Wear of SLS Materials under Plastic and Elastic Contact Conditions

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Abstract

Sliding wear behaviour of two SLS materials: LaserForm and DirectSteel has been investigated using Fretting tests, Pin-on-disc tests and microfretting tests. Wear test conditions were determined by calculating Hertzian pressure for various loading conditions, and wear tests were performed under both plastic and elastic contact conditions. Wear analysis was subsequently done to find out the wear resistance of materials. The wear volumes are presented against applied loads and dissipated energies. It has been found out that LaserForm is better than DirectSteel and there is no clear relation between hardness and wear resistance of materials.

Key words: : Selective Laser Sintering (SLS), Wear, LaserForm, DirectSteel

1 Introduction

Selective Laser Sintering (SLS) is an established technique for rapid prototyping and is rapidly growing as an efficient mean for realizing rapid manufacturing and rapid tooling [1]. It allows to manufacture products from metals, ceramic and polymers. One of the properties which has got yet insufficient attention from development engineers and scientists is the surface strength of produced parts as the attention has been mostly directed towards the development of porosity-free products furnishing highest possible strength. The surface properties which are of vital interest for rapid tooling/manufacturing is the wear resistance of products as wear rate is critical in certain application such as moulds, cutting tools, bearings, gears, biomedical implants [1,2].

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In order to fill the void, commercial SLS powders with promising tribological or wear properties have been introduced. The present investigation is concerned with the evaluation of wear properties of two commercial powders: LaserForm^{TM} (LF) and DirectSteel^{TM} (DS) [3].

2 Materials and Processing

2.1 LaserForm (LF)

LaserForm ST-100 is a polymer coated steel powder of average size 100 μm supplied by 3D Systems to be processed on SLS Sinterstations. The steel powder contains Cr- 12-14%, Mn- 1%, Si- 1% and the rest iron. These steel grains are coated with a proprietary organic binders containing less than 0.1% formaldehyde and phenol. The powders have been processed using following fabrication parameters: Laser Power- 12.5 W, Layer Thickness- 80 μm, Scan Spacing- 80 μm, Scan Speed- 1680 mm/sec and Spot Size- 600 μm.

The laser-sintered parts were debinded (polymer burn out) and infiltrated with bronze in an oven according to manufacturer's recommendations [4]. Oven cycle used for infiltrating consists of three steps [5]: debinding of polymers at 450 to 650°C, sintering of remaining steel after polymer burn-out at about 700°C, and infiltration of part at approximately 1050°C. The final composition of the part is about 60 % steel and 40 % bronze. The microstructure of infiltrated LaserForm sample is given in Figure 1.

The final parts have characteristics similar to P20 steel: hardness of 83.4 HRB, density 7.7 g/cm^3, Young's Modulus 137 GPa, Tensile yield strength 305 MPa,

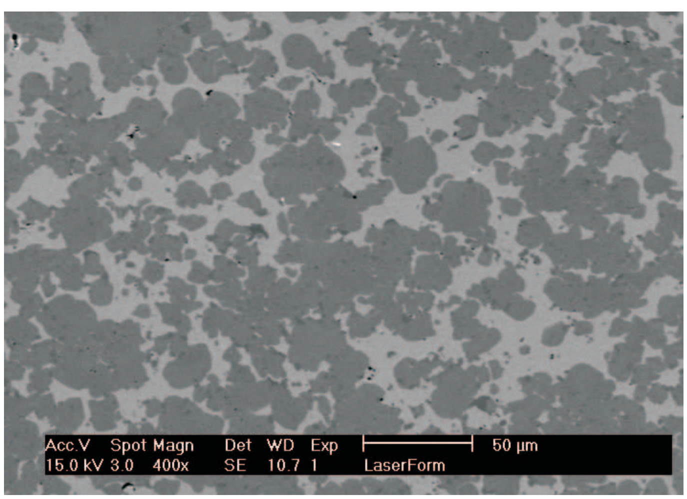


Fig. 1. Micrograph of infiltrated LaserForm

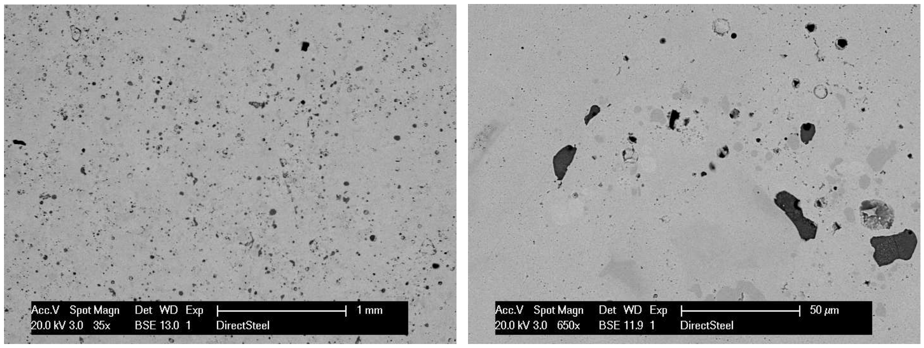


Fig. 2. SEM Micrographs of DirectSteel

Compressive yield strength 317 MPa and ultimate tensile strength 510 MPa.

2.2 DirectSteel (DS)

DirectSteel 20 V1 is a powder of average size 20 μm supplied by the company EOS. It consists of Fe 60%, Ni 31% and Cu_3P 9%, C 0.08%. Parts tested here were manufactured using a skin and core scanning strategy by a laser sintering machine EOSint M 250 Xtended equipped with a CO_2 laser. In this strategy, the outer skin of the parts is processed with higher laser energy density to make the surface denser and stronger in comparison to the core. Fabrication parameters used were: Layer Thickness 20 μm (skin) and 40 μm (core), Laser Power 20 W, Spot Size 300 μm, Hatching Distance 200 μm (skin) and 300 μm (core), Scan Speed- 255 mm/s (skin) and 111 mm/s (core).

Figure 2 shows microstructures of DirectSteel at different magnifications which depict the presence of pores (black spots and zones) in a DirectSteel sample.

The stated properties of the laser sintered materials are: density (skin) 7-7.6 g/cm^2, density (core) 6-6.3 g/cm^2, hardness 89.6 HRB, Young's Modulus 130 GPa and Ultimate tensile strength 600 MPa. The tensile/compressive yield strength of DirectSteel has been estimated to be 400 MPa.

3 Experiments

Wear tests have been done under plastic and elastic contact conditions mainly with a fretting (bidirectional sliding) test machine and a pin-on-disk (unidirectional sliding) test machine. The plastic contact conditions were determined by calculating the Hertzian pressure for various combinations of applied load and diameter of the counterbody ball. The details of Hertzian pressure are given below.

