Friction and wear are the most commonly encountered industrial problems leading to the replacement of components and assemblies in engineering. There have been great advances in the development of aerospace technology because of the use of titanium alloys. Titanium alloys have wide range of applications for which they have received considerable interest recently because they show an astonishing range of mechanical properties. The present investigation covers the study of dry sliding friction and wear of the Ti6Al4V alloy, which alone covers about 50% of the total world production of titanium alloys. The main objective of this study is to investigate the dry sliding friction and wear behaviour of titanium alloy (Ti-6Al-4V) sliding against EN31 steel. The results show that the wear rate of the Ti6Al4V alloy decreases with increasing sliding velocity and decreasing normal load with few exceptions thus showing typical transition characteristics. The average coefficient of friction decreases as the normal load increases with few exceptions. Also the average coefficient of friction increases as the sliding distance increases for all loads and sliding velocities. The average length of biggest, medium and smallest wear debris was found to be 1.026 µm, 0.711 µm and 0.401 µm respectively.

Keywords: friction, wear, Ti-6Al-4V alloy, dry sliding

1. Introduction

The primary attributes that make titanium an attractive material include high specific strength, easy formability, fatigue resistance and excellent corrosion resistance. This also explains their preferential use in the aerospace applications (like rocket engine parts, fuel tank, gas bottles), the chemical industry, medical engineering etc. It is also used in the airframe structures, such as landing-gear beams, hydraulic tubing, wing boxes, spacers, bolts, etc. Titanium alloys are used in fan-jet engines for which large front fans are required. An excellent strength-to-weight ratio of titanium along with the metallurgical stability at high temperatures and low creep rates make it favourable for jet engine components like blades and discs in the low and intermediate sections of compressors.

Another important area of application of titanium alloys is chemical and general engineering. The outstanding corrosion resistance of titanium in many environments is the prime reason for its use in these industries. For low-stress applications, commercially pure (CP) titanium is generally used, and for high strength applications Ti-6Al-4V or Ti-13Nb-13Zr alloys are used [1].

Sliding wear processes of ductile materials are often accompanied by severe plastic deformation [2]. A characteristic feature of the sliding wear of metals is the occurrence of transitions in the rate of material loss as a function of sliding velocity, applied load, and ambient temperature. In the mild (oxidational) wear regime, the sliding metals are separated by thin oxide films and direct metallic contact occurs only occasionally. Wear rates are low and the debris formed by the wear process is typically finely divided and consists of a mixture of metallic oxides. Mild wear is generally associated with the low loads and sliding velocities, although a severe form of oxidative wear can occur at high sliding velocities and low loads where high interfacial temperatures result in rapid oxide film growth [3].

A brief literature review related to dry sliding friction and wear characteristics of titanium alloys and their worn surface analysis is presented as follows: Bare titanium galls and seizes readily when in sliding contact with itself and most other metals [4]. Titanium, although a hexagonal metal, exhibits relatively high friction. The coefficient of friction for titanium sliding on titanium and on 440-C stainless steel decreased with increasing sliding velocity or interface temperature apparently because of an increase in the c/a lattice ratio as well as
influences exerted by other factors. The friction and wear characteristic of titanium may be improved by alloying the titanium with tin. This alloying resulted in an increase of the c/a lattice ratio [5]. Giltrow concluded that titanium alloy with hexagonal or near hexagonal structures exhibit greater resistance to abrasive wear than those with body centred cubic structures. In adhesive wear, hexagonal alloy shows lower coefficients of friction, in the range 0.4-0.6, than the cubic alloys whose coefficient of friction are approximately 1.0. N-hexadecane has little effect on the friction or wear of any of the alloys examined [6].

