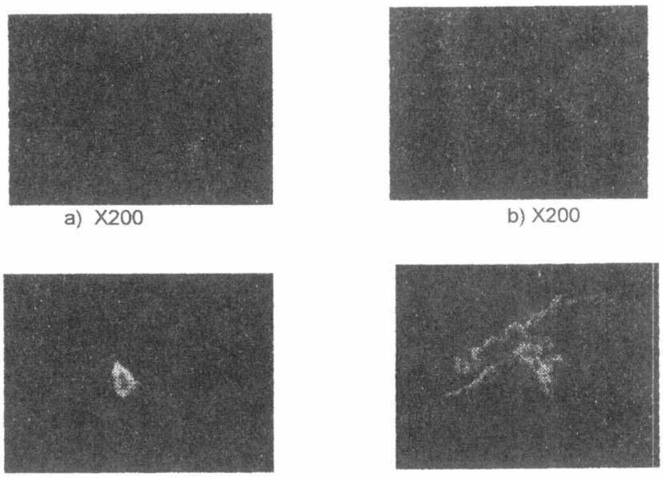



Fig.6.Coefficient of friction Vs. applied load under dry condition. (sliding speed 9.6 m/s)



a) X200 b) X200

a) X2000 b) X2000

Fig.7. SEM micrograph of wt.12% worn surface with lubrication.
a- p=50N ,v =9.6m/s b- p=100N ,v =13.7m/s

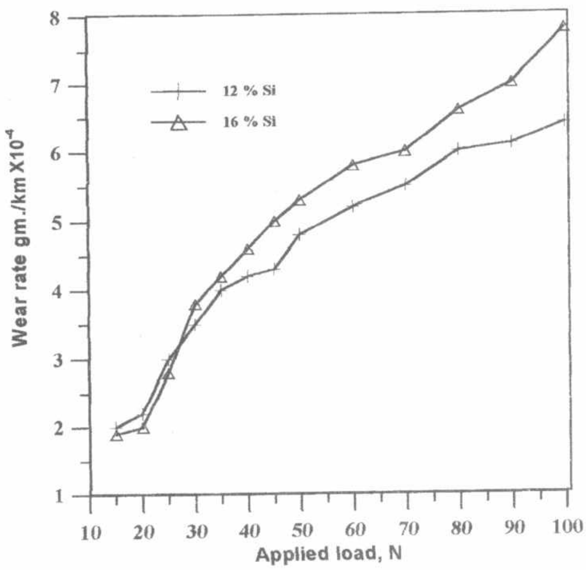



Fig.8 .Wear rate Vs.applied load under periodic lubrication.
(sliding speed 9.6 m/s)

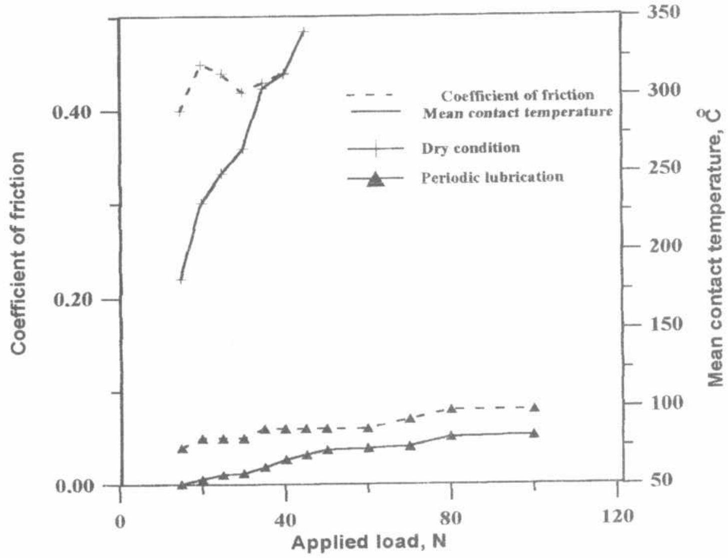



Fig.9.Mean contact temperature and coefficient of friction Vs.applied load of 12%Si.(sliding speed 9.6 m/s)

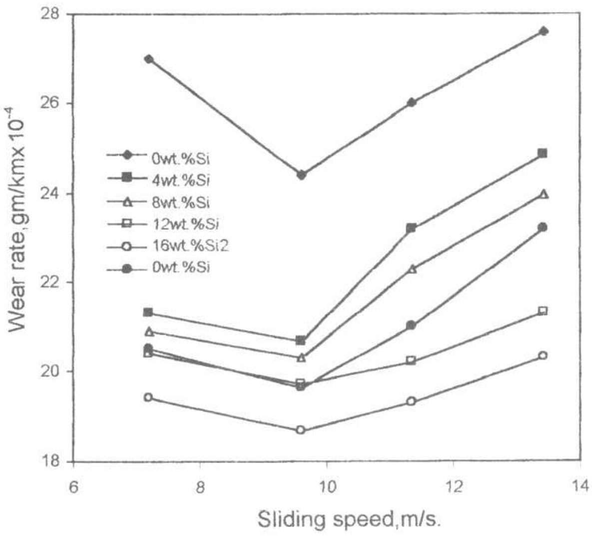



Fig.10.Wear rate Vs. sliding speed under dry condition.
( applied load 15 N )

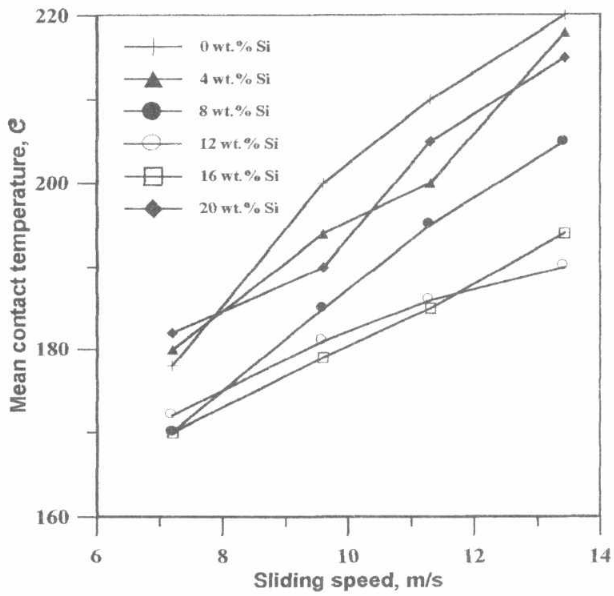



Fig.11. Mean contact temperature Vs. sliding speed under dry condition. (applied load15 N)