ENHANCEMENT OF SURFACE PROPERTIES AND WEAR RESISTANCE OF DIRECT METAL LASER SINTERED STAINLESS STEEL 17-4PH

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Abstract

It has been observed that the products obtained by means of 3D printing technology, even in the case of consideration of optimal parameters of printing technology recommended by the manufacturers of metal powders laser sintering systems, are characterized by certain structural discontinuities (pores and unmelted powder) in surface layer. Therefore, surface modification via shot peening is considered suitable for additive manufacturing of parts made of 17-4PH stainless steel. The specimens have been produced by means of EOSINT M280 system dedicated for laser sintering of metal powders. The objective of this study was to determine the effect of shot peening pressures (0.4 MPa and 0.6 MPa) and two types of blasting media (CrNi steel shot and ceramic beads based on ZrO_2) on the tribological characteristics, surface topography and hardness of specimens of DMLS 17-4PH stainless steel. Wear tests have been carried out by means of ball-on-disc tribotester in dry sliding method at room temperature (about 22ºC). Wear loss after tribology testing was calculated via profilometry measurements of the worn surface, i.e. wear grooves, using contact profilometer. Finally, the wear mechanism was investigated using a scanning electron microscope (SEM). Adhesive and abrasive wear were two predominant mechanisms of tribological deterioration. The general results of all tests indicate to favourable effect of shot peening process on the hardness and wear resistance of 17-4PH steel. The highest increase in hardness was obtained for the surfaces modified by steel shot and ceramic beads using a peening pressure of 0.6 MPa, respectively mean: 550±34 HV0.3 and 554±22.2 HV0.5. DMLS 17-4PH specimens modified by shot peening using steel beads and a pressure of 0.6 MPa exhibited the optimum surface morphology, hardness and microstructure, and thus improved wear.

Keywords: Additive manufacturing, 17-4PH steel, shot peening, direct metal laser sintered, wear resistance

1. INTRODUCTION

Direct metal laser sintering (DMLS) is a powder-bed-based metal additive manufacturing (AM) process which has been intensively developed in the last decade for the production of not only prototypes but also for the mass production of machine parts with complex geometries [1,2]. Much of the work focused on optimizing various process parameters to achieve high quality printed products [3,4]. However, the DMLS process faces various challenges including imperfections in the surface layer of products due to the use of 3D printing technology. So even when taking into account the optimal parameters of the printing technology recommended by manufacturers of metal powder laser sintering systems, the products are characterized by certain structural discontinuities (defects) in the surface layer. The surfaces of 3D printed products may contain unmelted grains of metal powder in the surface layer or show pores that are formed by the breakdown of the welding pool. The above defects can reduce the performance of such products. Most damage to machine parts (stress cracks, abrasive or corrosive wear) originates from the defects present in the surface layer. In addition, the technology of laser sintering of metal powders itself causes residual stresses in the products. Therefore, manufacturers of laser sintering systems recommend shot peening processing for 3D printed products as a technology to improve the performance characteristics of the machine part components processed in this manner. Literature data [2, 5] indicate that surface strengthening under shot peening introduces favorable compressive stresses and reduces the porosity of surface layers, which in turn translates into an increase in fatigue strength. In addition, as a result of the shot peening treatment, shot grains can penetrate the surface layer (become permanently embedded) and change the tribological characteristics and corrosion resistance of the products modified using this method [2,6].

Stainless steel 17-4PH (1.4542) is a precipitation-hardened grade with a martensitic structure. It is used for construction materials and related applications in power plants, matrix manufacturing, medical devices and the chemical industry, among others, when products are required to be highly resistant to abrasive wear while maintaining high corrosion resistance [2,7,8]. Wear factor is one of the critical factors governing the application of manufactured parts into a moving system [8]. The effect of surface modification or the application of various heat treatments on the tribological properties of 17-4PH steel was studied by the authors of the articles [2, 9] On the other hand, an analysis of research work [2,5,6] indicates that the surface layer properties and wear resistance of 3D printing products can be improved by applying shot peening. Therefore, the purpose of this study was to characterize the tribological properties of DMLS-produced 17-4PH stainless steel subjected to shot peening treatment. To the best of the authors' knowledge, the improvement of tribological properties in the shot peening process of 17-4PH steels with additive technologies has not yet been studied and requires an understanding of, among other things, the wear mechanisms occurring in the friction process. The only research in this area of the subject was presented in the work [2], with tests carried out with different parameters.