It was found that the titanium surface is most active after surface grinding. The greatest effect in galling resistance was achieved by iodizing low alloy titanium. The chemical thermal treatment process mainly improves the galling resistance of titanium and its alloys, the greatest effect is observed at high pressures and low sliding speed [7]. Dry- sliding friction between ceramic and titanium treated by laser irradiation (graphite coating) is minimized [8]. Wear rate was higher against the AISI M2 at the lowest sliding velocities, and it continuously decreased as velocity was increased. On the other hand, as the sliding velocity was increased wear rate first decreased, experienced a minimum and then became very severe in the case of sliding against the Ti-6Al-4V alloy. As surface temperature increased the plastic strain rate at the contacting asperities also increased and wear rate also increased in accordance with the theory of delamination [9]. Surfaces of the metastable -β alloys exhibited greater surface deformation and transfer than did Ti-6Al-4V pins, plowing being representative of surface damage for the two-phase α+β. The friction coefficients of the Ti-Nb-Zr-Ta alloys at low contact stress decreased with increasing sliding velocity during the first cycles, this dependence disappearing at high contact stress and not being observed for Ti-6Al-4V [10].

Alam and Haseeb demonstrated that in steady states Ti-24Al-11Nb had a substantially higher wear resistance (about 48 times) than that of Ti-6Al-4V alloy tested under a normal load of 45 N. Severe delamination is found to be responsible for the low wear resistance of Ti-6Al-4V. In the case of Ti-24Al-11Nb, two wear mechanisms had been suggested: delamination with lower degree of severity and oxidative wear [11]. The two titanium alloys had similar friction and wear performance, although their grain structures and compositions were different. Large frictional fluctuations occurred when metal and ceramic balls slide against Ti-alloy disks. Higher friction coefficient with larger fluctuation and high wear rate were observed at the lower sliding speed [12]. The dry sliding wear resistance of the oxidised titanium strongly depends on the material of the counterbody. The α-Ti (O)/C45 steel couples show the linear wear rates approximately 28-68 times lower than the Ti/C45 steel couple, and more than 150 times lower than the couples with T1 HSS counter face [13]. The temperature of β phase transformation for Ti-6Al-4V is closely related to that of turning point of friction coefficient and wear rate. The oxides are formed in the order of TiO, TiO2 and V2O3 with the friction temperature increasing [14]. From the experimental results of Ming et al., it could be seen that generally the friction coefficient and the wear rate of the Ti-6Al-4V alloy increases as sliding velocity increases before it decreases, showing typical transition characteristics. With the increase in the friction temperature the coefficient of friction of the Ti-6Al-4V alloy increases firstly and then falls rapidly [15]. Due to good heat transfer capability of copper the interface temperatures of Ti-6Al-4V/GCr15 pairs decreased with increasing sliding velocity and contact pressure. The main wear mechanism of Ti-6Al-4V is adhesive wear [16].

In dry sliding condition, there was no significant variation of the wear rate of the heat treated samples except for the sample deformed above β transus. Higher wear rate in this case is possibly because of the presence of acicular α [17]. Wear behaviour of Ti-5Al-4V-0.6Mo-0.4Fe (Ti54) alloy sliding against tungsten carbide is investigated for cryogenic sliding applications at different speeds, loads and distances. Empirical models based RSM are developed to predict wear characteristics of Ti54 alloy as a function of sliding conditions. The experimental and predicted results are to be found in good agreement. Wear volume of titanium increases with increase in speed and load especially at higher levels, the combined effect of both factors is dramatically larger for both dry and cryogenic sliding. Besides, cryogenic wear is substantially lower than dry wear. SEM and EDS analyses of worn surfaces and wear debris reveal that cryogenic sliding is significantly influenced by changing material properties along with boundary lubrication performance. The study has shown that modes in dry sliding are adhesion and delamination whereas in cryogenic sliding they are abrasion and delamination [18].

Friction and wear, as part of tribology scene, is now receiving considerably more attention, although still lagging behind fatigue and corrosion in research efforts. Sufficient is not known about friction and wear mechanisms (of titanium alloys) and their solution to encourage greater application of this knowledge. There are, however, a number of problems which cause considerable difficulty in translating the results of research into industrial practice.

