

A Study on Wear Behaviour of Laser Direct Metal Deposited High Strength H13 Tool Steel

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Abstract Laser assisted direct metal deposition (DMD) additive manufacturing process provides a realistic opportunity to create solid and porous structures from high strength metallic alloys that can be used as coatings, foams and sandwiched structures and as highly stressed components in contact with other metallic components. Very little studies seem to have been reported on the wear behaviour of parts fabricated by the laser DMD process in relation to various design parameters for various metals. This paper presents an investigation on the sliding wear behaviour of the DMD generated structures of high strength H13 tool steel using the pin-on-disc machine. The structures were machined and finished as pins for subsequent wear testing against a solid disc made of high carbon steel surface. The study includes effect on abrasive wear by variation of several design variables which include contact load, sliding speed and sliding distance. The mode of wear is chosen to be severe which consists of dry wear and speeds near or above 1 m/s. Wear volume and co-efficient of frictions are the two main wear parameters analysed in combination with the primary or design variables. The relationship between the design factors and the ensuing wear loss is discussed which proves the highly non-linear frictional behaviour. The results highlight a wear performance for laser generated H13 specimen that is strong and consistent although inferior to the wear behaviour of wrought tool steels. Despite lack of hot and cold working and any heat treatment, H13 specimens show little signs of micro-chipping and flaking under high loads.

Keywords Direct Metal Deposition, High Strength Tool Steel, Sliding Wear, Co-efficient of Friction

1. Introduction and Background

The term ‘Tribology’ introduced and defined by Peter Jost in 1966 [1] refers to the issues of friction, wear and lubrication when two surfaces come in contact and undergo relative motion with respect to each other. The complex

analysis of dry sliding wear mechanisms of metals, mainly steels are of utmost importance in design of machine elements like bearings, gears and linkages in addition to specialized applications like nuclear reactors [2]. For sliding velocities less than 50 mm/s, the mode of wear is termed as “severe” if the contact pressure between the surfaces reaches a magnitude that can rupture the thin oxide layer at metal interface resulting in direct metal to metal contact [3]. In severe mode, the surfaces become rough and torn with deep scars and the rate of wear is much higher than in “mild” wear which occurs without direct metal to metal contact.

Direct Metal Deposition (DMD) is an additive manufacturing (AM) technique in which metallic structures can be built layer by layer through laser melting of metallic powders and subsequent cladding on a substrate material [4]. The DMD process is essentially similar to fusion welding in which a moving melt pool (under the laser beam) is deposited on the metal substrate while an inert gas stream blows away the redundant powder and at the same time prevents oxidation of the molten deposition [5]. This process has the advantage of a relatively low heat input due to highly focussed laser beam and in fact it significantly reduces the intermixing of clad material into substrate. The added benefit is the minimal undesired deterioration of mechanical properties and distortion of the substrate [6]. The DMD system operates with a wide variety of metallic powders including high strength steels in sizes ranging from 45 to 100 microns. It also possesses the ability to mix metals in more than one ways to create graded and wafer structures [7] or bimetallic structures [8].

Wrought H13 is a martensitic steel alloy that exhibits exceptional hardness, strength and appreciable resistance to corrosion. But since the laser deposition process is thermal and laser tracks are directional, therefore, parts generated from metallic powders do not necessarily possess the same properties as wrought alloys. This paper investigates the surface wear characteristics of laser clad H13 tool steel specimen developed on a DMD system against a mild steel disc as counterface. The analysis is a step towards development of laser clad high strength metallic structures for possible industrial and customized applications;

or in other words to take the DMD process beyond the domain of coating and repair. The experiments were conducted in dry conditions under different conditions of contact pressure and sliding velocities. The calculated and observed parameters include wear volume of H13 pin, frictional force variation with time, surface roughness of pins and the wear scars.

2. Experimental Procedures

2.1. Sample Preparation on DMD

All the specimens were produced on the Precision Optical Manufacturing (POM) DMD machine operating with a CO₂ laser that can generate beam power up to 5 kW. In a DMD process the dimensional accuracy and surface finish of the part depend on the uniformity and repeatability of the clad height and width. Clad height and width are sensitive to variations in a number of process parameters such as powder flow rate (g/min), diameter of laser beam spot (mm), laser power (Watts) and laser scan speed (mm/min). Another variable s_{Focus} determines the beam spot size based on optical controls. The combination of these parameters needs to be optimized and continuously monitored to obtain the desired cladding output [9].