Material	Young's Modulus (GPa)	Poisson's ratio	Compressive yield strength (MPa)
Corundum	320	0.28	
LF	137	0.30	317
DS	130	0.30	400

Table 1
Young's Modulus, Poisson's ratio and Compressive yield strength of materials used in wear testing

3.1 Hertzian Pressure

For determining the applied experimental load to be used, Hertzian pressure (P) was calculated using following equations 1, 2, 3 and 4 that apply for a ball-on-flat contact model between isotropic, ideally elastic materials with perfectly smooth surfaces. The contact area induced by normal load F has a circular periphery with a Hertzian radius a. In equations 2, R is the radius of the ball counterbody and E is the Young's modulus which is calculated from equation 3 consisting of Young's moduli E_1, E_2, and Poisson's ratios v_1, v_2 of the ball and flat specimen, respectively. P_0 (eqn 4) is the maximum value of contact pressure P at the centre of contact circle [6].

$$P = \frac{F}{\pi a^2} \tag{1}$$

$$a = \left(\frac{3FR}{4E}\right)^{\frac{1}{3}} \tag{2}$$

$$\frac{1}{E} = \frac{1-(v_1)^2}{E_1} + \frac{1-(v_2)^2}{E_2} \tag{3}$$

$$P_0 = \frac{3}{2}P \tag{4}$$

For calculating Hertzian pressure, material properties as given in Table 1 were used.

4 Experiments under Plastic Contact Conditions

The maximum Hertzian pressure (P_0) calculated for both materials at various loads is given in Table 2. For the tests considered here (i.e. alumina ball of 10 mm diameter), the max. Hertzian pressures (P_0) thus obtained are all of higher magnitude than the (compressive) yield strength of material (see Table 1). This indicates that both materials would be subjected to plastic deformation

Material	E (Pa)	F (N)	a (μm)	P_0 (MPa)	Yield strength (MPa)
LF	1.05E+11	2	41.5	555	317
LF	1.05E+11	4	52.3	699	317
LF	1.05E+11	6	59.8	801	317
LF	1.05E+11	8	65.9	881	317
DS	1.01E+11	2	42	542	400
DS	1.01E+11	4	52.9	682	400
DS	1.01E+11	6	60.7	781	400
DS	1.01E+11	8	66.7	860	400

Table 2
Maximum Hertzian pressure calculated for both materials

during the wear tests under all given loads selected for experimentation.

4.1 Fretting (Bidirectional Sliding) Test

Fretting is a wear phenomenon occurring when two contacting solids are subjected to a relatively oscillatory tangential motion of small displacement amplitude [7]. Fretting can be applied by (1) keeping the counterbody fixed and linearly vibrating the specimen, (2) keeping the specimen fixed and linearly vibrating the counterbody. In the present case, type 1 has been adopted. A counterbody of 10 mm diameter corundum ball and of surface roughness 0.02 μm is placed against a flat polished specimen of roughness 0.05 μm for testing. The specimen is mounted on a translation table which can be oscillated by a stepping motor. The displacement of the specimen is measured by an inductive displacement transducer and the friction force is measured with a piezoelectric transducer. The friction coefficient and total dissipated energy are calculated from the on-line measured tangential force [8].

Experimental parameters were selected on the basis of some preliminary tests keeping in view the feasible parameters to be applied to another wear test method (Pin-on-disk test). The criteria for selection was to choose almost equivalent parameters in both test methods so that the results could be compared. The details of the experimental conditions are given in Table 3. Tests were done at various loads and various durations. The amplitude and frequency of oscillation as well as environmental conditions were kept constant for all experiments.

Quantity	Magnitude
Amplitude	100 μm
Frquency	10 Hz
No. of cycles	2000, 4000, 6000, 8000, 10000
Applied loads (N)	2, 4, 6, 8
Temperature	25°C
Humidity	52%

Table 3
Experimental parameters for fretting tests under plastic contact conditions

4.2 Results Obtained from Fretting Tests

The coefficient of friction (COF) for each experiment was evaluated on-line while wear volume of the fretting pit was obtained by the principle of white light interferometry using a WYKO device. The wear volumes obtained after each experiment are plotted in Figures 3 and 4 for LaserForm and DirectSteel materials, respectively. The figures show that the wear volume increases with the number of cycles for both materials. However, the rate of increase is higher in case of DirectSteel compared to LaserForm. It has also been found that at the highest applied load (8 N), the rate of increase of wear for LaserForm is significantly higher. With an increase in load, wear volume for LaserForm increases as expected, while in the case of DirectSteel, it increases with load from 2 to 6 N but decreases at load 8 N. The decrease could be attributed to the presence of about 12% of low melting point component Cu_3P (m.p 714°C) in DirectSteel. At higher load 8 N, friction between counterbody and DirectSteel generates enough heat to melt partially DirectSteel giving rise to non-removal of wear debris from the wear zone and consequently a decrease in wear volume. Comparison of wear volumes for all materials at various applied loads 2 N, 4 N, 6 N and 8 N are demonstrated in Figures 5 and 6, respectively. Figures 5 and 6 for lower loads 2 N, 4 N and 6 N show that wear in DirectSteel is always more than that of LaserForm. The difference in their wear rate is more pronounced at higher number of cycles for a given load. Though DirectSteel has higher hardness than LaserForm, it wears more than LaserForm showing that there is not always a direct relation between hardness and wear resistance of materials. Above-mentioned figures state that LaserForm has more wear resistance than DirectSteel. However, at a load of 8 N as shown in the lower side graph of Figure 6, the wear resistances of the two laser-sintered materials give opposite trends and LaserForm is found to have less wear resistance than that of DirectSteel.

In order to understand and explain the opposite trends obtained, wear volume was correlated with the energy dissipated for causing the wear. For this, the