2. MATERIALS AND EXPERIMENTAL METHODS

The test subject was EOS Stainless Steel GP1 stainless steel powder. Composition of this powder is similar to US classification 17-4 PH and European 1.4542 stainless steel materials. The disc-shaped samples with a diameter of ø=30 mm and a height of 6 mm were produced by DMLS technology using the EOSINT M280 system (EOS GmbH, Germany). Printing was carried out in an inert nitrogen atmosphere according to the optimal parameters recommended by the EOS manufacturer i.e.: laser power 200W, layer thickness 0.02 mm and laser spot size 0.1 mm. The external surfaces of the specimen (X-Y horizontal plane) were subjected to shot peening on a Peenmatic micro 750S device (IEPCO, Switzerland) with two mediums (manufacturer - Kuhmichel Abrasiv GmbH): i.e.: CrNi steel shot (ø400-900 µm) and ZrO_2-based ceramic beads (ø125-250 µm). Two different operating pressures were used: 0.4 and 0.6 MPa. The shot peening process was conducted perpendicular to the surface. The treatment time of the surface was 60 s and the distance of the nozzle from the surface to be treated was 20 mm. The reference specimens in the study were products (surfaces) obtained directly after sintering with DMLS (without modification). In this paper we will use the shorthand notations presented in **Table 1**. The morphology of the surface structure after pressing (shot peening) tests was evaluated using a Phenom ProX scanning electron microscope (Phenom World, Waltham, MA, USA) at 500x magnification using the topographic mode.

Table 1 Notations of specimens

Specimen notation	Shot type	Peening pressure (MPa)
DMLS	Unmodified surface after DMLS (reference)	
S4	Stainless steel	0.4
S6	Stainless steel	0.6
C4	Ceramic beads	0.4
C6	Ceramic beads	0.6

The surface roughness was evaluated on a Dektak 150 contact profilometer (Veeco Instruments, United States). The measurements were carried out on a measuring distance of 5 mm. For each sample, 10 measurements were made at randomly selected points. To take into account the effect of texture, 5 measurements along and 5 measurements in the direction perpendicular to the scanning direction of the laser beam were realized and, then, the average value was drawn. To compare the different DMLS samples, the average value of the surface roughness was evaluated using: arithmetic average roughness *Ra*, maximum profile valley depth of the roughness profile *Rv* and maximum profile peak height of the roughness profile *Rp*. The surface hardness measurements were made using a Vickers FM-700 micro hardness tester with an ARS 900 automatic system (Future-Tech Corp., Japan). The load used for the hardness test was 0.5 kgf (HV0.5) with a dwell time of 10 s. Ten indentations were made for each group of specimens. The coefficient of friction (COF) and wear rate were characterized on a ball-on-disc tribotester (CSM Instruments, Switzerland) under technically dry friction conditions (room temperature 22°C). The calibrated balls with a diameter of 6 mm made of 100Cr6 steel (63 HRC) were used as a counterspecimen (ball). The tribological tests were carried out under a load of 20N with a linear speed of 10 cm/s over a radius of 6 mm. The total test distance was 300 m during which the change in the coefficient of friction was recorded. The measurement of wear was the volumetric loss of the specimen formed as a trace of abrasion due to the cooperation of the specimen and the counterspecimen, measured using a Dektak 150 contact profilometer (Veeco Instruments, United States) according to the procedure outlined in [2]. The so-called wear factor K was then determined, which, in addition to volumetric wear, took into account the load and distance travel used during the test:

$$K = \frac{Wear\ volume}{Applied\ force \times sliding\ distance}\,[mm^3 N^{-1} m^{-1}] \tag{1}$$

After that, the surface of the wear tracks of the tested materials in order to identify the wear mechanisms were analyzed using a SEM microscope.

3. RESULTS AND DISCUSSION

The type, size and geometry of the particles or shot are among the key factors determining the degree of surface development [2, 5, 6]. The measured surface roughness parameters of the unmodified and post-shot peening samples are shown in **Table 2**. Surface treatment with steel shot caused an increase in surface roughness at both 0.4 and 0.6 MPa. On the other hand, a reduction in roughness was noted for surfaces shot with ceramic balls. At the same time, it would be necessary to take into account that the reduction in surface roughness for ceramic balls was obtained with almost 2-3 times smaller shot size, compared to CrNi shot. In addition, the increase in pressure in the case of ceramic bead and CrNi shot peening results in a smoother treatment pattern associated with a decrease in the parameter Ra. The smaller shot size results in smaller cavity sizes after peening (smaller Ra and Rv values), which in turn produces an increased number of strikes per unit area when the pressure is increased. In addition, for all treated surfaces in the case of indentation (valley) analysis, it was observed that an increase in peening pressure from 0.4 to 0.6 MPa results in a slight average increase in the parameter Rv.

