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Wear Performance of SLS/SLM Materials**

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Selective Laser Sintering (SLS) is a rapid prototyping technique and is used for rapid tooling and rapid manufacturing. One of its process variant SLM is increasingly used in place of the original SLS process for rapid manufacturing/rapid tooling. SLM relies on complete melting of metal-based powders and provides functional products competing in strength and better in features/complexity to the products obtained by conventional manufacturing methods.^[1]

The present paper deals with the wear behaviour of materials produced through SLS/SLM techniques. Not much work has done in this field except few works.^[2–4] In the present work, wear behaviour of various SLS/SLM has been characterized using fretting tests.

Experiments

SLM Materials and Processing

Following powders have been processed which are summarized in Table 1: (1) Stainless steel obtained from Concept Laser (CL) GmbH henceforth named as Concept stainless steel was processed on the KUL SLM machine, while (2) tool steel obtained from CL GmbH named as Concept tool steel, (3) stainless steel obtained from EOS GmbH named as EOS stainless steel, (4) Ti-6Al-4V obtained from CL GmbH and (5) locally made Co-Cr-Mo were processed on the Concept Laser (CL) Machine.

Details of the powders and processing parameters are given in coming sections.

Concept Stainless Steel

This powder is a spherical stainless steel powder of size 25–50 μm named as CL20ES supplied by Concept Laser GmbH. It is recommended for the production of acid- and corrosion-resistant parts or tool components for preproduction tools.

Table 1. Materials and Machines used for SLM.

Sl. No.	Materials Name	Trade Name	Source	SLM Machine
1	Concept Stainless Steel	CL20ES	CL GmbH	KUL
2	Concept Tool Steel	CL50WS	CL GmbH	CL
3	EOS Stainless Steel	17-4	EOS GmbH	CL
4	Ti-6Al-4V	CL 40Ti	CL GmbH	CL
5	Co-Cr-Mo	–	MTM	CL

The powder has been processed on the KUL SLM machine using following parameters: Laser Power- 150 W, Scan Spacing- 70 μm , Scan Speed- 400 mm/s and Layer Thickness- 30 μm . The products obtained are about 97% dense and their hardness is 17 HRC which is less than the stated hardness of 20 HRC for full dense products. It infers that the experimental parameters still need to be optimized for achieving the best results.

Concept Tool Steel

This powder is spherical powder of size 20–50 μm named CL50WS and supplied by Concept Laser GmbH. It is recommended for the production of parts with characteristic similar to hot-work steel 1.2343 as well as tool components of plastic injection moulds.

The powder has been processed in Concept Laser machine using the following processing parameters: LaserPower- 95 W, Scanning Speed- 200 mm/s, Scan Spacing- 140 μm , Layer Thickness- 30 μm . Processing was done by using the chessboard scanning strategy, that process successive square patches (islands). The processed part was about 99.5% dense and hardness was 31 HRC which is less than the suggested hardness of 35–40 HRC for a fully dense part. Though, the parts were processed with the recommended experimental parameters, they could not achieve the desired strength showing there is still a need of optimization of parameters for each individual machine.

EOS Stainless Steel

This powder is a proprietary stainless steel powder (Cr-15–17.5%, Ni-3–5%, Cu-3–5%, Mn-max 1%, Si-max 1%, Mo-max 0.5%, Nb-0.15–0.45%, C-max 0.07%, Fe-rest) of average size 25 μm named as EOS StainlessSteel 17-4 supplied by EOS

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GmbH and is developed for EOS' own machine EOSINT M 270.

It has been processed on the Concept Laser machine using the following parameters: Laser Power- 95 W, Scanning Speed- 350 mm/s, Scan Spacing- 140 μm , Layer Thickness- 30 μm , Scanning Strategy- chess board islands. The processed part is subsequently treated in an oven for 1 hr at 650 $^{\circ}\text{C}$ for removing residual stresses. The density obtained is 98 % and the hardness is 19 HRC.