Table 1. DMD Process Parameters

| Parameter | Unit | Value |
|----------------------|---------|---------|
| Laser energy | Watts | 500 |
| Beam (s_{Focus}) | Degrees | -17 |
| Scan speed | mm/min | 30 - 80 |
| Powder feed rate | g/min | 3 - 4 |

The DMD parameters used for preparing H13 specimen for wear testing are shown in Table 1. The parameters were

chosen for minimum power consumption but also for being capable of producing fully dense structures with minimal micro porosity.

The chemical composition of H13 tool steel powder used for preparing DMD specimen is provided in Table 2, which is conspicuous with lesser percentage of chromium and absence of nickel as well as high percentage of iron in comparison to stainless steels. The H13 tool steel powder was supplied by International Australasia Pty Ltd. The substrate used was mild steel with 0.1 – 0.15% carbon, which was previously tested for good compatibility with the clad material.

The wear specimens were cladded as cylindrical pins on the substrate pins of diameter 10 mm and length approximately 35 mm, which enables the substrate to be conveniently held in the arm of wear tester while cladding slides on the mild steel counterface. The cladded parts were turned and faced on lathe to produce a final diameter of 5 mm and length of 4 mm.

2.2. Pin on Disc Wear Tester

The friction and wear tests were conducted on a Koehler Instrument’s pin on disc wear tester. The machine provided the amount of disc wear (volume) and the tangential friction force at the interface versus time of sliding contact. It conforms to ASTM G-99 standard. The cylindrical H13 pin was held rigidly in the arm with its flat face maintained perpendicular to the surface of mild steel disc finished to a diameter of 165 mm. The frictional force during wear test is continuously measured by a beam type load cell while wear is monitored using an LVDT position sensor. The sensed data is transferred to the software through a dedicated controller and data acquisition system. The graphs are dynamically plotted between wear vs. time and frictional force vs. time. The hardware setup and schematics of process used for performing wear tests is shown in Fig.1 below.

Table 2. Chemical composition of H13 tool steel powder

| Element | Iron | Chromium | Molybdenum | Niobium | Manganese | Silicon | Carbon |
|-------------------|---------|----------|------------|---------|-----------|---------|--------|
| Composition Wt. % | Balance | 5 - 7 | 1.5 - 2 | 1 - 2 | 0.4 | 1 | 0.35 |

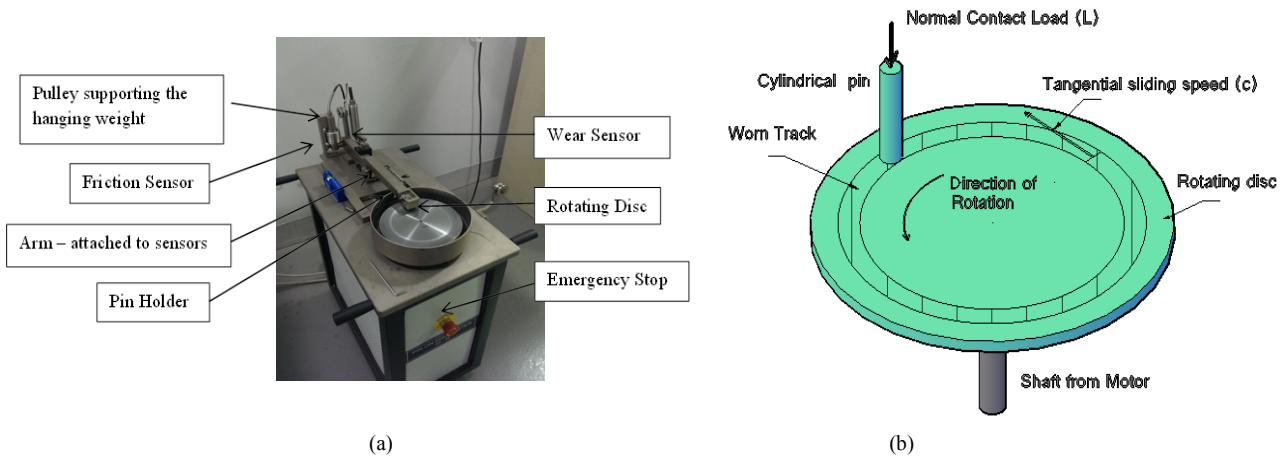


Figure 1. The pin on disc wear tester (a) Hardware setup with labelling of important parts (b) Schematic representation of testing process