Review of literature reveals that much of the work on sliding wear and friction characteristics of Ti6Al4V under dry condition has been carried out either for a combination of low load (10 N) and high speed (12-70 m/s) or high load (75-250 N) and low speed (0.3-0.8 m/s) operating conditions with MS, SS, HSS, AISI M2 steel, C45 steel and Ti as counter face. Very less work has been reported for a combination of medium load (10-50 N) and medium speed (1.0-3.0 m/s) and some of above materials as counter face. Ti6Al4V having a
hardness of around 36HRc has been analysed for sliding wear and friction behavior against materials such as MS having either quite low hardness (140 HV as cast) or against the materials such as SS, HSS, AISI M2 steel, C45 steel having very high hardness (hardened to 62 HRc). Further, in most of the reported literature very simple type of tribometer namely pin-on-disc machine has been used for experimentation. No work has been reported for medium operating conditions with steels having medium hardness levels as counter face. In view of the increasing use of Ti especially grade-5 for various engineering applications, it becomes imperative to explore the wear and friction behavior of this material for medium set of operating conditions with different materials as counter face using even more advanced tribometers. The present work is an attempt in this direction, in which the sliding friction and wear behavior of Ti6Al4V is investigated for medium set of operating parameters against EN31 steel using a multi-tribo tester.

The effect of variation of normal load, sliding velocity and sliding distance on average coefficient of friction and average wear rate has been evaluated.

2. Experimental setup

The experimental setup used for carrying out the investigations is shown in Fig. 1. Various instruments/equipment used are described in the succeeding paragraphs.

2.1. Instrumentation used

The major equipments used for carrying out the experimental investigations (on line and off-line) are: multi-tribo tester and a profile projector apart from a precision weighing machine.

2.1.1 Multi Tribo Tester

Multi-tribo Tester (Ducom Instruments Pvt. Ltd., Bangalore, India) with software (Winducom 2008) for measurements of frictional force, wear, coefficient of friction and temperature of lubricant oil on wide range of materials such as metals, ceramics, polymers, composites and coatings and also used to study pure sliding, partial sliding and pure rolling, dry or lubricated contacts is shown in Fig. 1 and its major specification are listed in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Min</th>
<th>Max</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load</td>
<td>N</td>
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<td>1000</td>
<td></td>
</tr>
<tr>
<td>Speed</td>
<td>RPM</td>
<td>0</td>
<td>2000</td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>°C</td>
<td>Ambient</td>
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<td></td>
</tr>
<tr>
<td>Wear</td>
<td>mm</td>
<td>0</td>
<td>2</td>
<td>Least count 1 µm</td>
</tr>
</tbody>
</table>

2.1.2 Profile projector

Profile Projector (Radical Instruments) used for measuring the size of small wear debris is shown in Fig. 2. The main parts of profile projector are vertical light source, work table for placing specimen, micrometers for adjustment along X & Y axis, screen and rotating knob for adjusting light source, magnification lens (10X) and angle twisting knob (Fig. 2).

Fig. 1 Experimental setup showing Multi Tribo Tester and computer link to Multi Tribo Tester through software (Winducom 2008), Inset shows the contact region

Fig. 2 Measuring the size of wear debris collected at dry condition with Profile Projector (Radical Instruments)

2.2. Workpiece material

Titanium alloy grade-5 (Ti-6Al-4V) used for experimentation was procured in the form of 32 mm × 30 mm × 220 mm rectangular bar form M/S Nisarg International Mumbai, Maharashtra, India and used for making pin samples of 6.35 mm × 6.35 mm × 9 mm size as per the requirement of adaptor of multi-tribo tester.

Chemical composition of Titanium alloy was determined to ascertain the grade of procured material.
and the results are given in Table 2. Hardness of the specimen was found to be 36 HRc. The size and shape of the counter face material (EN-31 steel) were $\phi 60$ mm (major dia.) $\times \phi 25$ mm (minor dia.) $\times 20$ mm (thickness) and disc (flat roller), respectively. Chemical composition of EN31 steel (counter face) is given in Table 3. It is hardened to 51 HRc and has a tensile strength of 1600 MPa and an elongation of 1-2%.

Microstructure of Ti alloy was studied at 500X and optical micrograph shows Widmanstätten $\alpha$ structure with $\alpha$ phase present on prior $\beta$ grain boundaries (Fig. 3).

![Fig. 3 Micrograph of Titanium alloy (Ti6Al4V) at 500X](image)

2.3. Experimental procedure

Titanium alloy grade-5 (Ti-6Al-4V) is used for investigation and comparison. The selection of EN31 steel counter face (51 HRc) was decided for various reasons. First, many tribological system comprise dry sliding against a steel counter face. Second, this steel has higher hardness than the selected titanium alloy and it is expected that deformation processes during sliding, in this case, be confined to the Ti-alloy. Third, it has a thermal conductivity which is about double that of the Ti6Al4V alloy. The friction and wear experiments were carried out on Multi-tribo tester under dry conditions.