Ti-6Al-4V and Co-Cr-Mo

The Ti-6Al-4V powder is obtained from Concept Laser GmbH and its trade name is CL40Ti. It is of size 25–45 μm (average size- 35 μm) and is spherical in shape. Co-Cr-Mo is locally made using an induction melting gas atomization process and is of average size of 50 μm . Its composition is Co-63 %, Cr-29.53 %, Mo-5 %, Si-1 %, Mn-0.5 %, Fe-0.5 %, N-0.3 %, C-0.17 %. These materials are widely used in medical applications because of their excellent bio-compatibility.

Both powders have been processed on the Concept Laser machine using following parameters: Laser Power- 95, 95 W, Layer Thickness- 30, 40 μm , Scan Speed- 125, 200 mm/s, Scan Spacing- 130, 140 μm for Ti-6Al-4V and Co-Cr-Mo respectively. SLM parts thus obtained gave more than 99 % density. Details of other characteristics can be found elsewhere.^[5]

SLS Materials and Processing

LaserForm

LaserForm ST-100 is a polymer coated steel powder of average size 100 μm supplied by 3D Systems to be processed on DTM SLS Sinterstations. The steel powder contains Cr-12–14 %, Mn-1 %, Si-1 % and the rest iron. These steel grains are coated with appropriate 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. Oven cycle used for infiltrating consists of three steps:^[6] debinding of polymers at 450 to 650 $^{\circ}\text{C}$, sintering of remaining steel after polymer burn-out at about 700 $^{\circ}\text{C}$, and infiltration of part at approximately 1050 $^{\circ}\text{C}$. The final composition of the part is about 60 % steel and 40 % bronze.

The final parts have characteristics similar to P20 steel: hardness of 83.4 HRC, density 7.7 g/cm³, Young's Modulus 137 GPa, Tensile yield strength 305 MPa, Compressive yield strength 317 MPa and ultimate tensile strength 510 MPa.

DirectSteel

DirectSteel 20 V1 is a powder of average size 20 μm supplied by the company EOS. It consists of Fe 60 %, Ni 31 % and Cu₃P 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 CO₂ 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 are: 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).

The stated properties of the laser sintered materials are: density (skin) 7–7.6 g/cm³, density (core) 6–6.3 g/cm³, hardness 89.6 HRC, Young's Modulus 130 GPa and Ultimate tensile strength 600 MPa.^[7]

Fretting Wear Test

Fretting is a wear phenomenon occurring when two contacting solids are subjected to a relatively oscillatory tangential motion of small displacement amplitude.^[8] 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. 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.^[9] A schematic diagram of a fretting test and part of a fretting apparatus is given in Figure 1.

Fig. 1. Schematic diagram of the fretting test (left diagram) and the fretting test setting (right photograph).

Fretting tests were performed to evaluate the wear characteristic of those SLS/SLM materials. The amplitude and frequency of oscillation as well as environmental conditions were kept constant for all experiments. Experimental parameters were selected in such a way that all tests could be executed under elastic contact conditions. A chrome steelball of 30 mm was selected as counterbody. The parameters for the tests were as follows: Applied load- 2, 4, 6 N, Sliding distance (amplitude)- 200 μ m, Frequency- 10 Hz, No. of cycles- 10,000, Temperature- 25 °C and Humidity- 52 %.

Results and Discussions

The Coefficient of Friction (COF) and wear volumes were determined for each material. COFs were found to be between 0.5 and 0.8 for all samples and showed a decrease with an increase in applied loads. Wear volumes obtained for all samples are given in Table 2. Wear volumes for SLS materials such as LaserForm and DirectSteel are also given for comparison. Wear volume of milled tool steel are also added in the table for comparing with the wear resistance of SLS/SLM material with that of a conventional manufactured material. The composition of the tool steel in percentage is C-0.40, Cr-1.90, Mo-0.20, Mn-1.5, S-0.07, Si-0.40, Fe-bal and its hardness is 31.6 HRC.