During operation the disc is rotated at different speeds while the pin slides on the disc surface under a load applied in a direction normal to the interface between pin and the disc through a pulley supported hanging weight connected to the pin holding arm. As the pin slides on the disc, it forms circular worn tracks with certain amount of materials removed from both pin and the disc depending upon their strength, hardness and surface condition.

2.3. Specimen Properties

In this investigation laser generated H13 pins are tested for sliding wear against a mild steel disc. The pins were roughly turned and faced after laser cladding, while the disc was faced to a finer finish on lathe machine. This configuration is adopted to remove any oxide layer from the surface of pins after laser cladding and encourage *severe wearing mode* as soon as the sliding contact is initiated. The pins were ultrasonically cleaned and the disc washed with ethanol to remove any debris and dust from the surfaces. All the experiments are conducted without any lubricant at room temperature which was maintained between 18 - 22°C.

ASTM G-99 recommends testing of several properties for the pin and disc prior to wear test so that behaviour of materials undergoing sliding friction can be ascertained thoroughly. First is the surface roughness of pin and disc. The surface roughness parameters based on three points test for the machined mild steel disc and H13 pin before wear are presented in Table 3.

Table 3. Surface Roughness Parameters of specimen before wear

| Amplitude Parameters | Mild Steel Disc | H13 Laser Cladded Pin |
|--------------------------------------|--------------------|-----------------------|
| Arithmetic mean roughness (R_a) | 0.89 μm | 1.71 μm |
| Total Profile Height (R_t) | 5.95 μm | 10.3 μm |
| Surface roughness depth (R_z) | 5.11 μm | 8.33 μm |
| Root mean square roughness (R_q) | 1.08 μm | 2.08 μm |

The other important property is hardness which also gives a measure of strength of the specimens. The Vickers microhardness tests were conducted for mild steel disc under 100gf and for H13 pins under 500gf. Overall 5 readings were

taken along two radial directions perpendicular to each other. The obtained average hardness values were 168 HV for the mild steel disc and 459.6 HV for H13 pins. Bressan and Schopf [10] reported a Vickers micro-hardness value of 687 HV for wrought H13 bars available as commercial grade tool steel. In comparison, the hardness of laser cladded H13 is appreciably less, which is understandable because the pins in this research are used in as-cladded condition without any heat treatment and cold or hot working.

3. Results and Discussion

3.1. Friction and Wear Data Acquisition

Investigation is carried out with different contact loads of 19.2, 24.52 and 49.05 N while the sliding distances were varied from 1 km to over 5 km through the combination of disc rpm and the *diameter of wear circle*. The pins were carefully cleaned after wear test and weighed again to determine the mass of material removed due to wear. Dividing mass by the density of H13 tool steel gave the values of pin wear volume. If the environment (dry or wet) and temperature at which experiments are conducted is not varying then sliding speed, sliding distance and contact pressure (normal load) at the interface of pin and disc become the main factors or primary variables to determine and gauge wear parameters [3]. Then the most important investigated or secondary parameters are co-efficient of friction (μ) and wear volume during the period of sliding wear.

Data acquisition software plots the graphs of frictional force as measured by the beam sensors from where corresponding graphs of μ were plotted and analysed. These plots illustrating evolution of μ with respect to time of sliding are presented in Fig 2. In all six set of experiments with repeated readings were conducted and the data for secondary variables in relation to the primary variables is presented in Table 4. The experiments are designated by the letters 'EW' meaning 'experiment on wear' followed by a digit which represents a particular combination of sliding distance, sliding speed and normal contact load.