The experiments were designed by two levels full factorial method. While selecting parameters, capabilities of the machine were also taken into account. The parameters used in the experiments are given in Table 4. Repeatability was observed in all the experiments by repeating each experiment twice or thrice and the average value was taken.  In total twenty five number experiments were conducted on multi-tribo tester. The average atmospheric temperature and humidity level for the duration of experimentation were 23°C and 52%.

Various combinations of different parameters for friction and wear experimentation on multi-tribo tester for selected material i.e. Ti-6Al-4V is given in Table 5.
3. Results and discussion

The variation of wear rate and average coefficient of friction for Ti6Al4V as a function of sliding velocity, load and sliding distance are presented and discussed in the following subsections. This section also covers the analysis of wear debris at different loads.

3.1. Wear rate as a function of sliding velocity

The variation of wear rate for Ti6Al4V as a function of sliding velocity is shown in Fig. 4. It can be clearly seen that for normal loads up to 40 N the wear rate decreases monotonically with increasing sliding velocity. At highest load of 50 N, it shows different behaviour; upto sliding velocity of 1.5 m/s wear rate decreases but afterwards wear rate abruptly increases till sliding velocity of 2 m/s and then decreases up to sliding velocity of 2.6 m/s. Increase in the wear rate at 2 m/s is attributed to the increase in the contact temperature and suggest severe sliding conditions with plastic deformation and flow of the softer material thus indicating a possible three body abrasion. Similar trends have also been reported under lower values of operating parameters by some earlier investigators [13,14,19]. In general, the wear rate decreases with increasing sliding velocity and decreasing normal load with few exceptions.

3.2. Wear rate as a function of normal load

Fig. 5 gives the variation of wear rate for Ti6Al4V as a function of normal load. It is observed that the wear rate decreases first upto a normal load of 30 N then it abruptly increases upto a normal load of 40 N and finally decreases for sliding velocities 0.52, 1.05 and 1.57 m/s. But for higher sliding velocities i.e. for 2.09 and 2.62 m/s wear rate increases continuously for normal load of 30 N to 50 N. It was noted that the highest wear rate values were obtained for 0.52, 1.05 and 1.57 m/s under a 40 N load. But for 2.09 and 2.62 m/s the highest wear rate was obtained under a normal load of 50 N. At higher sliding velocities, 10 out of 25 samples indicated different wear behaviour (wear rate increased linearly) possibly due to frictional heating at higher sliding velocity and due to low thermal conductivity of titanium alloy (Ti6Al4V).

Table 4 Parameters for friction and wear experimentation on Multi-Tribo Tester

<table>
<thead>
<tr>
<th>Expt. No.</th>
<th>Load (N)</th>
<th>Contact Pressure (MPa)</th>
<th>Sliding Velocity (m/s)</th>
<th>Sliding Distance (m)</th>
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<td>0.52</td>
<td>314.16</td>
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<tr>
<td>2.</td>
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<td>1.05</td>
<td>628.32</td>
</tr>
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<td>3.</td>
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<td>1.57</td>
<td>942.48</td>
</tr>
<tr>
<td>4.</td>
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<td>2.09</td>
<td>1256.64</td>
</tr>
<tr>
<td>5.</td>
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<td>1570.79</td>
</tr>
<tr>
<td>6.</td>
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<td>0.52</td>
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<tr>
<td>7.</td>
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<td>628.32</td>
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<tr>
<td>8.</td>
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<tr>
<td>9.</td>
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<tr>
<td>10.</td>
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<td>2.62</td>
<td>1570.79</td>
</tr>
<tr>
<td>11.</td>
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<tr>
<td>13.</td>
<td>30</td>
<td>0.744</td>
<td>1.57</td>
<td>942.48</td>
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<tr>
<td>14.</td>
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<td>0.744</td>
<td>2.09</td>
<td>1256.64</td>
</tr>
<tr>
<td>15.</td>
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<td>0.744</td>
<td>2.62</td>
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</tr>
<tr>
<td>16.</td>
<td>40</td>
<td>0.992</td>
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<td>17.</td>
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<tr>
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<td>25.</td>
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<td>1.24</td>
<td>2.62</td>
<td>1570.79</td>
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</table>
3.3. Average coefficient of friction as a function of sliding velocity