Table 2 shows that the wear of Concept tool steel is maximum and much more than other materials. This was unex-

pected as tool steel is supposed to furnish better wear resistance than other steels. Wear of EOS stainless steel is more than Concept stainless steel. It shows that wear resistance of steel-based SLM materials is not dependant on their hardness and decreases with an increase in hardness.

Bio-materials Ti-6Al-4V and Co-Cr-Mo give least wear-resistance and are not suitable for any wear applications. The performance of SLS material LaserForm is unexpectedly better than both SLM stainless steels. It could be due to the presence of low-friction element (copper) in LaserForm which helped increase its wear resistant. It shows that the composition of material is more important than the type of processing for developing a wear-resistant material.

Another conventionally produced tool steel UHB 11 (C 0.5, Si 0.3, Mn 0.6, S 0.04, Fe rest) (hardened at 850 °C, 30 min., quenching medium water) was also used for the wear testing under the same condition to observe the effect of hardening on the wear performance. It was found that hardening increases its wear resistance almost twice but even then the wear resistance is far less than the SLS/SLM materials. Its wear resistance is also very different from another tool steel used showing again that composition significantly influences the wear behaviour of materials.

All iron-based SLS/SLM materials give higher wear resistance than conventionally produced milled tool steel showing that SLS/SLM techniques are capable of producing products with superior properties and can be efficiently used for rapid tooling.

Fretting wear zones of Concept stainless steel, Concept tool steel and EOS stainless steel are given in Figure 2. These have been obtained after cleaning the samples in an ultrasonic bath after fretting tests. Micrographs show that thin films have been formed on fretting zones of the stainless steel samples while agglomerated debris are shown in the wear zone of tool steel. These films protect the surface from further wear and are responsible for smaller wear volumes in comparison to that of tool steel. Micrograph of tool steel wear zones shows scratching lines stating that abrasive wear is the main cause for its fretting degradation.

Stainless steels are electro etched using 10 % oxalic acid to reveal the microstructure of their wear zones. Figure 3 shows the micrographs obtained for Concept stainless steel. The micrograph shows that the wear surface is full of circular depressions. These plastic depressions are the result of trapping of hard wear debris (from chrome steel) between fretting surfaces. It demonstrates that the main mechanism of wear of stainless steel is the excavation of surface by wear debris.

Conclusions

SLM stainless steel gives better wear resistance than SLM tool steel. The wear resistance of tool steel

Table 2. Wear volumes obtained after fretting tests.

Material	Applied Load (N)	Wear Vol. (10^3 m^3)
Concept Stainless Steel	2	15
	6	51
Concept Tool Steel	2	198
	6	462
EOS Stainless Steel	2	39
	6	66
Ti-6Al-4V	2	7362
	6	9337
Co-Cr-Mo	2	1474
	6	2252
LaserForm	2	10.7
	4	29.6
DirectSteel	2	53.9
	4	83
Milled tool steel	2	360
	4	420
	6	586
tool steel (UHB 11)	6	5442
Hardened tool steel (UHB 11)	6	3899

Fig. 2. Fretting wear zones of Concept stainless steel, Concept tool steel and EOS stainless steel respectively.

Fig. 3. Micrographs of etched fretting wear zone of Concept stainless steel.

could be improved by incorporating low friction element in its composition. COF for all materials are high which shows that an extensive research needs to be done for decreasing the COF.

The materials tested were not 100% dense. Better wear resistance could probably be obtained for full dense materials which could be achieved by careful optimization of SLM parameters.

A dedicated SLS material (i.e. LaserForm) has given better wear resistance than SLM stainless steel and tool steel. It shows that preferring SLM over SLS for Rapid Tooling is not necessarily the best choice.

Wear volume of conventionally produced tool steel is very high in comparison to all other materials showing that SLS/SLM technique is capable to offer excellent surface properties.

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