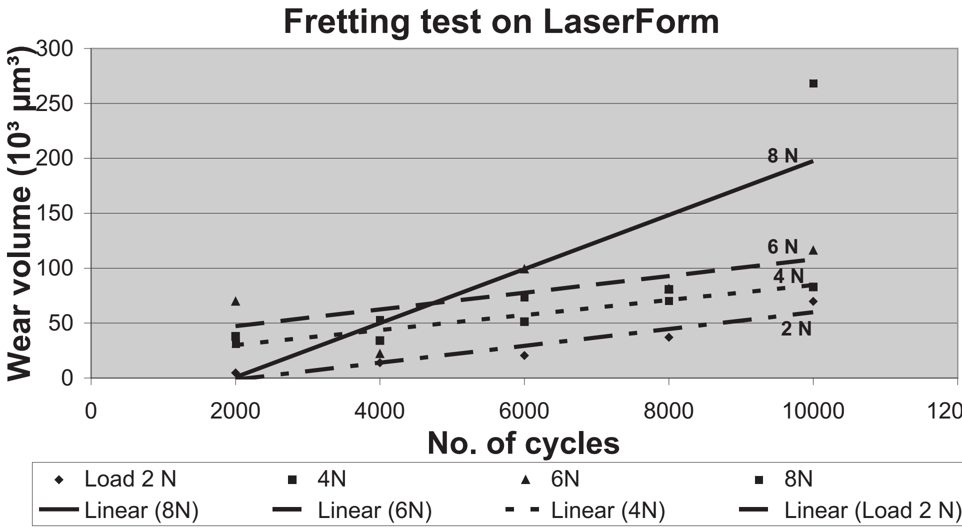


Fig. 3. Variation of wear volumes for LaserForm after fretting test

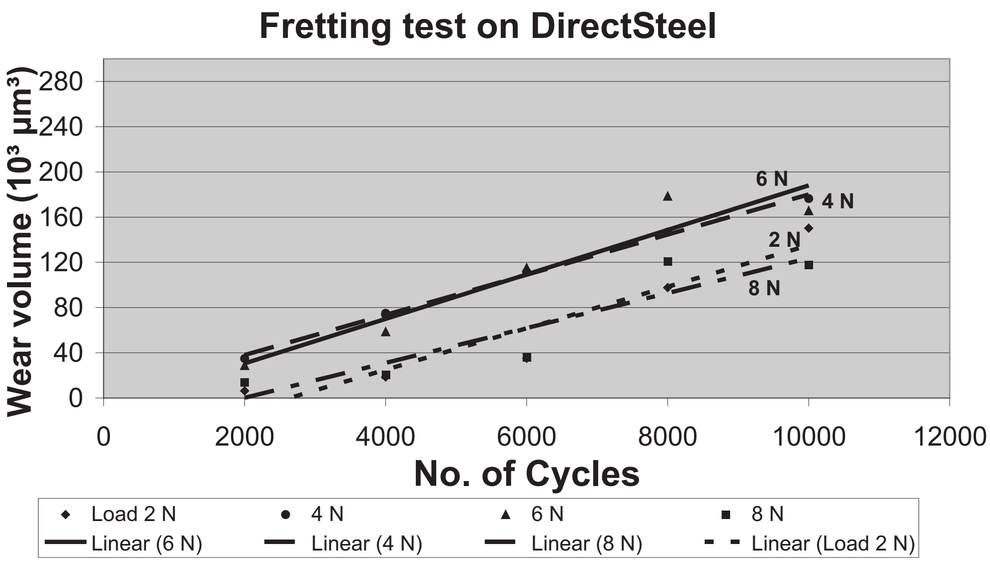


Fig. 4. Variation of wear volumes for DirectSteel after fretting test

total dissipated energy which is on-line recorded and is equal to the sum of the product of tangential force and linear displacement in a displacement loop is taken into account [9]. The wear volume for both LaserForm and DirectSteel plotted against cumulative dissipated energy is shown in Figure 7. The figure shows that at low dissipated energy which corresponds to low applied load, the wear volume of LaserForm is less than that of DirectSteel and it agrees well with the trend obtained in Figure 5 and the upper side graph of Figure 6, while at higher dissipated energy which corresponds to higher applied load, the wear volume of LaserForm is very high and it certainly does not behave as well as it did in case of low dissipated energy. At higher dissipated energy, there is a no corresponding point for DirectSteel. By extrapolation, it becomes clear that the wear volume of LaserForm is more than that of DirectSteel. This result is also clear from the lower side graph of Figure 6 demonstrating the comparison of wear volume at load 8 N.

From Figure 7, low dissipated energy comes to be less than 2.24 joule. However, how much applied load could be called 'low' and would give rise to low dissipation energy is not identified quantitatively. Nevertheless, it gives a relative description of the occurred phenomena. The COF obtained was not taken into account for making any inferences as they showed an erroneous trend of decreasing to lowest values (0.1 or 0.2) with increasing applied load.

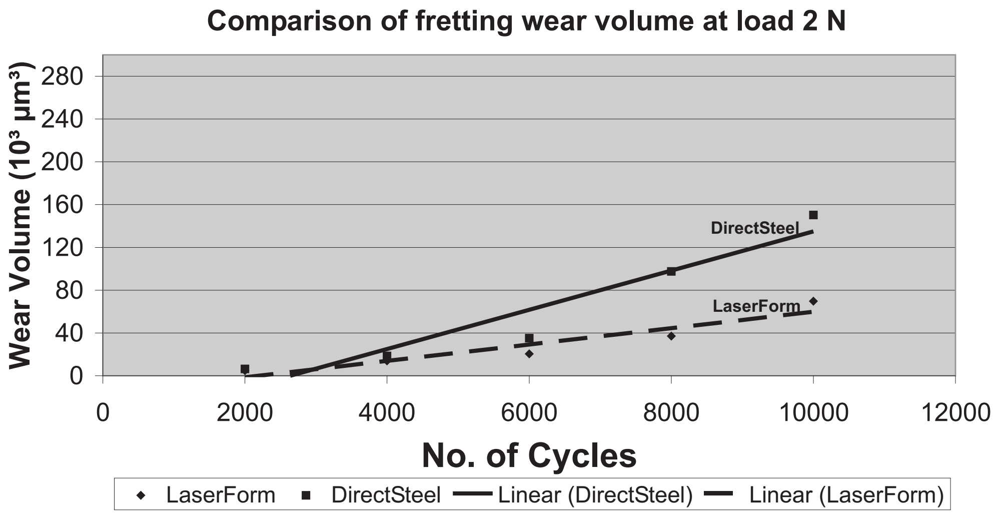
4.3 Pin-on-disk (Unidirectional Sliding) Test

A Pin-on-disk (POD) test is a unidirectional sliding wear test in which a counterbody in the form of pin or ball is pressed at a certain load to a disk which is rotated at a certain velocity for a definite time to assess the wear resistance of the disc materials by measuring the wear depth created on the disk [10].

Experimental conditions selected were limited by material strength, number of specimens and the test apparatus. Maximum applied load was selected in such a way that it could not cause excessive wear. Much wear also means wider wear tracks which limit the maximum number of wear tracks that could be made on a given specimen. Economizing the number of specimens for POD tests was also an aim as sample preparation by SLS for a POD test was not as convenient as for fretting tests. Minimum applied load was chosen such that it could make a measurable track. The test apparatus also has its limitations as the maximum rotational speed that could be given to the disk is 400 revolutions/minute. It restricts the maximum speed determined for experimentations. Besides, higher speeds may cause vibration between ball and disk resulting in non-uniform tracks. Thus, the maximum speed selected was 1 m/s. The experimental parameters and conditions used are given in Table 4. The counterbody ball used was same as that used earlier for fretting tests i.e. a 10 mm diameter alumina ball. As a POD test is also a ball-on-flat type test, the Hertzian pressures calculated for fretting tests (ball-on-flat type model) were also applicable in this case.