Table 4. Measured and evaluated friction and wear data for varying primary variables

| Experimental designation | Sliding Distance | Sliding speed | Disc Speed | Contact Load | Wear Volume | Co-efficient of Friction | |
|--------------------------|------------------|---------------|------------|--------------|-------------------|--------------------------|---------|
| | (m) | (m/s) | (RPM) | (N) | (mm^3) | Maximum | Average |
| EW1 | 1272.1 | 0.706 | 150 | 49.05 | 2.577 | 1.348 | 0.865 |
| EW2 | 2261.52 | 0.942 | 150 | 49.05 | 3.718 | 1.409 | 0.841 |
| EW3 | 2638.44 | 1.099 | 150 | 19.62 | 2.782 | 1.682 | 0.781 |
| EW4 | 3806.13 | 1.109 | 200 | 24.52 | 2.115 | 1.695 | 0.963 |
| EW5 | 4899.96 | 2.041 | 300 | 49.05 | 4.769 | 0.607 | 0.437 |
| EW6 | 5276.88 | 2.198 | 300 | 19.62 | 0.115 | 1.332 | 0.846 |

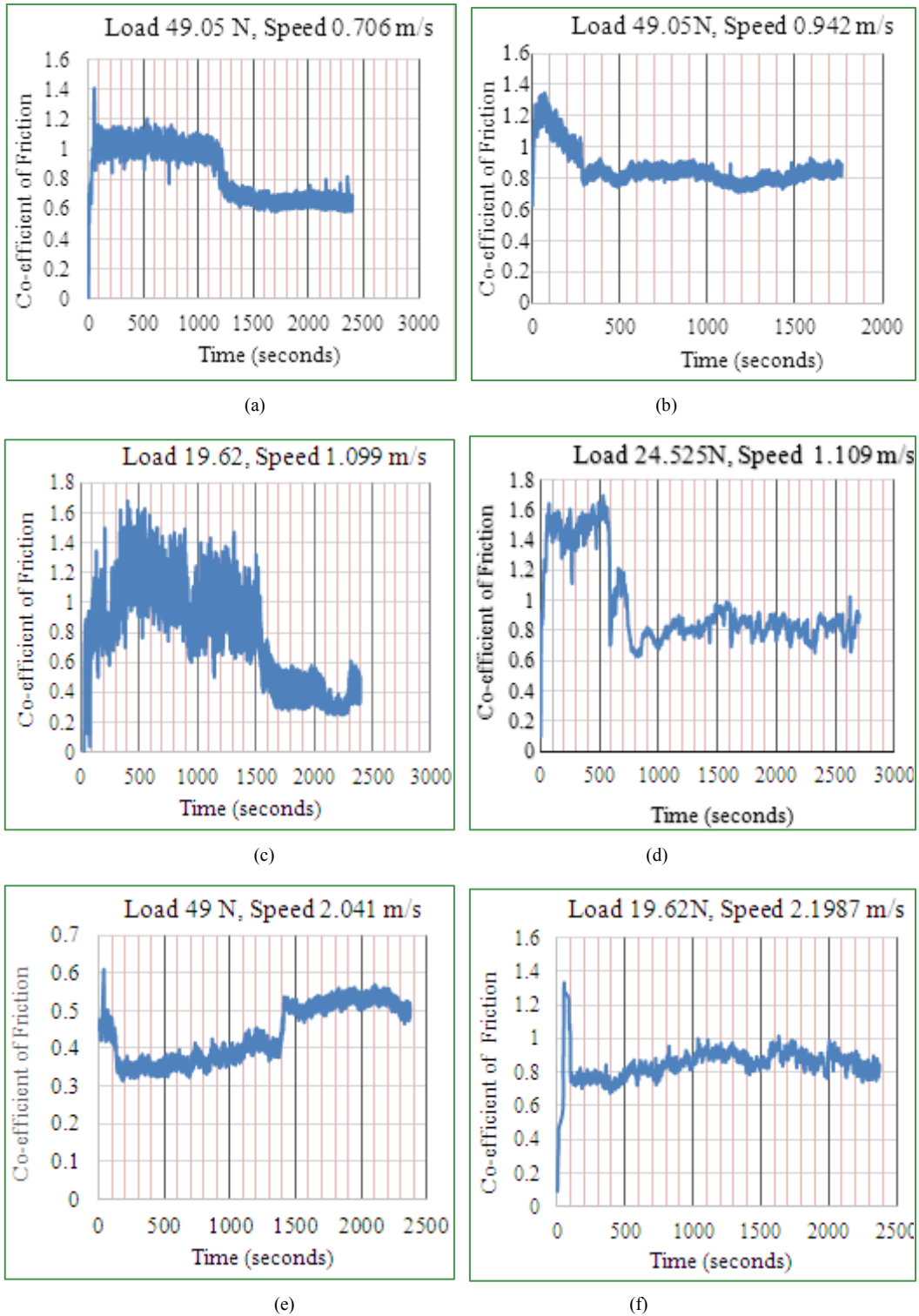


Figure 2. Evolution of co-efficient of friction with time for sliding wear as per data set in table 4