It is shown in Fig. 6 that for all loads the value of average coefficient of friction were fluctuant and the fluctuant value of 10 N load was higher than that of 30 N load. The highest value of average coefficient of friction is obtained at 10 N normal load, as the sliding velocity increases from 0.52 m/s to 2.09 m/s the value of average coefficient of friction decreases and finally increases at 2.62 m/s velocity. The large fluctuation of the friction coefficient at 10 N load was possibly due to formation of cyclic, localized fracture of a transfer layer of softer material which is of titanium alloy in this case thus indicating that the possible wear mechanism here is three body abrasion. Similar results have been reported by some earlier investigators for ceramic, polymer and metal counter face materials [12].

30 N normal load shows (Fig. 6) the different behaviour than 20, 40 and 50 N load, the value of average coefficient of friction is constant for velocity values of 0.52 m/s to 2.09 m/s but it abruptly increases at 2.62 m/s, the plausible reason for this could be the increase in contact temperature as a result of increase in contact pressure. An aspect common to the entire range of normal loads represented in Fig. 6 is that two of them (i.e. 20 N and 40 N) exhibited transition behaviour for values of average coefficient of friction from decreasing to increasing beyond a critical value of sliding velocity.

The values of average coefficient of friction at 20-50 N load is observed to be very low than at 10 N load, which can be attributed to two reasons: first, the presence of the solid lubricant (carbon in EN-31 steel) contributes in the reduction of the coefficient of friction. The solid lubricant particles get on to the contact surface during the sliding process and reduce the friction. Secondly, the decrease in friction after certain critical temperature has been observed around 882°C for pure titanium [1]. Phase transformation from β-phase of body centred cubic (bcc) to α-phase hexagonal close packed (hcp) crystal structure occurs at this critical temperature. Because of presence of vanadium in Ti-6Al-4V alloy, phase transformation temperature has been lower than 882°C. Also it was reported earlier that the titanium alloy sliding against 440C SS is much more stable at bcc than hcp crystal structure [5]. When the frictional temperature is higher than β transformation temperature, β crystal grows rapidly and plasticity of Ti-6Al-4V alloy is reduced [14]. Therefore the value of coefficient of friction is lower and fluctuant.

3.4. Average coefficient of friction as a function of normal load

Fig. 7 gives the variation of average coefficient of friction for Ti6Al4V as a function of normal load. It is observed that for almost all sliding velocities the average coefficient of friction decreases abruptly after 10 N normal load and from 20 N to 50 N it shows a fluctuating behaviour. Higher sliding velocity (i.e 2.62 m/s) indicate different behaviour possibly due to frictional heating at higher sliding velocity and due to low thermal conductivity of titanium alloy (Ti6Al4V). However, the extremely high value of friction coefficient at maximum sliding velocity for 30 N load can be attributed to the experimental error. In general, the average coefficient of friction decreases as the normal load increases with few exceptions.

3.5. Average wear as a function of sliding distance

The variation of average wear for Ti6Al4V as a function of sliding distance for a sliding velocity of 0.52 m/s is shown in Fig. 8. It is seen that for all the loads the highest average wear is obtained at 40 N and lowest average wear is given for 30 N. The other normal loads (i.e. 10, 20 and 50 N) give the intermediate values of average wear. In general, the average wear increases as
the sliding distance increases for all the loads. The reason for this is that due to the sticking of titanium alloy on the counter face roller, the temperature increases and due to low thermal conductivity of titanium alloy (Ti6Al4V) average wear of sample increases. The trend shown for all loads increase almost linearly; this is true because wear is directly proportional to sliding distance.

Fig. 9 gives the variation of average wear for Ti6Al4V as a function of sliding distance at 1.05 m/s. It is observed that the average wear increases as the sliding distance increases for all the loads. It is also observed that the highest average wear and the lowest average wear are obtained at 40 N and 30 N respectively. The intermediate values of average wear are obtained at normal loads of 10, 20 and 50 N.