4.4 Results Obtained from POD Tests

After wear tests, wear tracks were observed and the amount of wear was measured by selecting an area of the track and assessing its depth with the help of a WYKO white light interferometer. The wear volume thus obtained



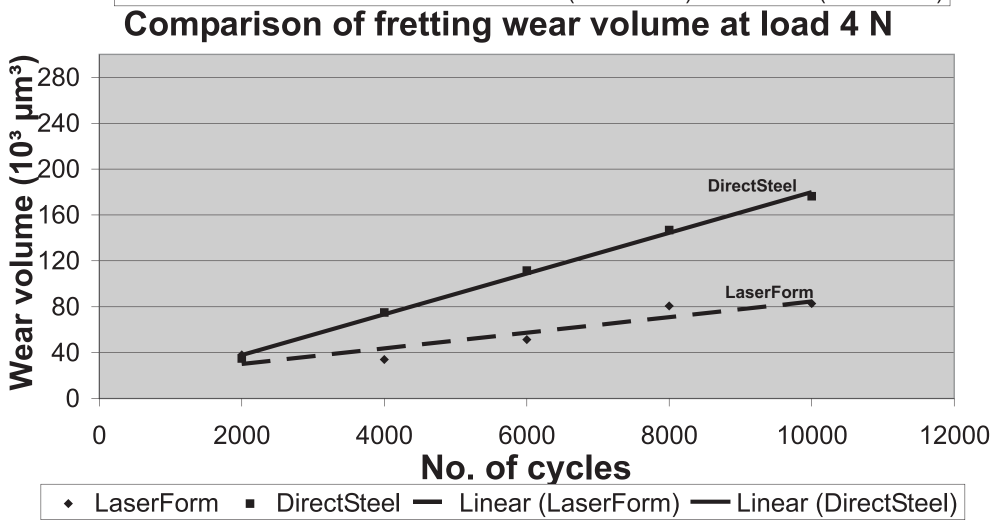
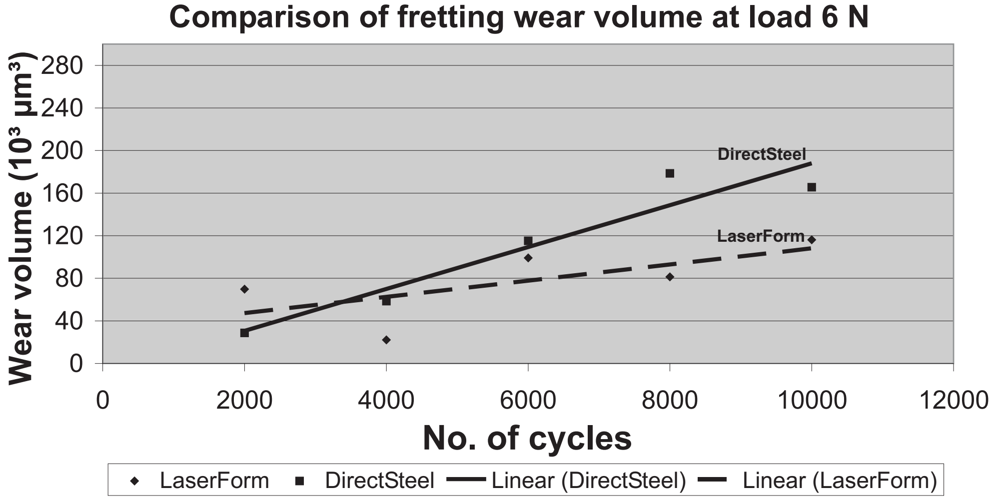


Fig. 5. Comparison of wear volumes for tested materials after fretting at load of 2N (upper figure) and 4N (lower figure)

Quantity	Magnitude
Applied load (N)	1.96, 3, 5.84, 7.8/8.81
Speed (m/s)	0.2, 0.4, 0.6, 0.8, 1
No. of revolutions	2000/10000
Sample size	60 mm diameter, 7 mm thick
Temperature	25°C
Humidity	52%

Table 4
Experimental parameters and conditions for Pin-on-disk tests



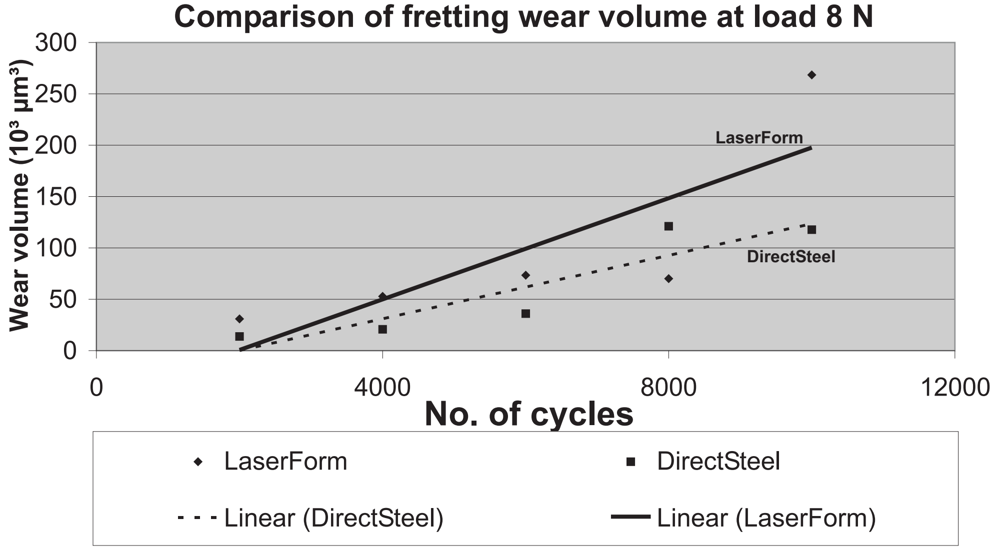


Fig. 6. Comparison of wear volumes for tested materials after fretting at load of 6N (upper figure) and 8N (lower figure)

was used to find the dimensional wear constant k which is given by Archard's wear equation shown by equation 5.

$$k = \frac{K}{H} = \frac{W}{D.N} \tag{5}$$

Where K, H are a wear coefficient and the material hardness, respectively. While W, D and N denote wear volume, sliding distance and applied load, respectively. k has units of Pa^{-1} but is quoted in terms of wear volume per unit load per unit sliding distance, unit $mm^3N^{-1}m^{-1}$ [11].

Depending on various positions of ball relative to the centre of disk, tracks of various diameters were made. This also determined the rotational speeds (given in revolution/minute) of the disk. The sliding distance covered has been

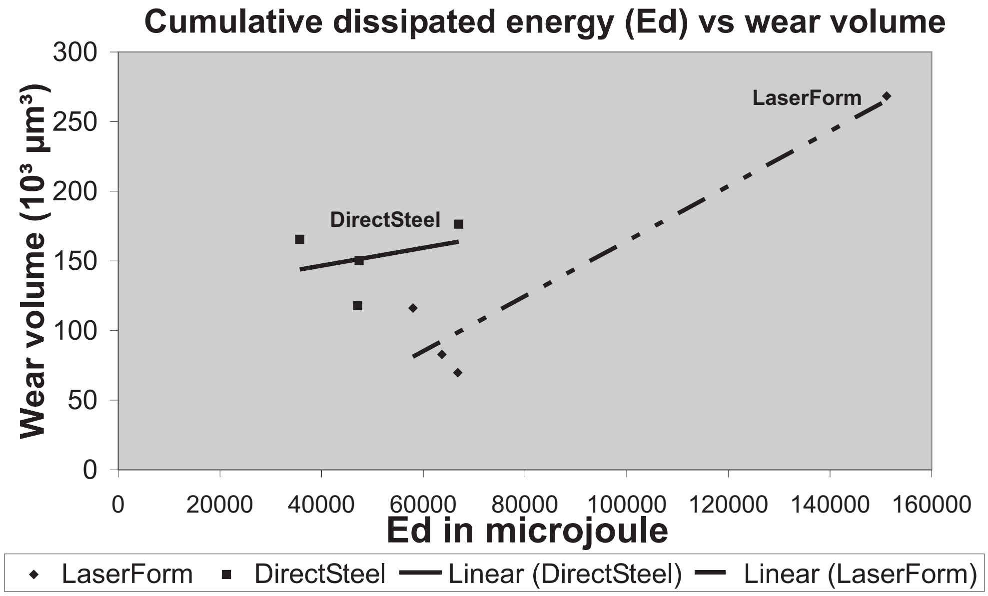


Fig. 7. Cumulative dissipated energy vs. wear volume for LaserForm and DirectSteel after fretting tests

calculated from the values of diameter, rotational speed and the number of revolutions for each experiment.