3.2. Coefficient of Friction (μ)

Although the value of co-efficient of friction (μ) is assumed to be constant for a set of given materials, but in fact its value varies over a wide range depending upon the sliding speeds, condition of the surfaces and the contact pressure [11]. The maximum and average values of μ are given in

table 4 which reveals a high degree of variation in its recorded values. Important noticeable points from the data in Table 4 and graphs of Fig. 2 are presented as follows:

- i. The maximum spikes in values of μ are observed at low loads and lower sliding speeds. This is due to the less energy available to shear the interlocking asperities between the sliding surfaces and thus more resistance to

- motion. Blau [12] also reported decrease in the value of μ with increasing contact load (normal forces) while investigating sliding friction of AISI 440C stainless steel against the Ni_3Al alloy.
- ii. Maximum oscillation in the graphs of μ is associated with low contact load and high sliding velocity as shown in Fig 2(c). This is due to the fact that sufficient bumping takes place when two rough surfaces with less holding pressure slide past each other at high speeds. Reduction of oscillation in the plot of μ can be observed clearly in Fig 2(d) when the load is increased from 19.62 N to 24.52 N at nearly the same sliding velocity.
 - iii. For speeds greater than 2 m/s, the value of μ becomes stable after initial spike of 1.332 for low contact loads as illustrated in Fig 2(f). This represents the behaviour in which rapid sliding motion overcomes the asperities and roughness of surfaces in the beginning stages.
 - iv. Heavy contact load with appreciable slower speeds (<1 m/s) also induces a behaviour in which μ shows a more or less constant value after an initial spike. At lower speeds, a distinct step is observable, as in Fig 2(a), showing decrease in co-efficient of friction from 1.0 to 0.7 after approximately 1 km of sliding distance, while at a relatively higher sliding speed, as in Fig 2(b), μ keeps on oscillating about a mean value of 0.8. It indicates that the effect of normal forces in reducing roughness of the sliding surfaces is more pronounced at lower speeds.
 - v. The combined effect of high load and high speed results in the lowest values for coefficient of friction as shown in Fig 2(e). But the interesting behaviour observed is that the value of μ increased from 0.4 to 0.55 after 1.2 km sliding. This may be due to ploughing effects of pin into the disc surface, a behaviour aided by the presence of high contact pressure.
 - vi. With respect to the sliding distance, the value of μ tends to get slightly lower, which is due to burnishing of rough surfaces exposed to each other for longer periods of time. But it appears that for strong materials like steels sliding distance is not a significant factor in

comparison to sliding speed and contact load.

The high difference between minimum and maximum recorded values of coefficient of friction (0.25 to 1.69) with the sliding speed and contact pressure clearly indicates that the frictional behaviour of steels in sliding contact is highly vulnerable to numerous factors and can never be assumed as fixed or even completely defined. There are many other factors like temperature changes during wear and stiffness of the measuring setup which could affect the values for μ even under steady state operation.

3.3. Wear Volume

Since the H13 pins tested for sliding wear under severe conditions are laser generated and they are neither wrought type nor heat treated, it is very important to estimate the volume lost from their bulk after every experiment. Based on Table 4, variation of wear volume with sliding speed and contact load is illustrated in Fig 3. The values are plotted as a line graph with wear volume represented in $\text{mm}^3/100$ and sliding speed in $(\text{m/s})/10$. The scaling is necessary to elucidate the values of wear volume with respect to disc speed and contact load.