It can be clearly seen (Fig. 10) that the average wear increases as the sliding distance increases for all the loads, for sliding velocity of 1.57 m/s. However, the magnitude of wear at corresponding sliding distances in comparison to the sliding velocity of 0.52 and 1.05 m/s is smaller. For all the loads the highest average wear is obtained at 40 N but the lowest average wear is given by both 10 and 30 N. The normal loads of 20 and 50 N give the intermediate values of average wear.

The variation of average wear for Ti6Al4V as a function of sliding distance for 2.09 m/s is shown in Fig. 11. The graph shows an increasing trend of average wear with increasing sliding distance at all loads as in case of 0.52, 1.05 and 1.57 m/s. The magnitude of average wear at corresponding sliding distances are, however, much higher than in case of 0.52, 1.05 and
Among all the loads, the highest average wear is obtained at 50 N and lowest average wear is given by 30 N. The intermediate values of average wear are obtained at normal load 10, 20 and 40 N. Fig. 12 gives the variation of average wear for Ti6Al4V as a function of sliding distance for 2.62 m/s. It is observed that the average wear increases as the sliding distance increases for all the loads. The characteristics shown by this graph are same as shown by graphs in Figs. 8-11. However, the overall average wear magnitudes are observed to be smaller in comparison to 0.52, 1.05, 1.57 and 2.09 m/s at all the corresponding sliding distances. The highest value of average wear is obtained at 50 N and lowest average wear is given by 10 and 20 N. The other normal loads of 30 and 40 N give the intermediate values of average wear.

The disturbance in the order of 30 and 40 N is due to many reasons; at higher sliding velocities contact temperature of the sample and counter face for 30 N may increase which results in increase in average wear in comparison to sample of 40 N. As the thermal conductivity of titanium alloy (Ti6Al4V) is very low (i.e. 6.7 W/m·K), therefore, average wear increases (for samples of 30 N) at higher temperature.

3.6. Analysis of the wear debris

The wear debris collected after sliding friction and wear test were analyzed with the help of profile projector. It was observed that debris of various sizes and shapes have formed during experimentation due to various wear mechanisms such as sliding, fatigue and cutting etc. The average size of biggest wear debris has length of 1.026 µm and width equal to 0.589 µm. Similarly, the average size of medium and smallest wear debris is found to be: Length = 0.711 µm, Width = 0.442 µm and Length = 0.401 µm, Width = 0.341 µm respectively (Fig. 13).

4. Conclusion

In this study, material characteristics such as sliding friction and wear are investigated for titanium grade-5 alloy using multi-tribo tester. The effect of parameters such as sliding velocity, normal load and sliding distance on coefficient of friction and wear rate are evaluated for dry sliding friction and wear during experimentation. Total twenty five (25 Nos.) experiments were conducted to obtain dry sliding friction and wear.

Frictional force (N) and wear (µm) are measured on-line by using Winducom 2008 software linked with multi-tribo tester and the parameters such as coefficient of friction and wear rate (or average wear) are evaluated and analysed to find the effect of sliding velocity, sliding distance and normal load on these parameters. The major conclusions of this study are:

- In general, the wear rate of Ti6Al4V alloy decreases with increasing sliding velocity and decreasing normal load with few exceptions.
- The wear rate of the Ti6Al4V alloy decreases with increasing normal load up to 30 N, then it abruptly increases for a normal load of 40 N and finally decreases at 0.52, 1.05 and 1.57 m/s sliding velocities. 40 N normal load indicated different wear behaviour possibly due to frictional heating at higher sliding velocity.
- The average coefficient of friction was fluctuant and the large fluctuation of the friction coefficient at 10 N load was possibly due to formation of cyclic, localized fracture of a transfer layer of softer material, thus indicating three body abrasion to be the possible wear mechanism.
- In general, the average coefficient of friction decreases as the normal load increases with few exceptions.
- The average coefficient of friction increases as the sliding distance increases for all loads and at every sliding velocity.
- Wear debris of various sizes and shapes were formed during sliding friction and wear. The average length of biggest, medium and smallest wear debris was found to be 1.026 µm, 0.711 µm and 0.401 µm, respectively.

References