In order to find out the effect of applied load on the dimensional wear constant, mean dimensional wear constant has been calculated by summing up all the values of dimensional wear constants for a given load and dividing it by the number of values taken. Mean dimensional wear constants are given in Table 5 and plotted in Figure 8. The figure shows that with an increase in applied load, wear of both material increases. However, the wear in LaserForm is significantly higher than that in DirectSteel. It illustrates clearly that the wear resistance of LaserForm is the lower. It gives a linear relationship between hardness of the material concerned and its wear resistance for pin-on-disc tests: the harder the material, more is its wear resistance. For getting energy-dependent information from the wearing system, a new quantity referred to as ”approximate dissipated energy” (E) is contemplated. It is given by the product of Coefficient of Friction (COF), distance covered during wearing (D) and applied load (N), and is shown by equation 6. The equation does not give an exact dissipated energy as the COF is not constant but changes with distance. However, it gives an overall estimation that could be used for comparing different materials or processes.

$$E = COF.D.N \tag{6}$$

The Coefficient of Friction (COFav.) along with its standard deviation for all

Material	Applied load (N)	mean $k.10^3$
LF	1.96	119.396
LF	3	842.358
LF	5.84	1005.1
LF	7.8	935.57
DS	1.96	32.98
DS	3	72.12
DS	5.84	204
DS	7.8	361.71

Table 5
Mean Dimensional wear constants obtained for both materials after POD test

Material	speed (m/s)	Load (N)	COF (av.)	Dissi. energy (J)	$W.10^6 \mu m^3$
LF	0.1	1.96	0.707	2609.53	81.50
LF	0.2	7.8	0.550	808.624	822.92
DS	0.2	1.96	0.665	294.66	9.14
DS	0.2	7.8	0.766	1426.32	195.20

Table 6
Wear volume and dissipated energy for LaserForm and DirectSteel at lowest and highest applied loads

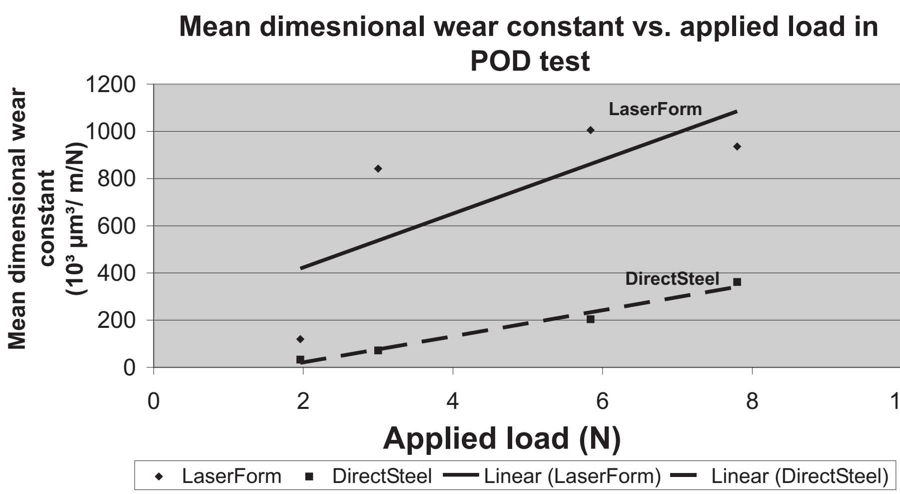


Fig. 8. Mean dimensional wear constant vs. applied load after POD tests

materials have been observed. In order to emphasize the difference in COF obtained, only COF obtained for lowest and highest loads have been taken into account for calculation. Besides, the COF obtained only at lower sliding

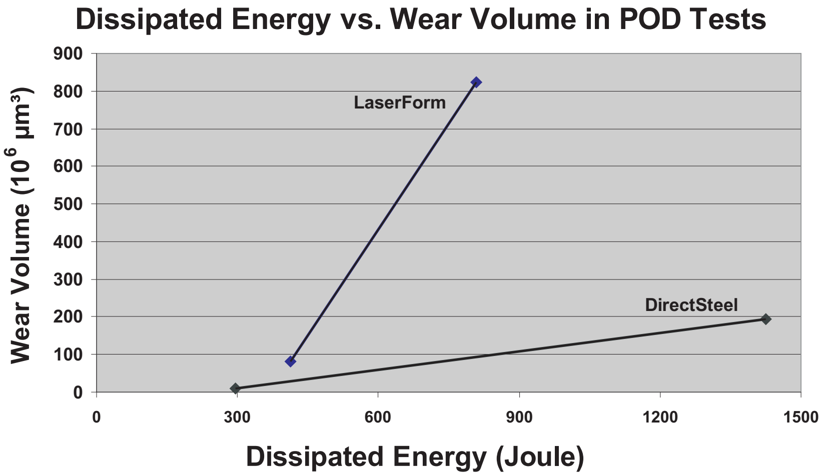


Fig. 9. Dissipated energy vs. wear volume after POD tests

speed is considered.

The dissipated energy has been calculated using the equation 6 and is given in Table 6 for all materials at selected extreme parameters. Wear volume is plotted against dissipated energy as shown in Figure 9 for LaserForm and DirectSteel. The Figure 9 shows an increase in wear with an increase in dissipated energy. The wear in case of LaserForm is far more than that of DirectSteel. This result is in agreement with earlier results which show an increase in wear with an increase in load for all materials (see Figure 8).

4.5 Discussion

Both wear tests i.e. fretting test and POD test are used for evaluating different types of wear phenomena. The wear and surface fracture mechanisms for both tests are different. However, both tests could be interrelated as the wear in both processes are dependent in part upon the total energy supplied to the mutually interacting systems. The dissipated energy determined and the amount of wear (wear volume) caused by the dissipated energy, which are plotted in Figures 7 and 9 for fretting test and POD test, respectively, could, independent of the test procedure, be used for comparing wear resistances of materials.

Figure 7 shows the energy dissipated vs. wear volume for fretting tests. It shows that at low energy (less than 2.24 joule), wear resistance of LaserForm is better than that of DirectSteel while at higher dissipated energy, wear resistance of Directsteel is better than that of LaserForm. Figure 9 which has been plotted for POD tests shows clearly that the wear resistance of DirectSteel is always better than that of LaserForm.

As dissipated energy in case of fretting test and POD test are of the order of joule and kilo joule, respectively, as shown by the energy axis of the Figures 7 and 9, respectively, considering both figures concurrently, it is clear that at low dissipated energy, wear resistance of LaserForm is better while at high dissipated energy DirectSteel is better.