Experiment Number 5 (EW5) represents the highest wear volume value of 4.769 mm^3 as it pertains to maximum load and nearly highest values of sliding speed and distance. On the other hand, EW6 shows the lowest wear volume value of 0.11538 mm^3 for the minimum load but it shows the highest values of sliding speed and distance. This difference is self-explanatory but the fact which proves frictional behaviour as highly non-linear is that at a slightly higher load and reduced speed for data in EW4, the wear volume increases from 0.11538 to 2.115 mm^3 even though the sliding distance is reduced by about 1.4 km. Similarly at equal load by reducing the sliding speed and distance by nearly a magnitude of half, the reduction in wear volume is only 22%; a fact highlighted by data comparison of EW4 and EW2.

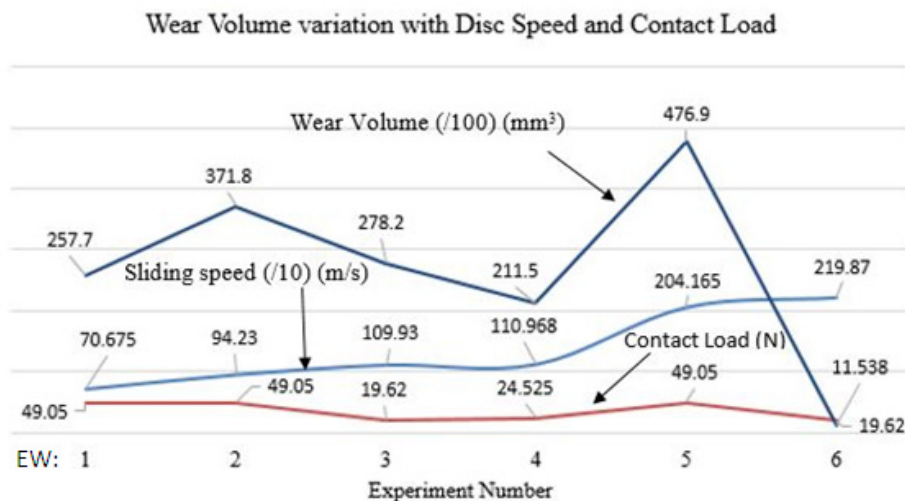


Figure 3. Wear volume variation of H13 pins for experiments EW1 to EW6 with respect to sliding speed and contact load

4. Condition of Worn Pins

The laser generated H13 pins undergo severe abrasion and wearing particularly when tested under high load (49.05 N) and low disc speed (150 rpm). For such conditions the surface roughness measurement gives the parameters as shown in Table 5.

Table 5. Surface Roughness Parameters of H13 pin under severe wear

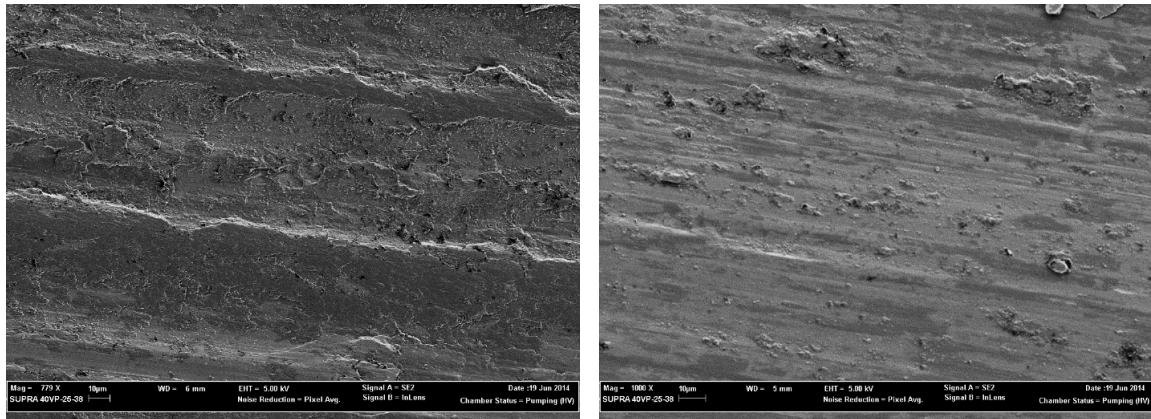
| Amplitude Parameters | Values |
|--------------------------------------|--------------------|
| Arithmetic mean roughness (R_a) | 4.89 μm |
| Total Profile Height (R_t) | 32 μm |
| Surface roughness depth (R_z) | 24.1 μm |
| Root mean square roughness (R_q) | 5.9 μm |