5 Experiments under Elastic Contact Conditions

In order to have lower Hertzian pressures than the yield strength of the materials, a chrome-steel ball (composition- C- 0.98 to 1.1 %, Cr- 1.3 to 1.6 %, Mn- 0.25 to 0.45 %, Si- 0.15 to 0.35 %, S- 0.025 % max., P- 0.025 % max.) with a diameter of 30 mm was used. The mechanical properties of chrome-steel ball are: Young's Modulus- 203.4 GPa, Tensile Strength- 2.24 GPa, Yield Strength- 2.03 GPa.

The Hertzian pressures calculated using equations 1, 2, 3 and 4 for balls of 30 mm diameter made from chrome steel are given in Table 7.

Material	E (Pa)	a (μm)	F (N)	P_0 (MPa)	Yield strength (MPa)
LF	0.89E+11	63.0	2	241	317
LF	0.89E+11	79.4	4	303	317
LF	0.89E+11	90.9	6	347	317
LF	0.89E+11	100.0	8	382	317
DS	0.87E+11	63.7	2	236	400
DS	0.87E+11	80.2	4	297	400
DS	0.87E+11	91..8	6	340	400
DS	0.87E+11	101.1	8	374	400

Table 7
Maximum Hertzian pressure (P_0) calculated for LaserForm and DirectSteel against a counterbody of 30 mm diameter chrome-steel ball

The yield strengths of LaserForm and DirectSteel are 317 (compressive) and 400 MPa (estimated), respectively. Table 7 shows that for the applied loads of 2 and 4 N, the Hertzian pressures are below the yield strength limit and they can be used for experiments.

The experimental parameters chosen are given in Table 8. The number of tested parameter values were decreased and their selection were influenced by the earlier experiments done under plastic contact conditions. Amplitude or displacement for experimentation was taken as 200 μm instead of both 100 and 200 μm because 200 μm is able to give sufficient information.

The number of cycles was taken as 10000 as smaller cycle numbers like 2000, 4000, 6000 and 8000 could not give more information but that the wear volume is linearly dependent on the number of cycles. The applied loads were selected as 2 and 4 N because higher values did not generate elastic contact conditions for LaserForm material. In order to verify again that experiments

Quantity	Magnitude
Amplitude	200 μm
Frquency	10 Hz
No. of cycles	10000
Applied loads (N)	2, 4
Temperature	25°C
Humidity	52%

Table 8
Experimental parameters for fretting tests under elastic contact conditions

were under elastic contact conditions, tangential force vs displacement were plotted for both materials after 9000 cycles. The applied load taken was the maximum one, i.e. 4N. The plots are given in Figure 10. The curves are approximately rectangular showing that movement of counterbody against the material surface occurred without getting hindered by plastic deformation. This also shows that temperature rise during fretting was not critical to cause a shift in the elastic contact condition.

Coefficients of friction (COF) obtained for LaserForm and DirectSteel were found to be between 0.7 and 0.8 for applied loads of 2 and 4 N. Comparing these COF with COF for iron-iron (COF=1) and Cu-iron (COF=1), the obtained values were found to be expected.

It also depicts that they are not low COF materials. For the purpose of rapid tooling (COF should be 0.1,0.2), these COF are not low enough, which could be achieved either by changing the material compositions or by subjecting materials to surface treatments.

The wear volumes as measured with the WYKO machine are given in Table 9.

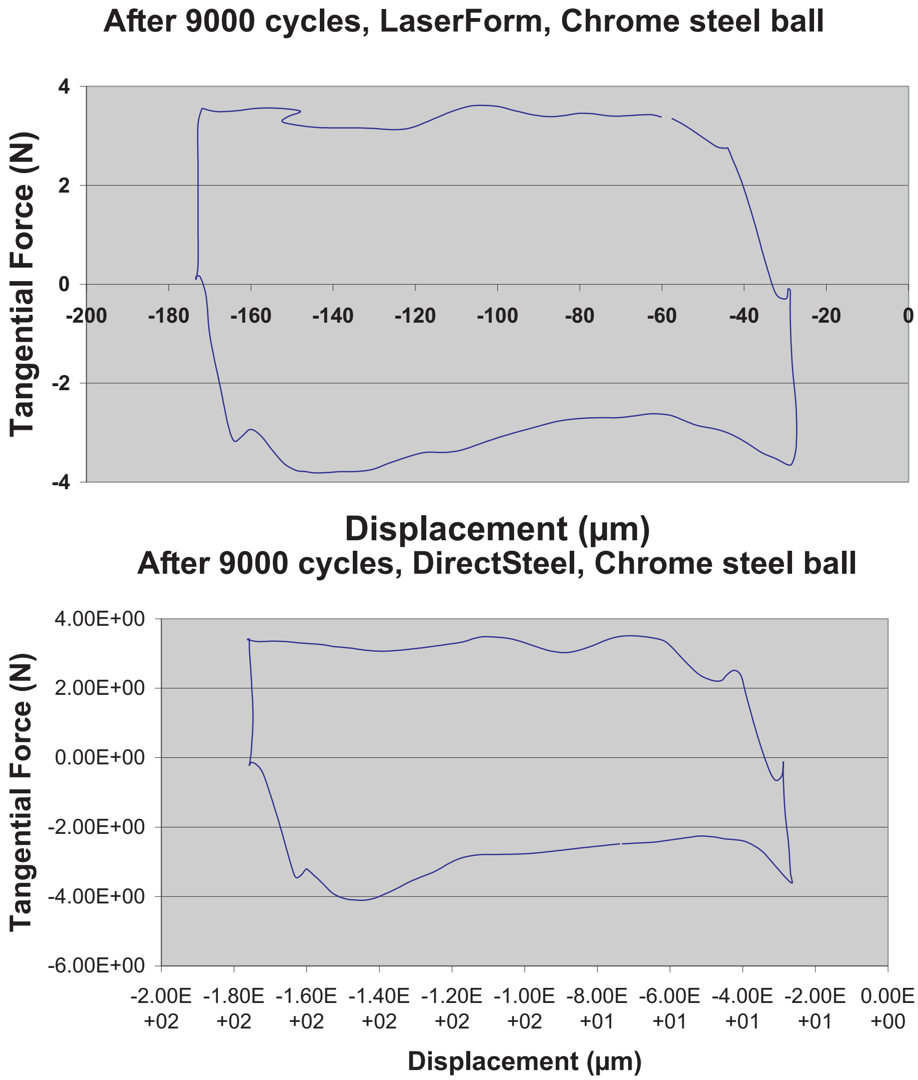


Fig. 10. Tangential force versus displacement after 9000 fretting cycles for LaserForm and DirectSteel

It shows that, for all the applied loads, wear volumes for DirectSteel are more than that for LaserForm showing that LaserForm is more wear resistant than DirectSteel. At 2 N load, the wear volume in DirectSteel is five times more than that of LaserForm while at 4 N, it is about three times more, indicating that wear rate difference between the two materials decreases with an increase in load. This shows that at higher loads the benefit of LaserForm may vanish. However, higher loads will yield plastic contact conditions.

5.2 POD Tests and Results

The applied loads for experimentation were selected as 1.96 and 4 N approximately, similar to that selected for fretting tests. Sliding speed was selected

Material	Applied Load (N)	Wear vol. ($10^3 \mu m^3$)
LF	2	10.695
LF	4	29.458
DS	2	53.905
DS	4	83.003

Table 9
Wear volumes after fretting under elastic contact conditions

earlier as 0.1 and 0.5 m/s, while at higher speed, the COF depicted, fluctuations and that speed was not used for further experiments. The number of revolutions for all experiments was restricted to 1000.

The COFs obtained for both LaserForm and DirectSteel were between 0.6 and 0.8. They are not very different from those obtained from fretting tests.

Wear volumes measured after POD tests are given in Table 10. It shows that the wear volume increases with an increase in load or sliding speed for a given material. For the same experimental condition, DirectSteel gives slightly more wear than LaserForm showing that LaserForm is still more wear resistant than DirectSteel. However, in comparison to fretting tests, where the difference in wear volumes for both materials were high, POD tests yield a lower difference. LaserForm again proves to be more wear-resistant. It can also be evidenced from the plot of dissipated energy vs. wear volume in Figure 11.

Material	Speed (m/s)	load (N)	Dia. (mm)	Rot. speed rev./min	wear vol. ($10^6 \mu m^3$)
LF	0.1	1.96	51	37	0.119
LF	0.1	4	41	47	0.149
LF	0.5	1.96	51	187	0.269
LF	0.5	4	41	233	2.608
DS	0.1	1.96	51	37	0.122
DS	0.1	4	41	47	0.324
DS	0.5	1.96	51	187	1.186

Table 10
Wear volumes after POD tests under elastic contact conditions

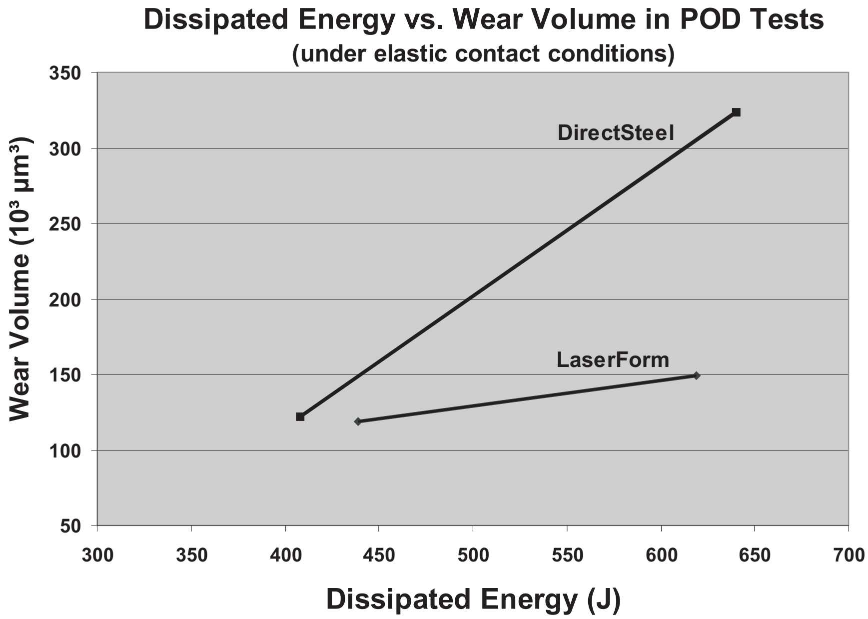


Fig. 11. Dissipated energy vs wear volume for LaserForm and DirectSteel after POD tests under elastic contact conditions

5.3 Micro-Fretting Tests and Results

In order to investigate the wear behaviour under milli-newton load using smaller counterbody, fretting tests were performed in a tribotester (trade name BASALT-MUST). The normal force, tangential force and sliding distance are continuously measured against time using a fibre optic sensor fitted in the cantilever. A detailed explanation can be found elsewhere [12].

Experimental parameters selected were: applied load- 50 mN, frequency- 1 Hz and sliding distance- 200 μm. The counterbody selected was an alumina ball of 5 mm diameter. The Hertzian pressures calculated using the above data were found to be 258 and 251 MPa for LaserForm and DirectSteel, respectively, which are well below their respective yield strengths of 317 and 400 MPa. This shows that the experiments conducted were completely under elastic contact conditions.

The coefficients of friction (COF) obtained for the materials were between 0.6 and 0.7.

Tangential forces versus displacement graphs were made for LaserForm and DirectSteel after various cycles (100, 3000 and 8000) and are illustrated in Figures 12 and 13, respectively.