Compared with the values of pin roughness given in Table 3 (before wear), it can be easily observed that the surface roughness of the pin is increased many times. Particularly noticeable is the value of R_z which increased from 8.33 to 24.1 μm . This fact is further illustrated when the surfaces of worn H13 laser generated pins were ultrasonically cleaned and viewed with a scanning electron microscope. The wear

scars generated due to sliding friction and wear are easily recognizable on the pin surfaces. The wear mechanism is quite similar to the wear of laser hardened carbon steels as mentioned by Sridhar et al [13]. The configuration of wear predominantly consists of oxidation of the contact surface of the pin with micro-ploughing of the disc surface leading to removal of the oxides from the surface and the metal subsequently.

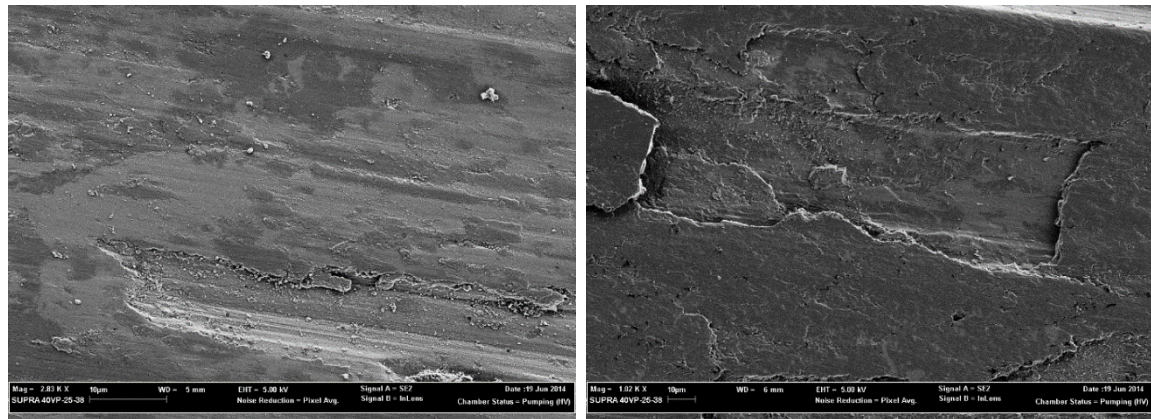
Fig. 4 highlights the difference between the conditions of surfaces of pins worn under different contact loads. The deep scars showing ploughing of the surface is clearly visible in Fig 4(a) for 49.05 N load and low speeds while deep scars are visible in Fig 4(b) for the pin surface subjected to 19.62 N load and same tangential speed.

When the sliding or abrasion wear takes place under severe conditions, there is strong possibility of material being gouged and flaked from the rubbing surfaces. Fig 5 (a) presents the ploughing and gouging effect at a magnification of 2.83k while Fig 5(b) illustrates the flaking of H13 pin surfaces magnified 1.02k times when subjected to wear tests under high contact loads.



(a) (b)

Figure 4. SEM micrographs of worn pins (a) Contact Load 49 N and 150 rpm (x779) (b) Contact Load 19.62 N and 150 rpm (x1000)



(a) (b)

Figure 5. SEM micrographs of worn pins under high contact load (a) Ploughing (b) Flaking

5. Conclusions

In this study, the values of two wear parameters namely co-efficient of friction and pin volume lost due to wear were carefully monitored and analysed against the two most important primary variables of sliding wear, which are sliding speed and contact load, at the interface of pin and disc. The results show that the values of co-efficient of friction plotted as graphs with respect to time of sliding have large variations, and this behaviour is found to be compatible with that of sliding wear of steels already published in the literature. The possible causes of frictional behaviour have been examined in combination with the primary variables to ascertain the wear characteristics of the system. The analysis of wear volume loss for different data sets also strengthens the fact that sliding wear is a highly non-linear phenomenon and must be viewed as a system behaviour which may also include stiffness of the system used for performing the experiment. Upon examining the roughness profiles before and after wear and the SEM micrographs of worn pin surfaces, it appears that the wear characteristics of laser clad H13 is inferior to the wrought and heat treated tool steels. However, the overall performance of laser generated tool steel is highly satisfactory particularly due to the fact that these materials are tested with no post-cladding treatment that can augment its strength and hardness.

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