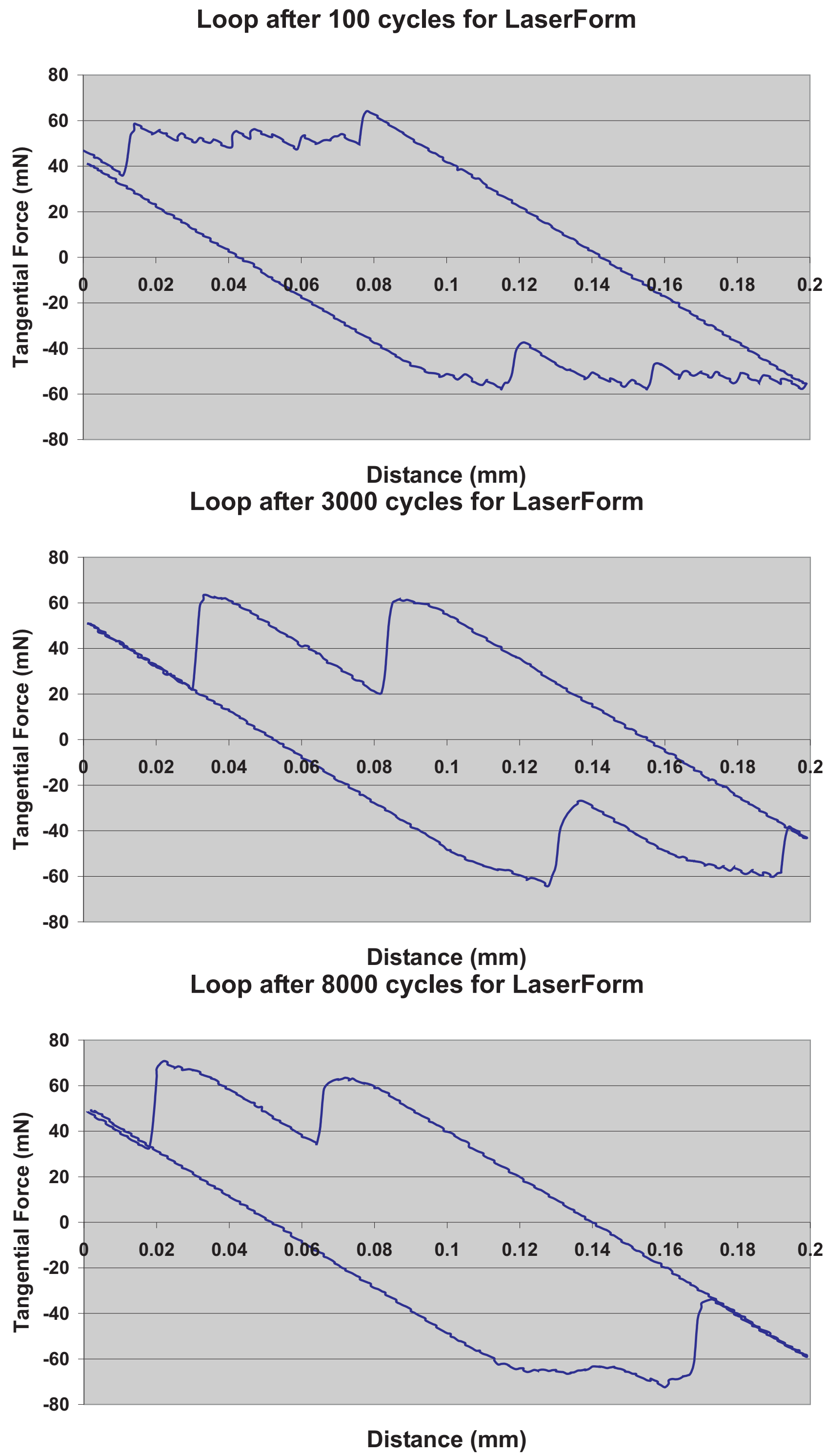


Fig. 12. Tangential forces vs displacement after 100, 3000 and 8000 cycles for LaserForm from micro-fretting tests

Figure 12 shows that after 3000 cycles, tangential forces show a drastic change with a variation in sliding distance. LaserForm consists of two distinct phases, i.e. iron-based grains and infiltrated bronze grains (see Figure 1), which have

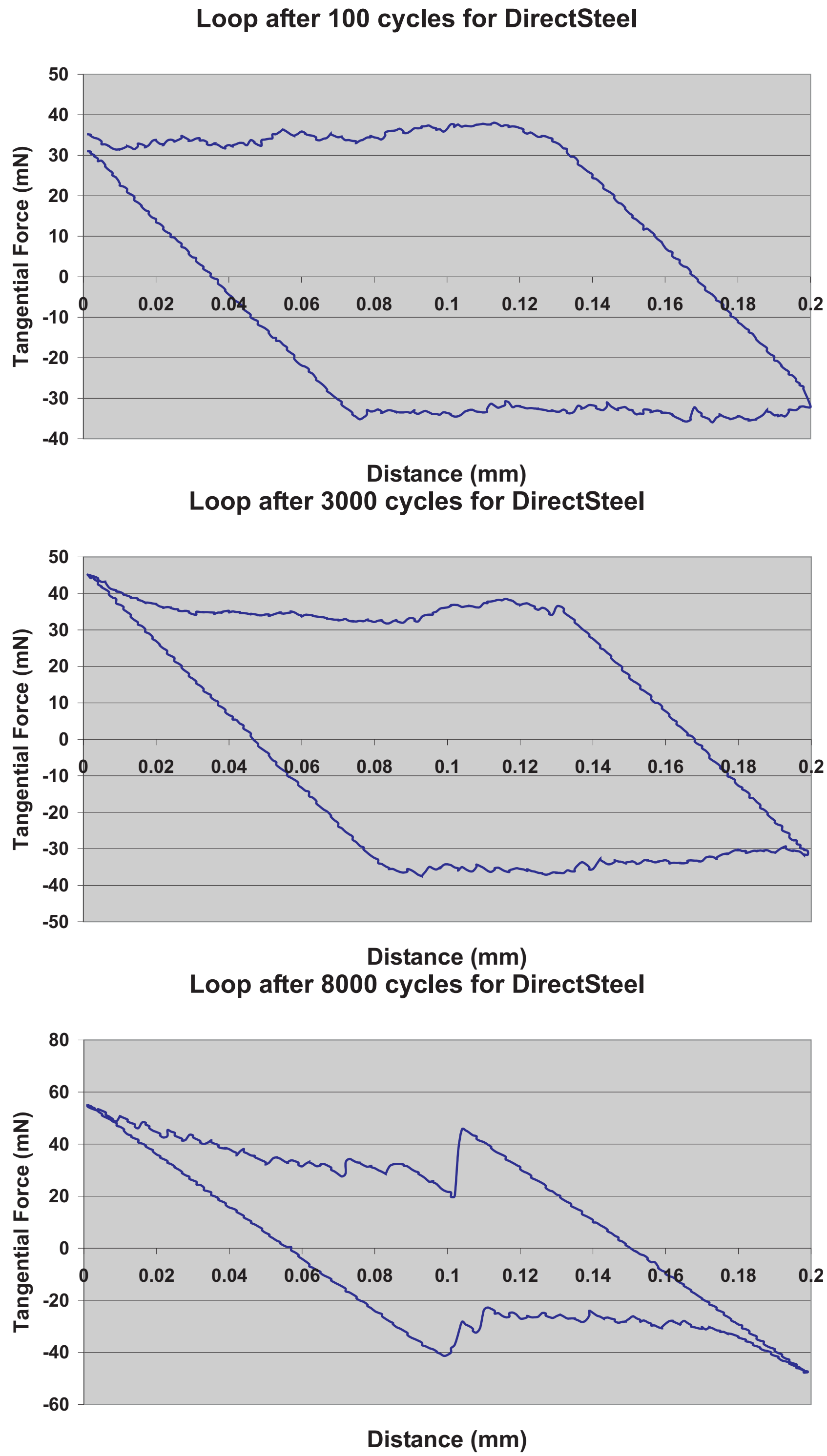


Fig. 13. Tangential forces vs displacement after 100, 3000 and 8000 cycles for DirectSteel from micro-fretting tests

distinct friction characteristics. The various friction resistance of distinct grains are reflected in a drastic change in tangential forces. This is not observed at an earlier stage (just after 100 cycles) because of the presence of an oxidized layer: see the first graph of Figure 12. After longer cycles, wear debris are amassed on the wear zone which does not let the distinct grain characteristic to be pronounced so distinctly (as shown in the last graph for 8000 cycles).

These characteristics are missing in case of DirectSteel which is a much more homogeneous material (see Figure 2) without two distinct phases. The graphs obtained after 100, 3000 and 8000 cycles do not show any qualitative difference as shown in Figure 13.

The wear volumes measured after micro-fretting tests for LaserForm and DirectSteel were found to be 250 and 2000 μm^3, respectively. It shows that LaserForm is far more wear-resistant that DirectSteel. As micro-fretting test involves micro joule energy it shows that for lower dissipated energy wearing system, LaserForm performs better than DirectSteel.

6 Conclusion

LaserForm is a better wear resistant material for injection mould but DirectSteel is also a better wear resistant material at higher dissipated energy and could also be preferably used for other applications.

The present investigation has shown that there is no clear relation between hardness and wear resistance of materials and the composition of the material is an important factor to be taken into account.

The effect of various material phases or grains can be observed using micro-fretting tests.

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