Table 2 Roughness parameters of untreated (marked as DMLS) and shot peened surfaces.

Sample	Ra (μm)	Rv (μm)	Rp (μm)
DMLS	5.04±0.56	-11.68±2.84	12.14±2.02
S4	5.71±0.26	-12.55±0.43	15.34±0.21
S6	5.41±0.98	-12.64±1.59	11.33±2.47
C4	4.39±1.43	-10.47±1.82	9.49±1.13
C6	4.21±0.81	-11.56±3.53	10.47±2.36

SEM analysis (**Figure 1**) of surface morphology of the as-printed specimens (DMLS) reveal the presence of surface features that are typical of additive manufactured parts, such as unmelted metal powder grains and weld pool collapse along the laser melted track. Such defects in the surface layer can contribute to lower strength parameters [2, 6], hence the rationale for surface modification of the resulting DMLS technology products. According to the authors of the works [4, 6], the formation of surface-related weld pool collapse is influenced by too much penetration of the laser beam deep into the substrate or into the previously scorched layer. In contrast, SEM analysis of the specimens after surface treatment showed plastic deformation and spherical craters. The above observations of the surface are in agreement with the results of roughness parameters Ra. The smallest significant changes in the surface topography are observed for the specimen which was peened at the highest pressure - 0.4 MPa.

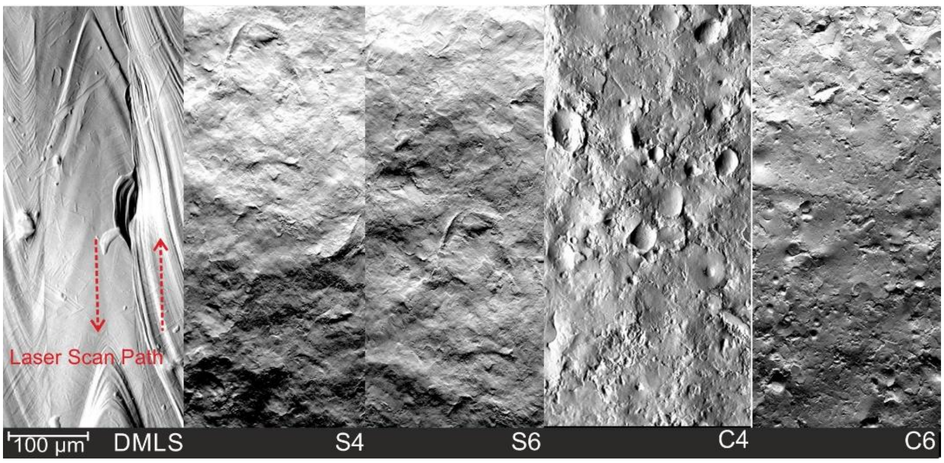

Figure 1 SEM micrographs representation of sample surface area before (marked as DMLS) and after shot peening

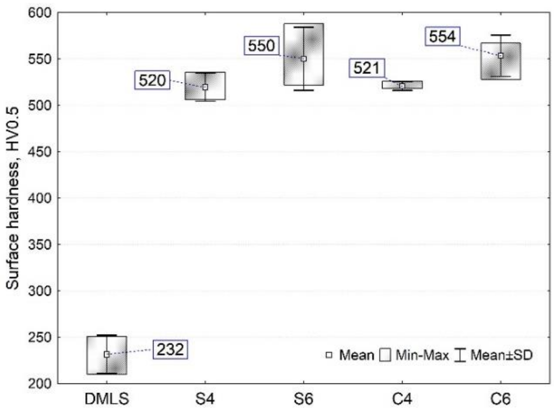

Figure 2 Surface hardness of untreated and shot peened 17-4PH steel

Surface hardness tests (**Figure 2**) showed an increase in average values for all modified surfaces compared to reference samples - DMLS. The average hardness of the unmodified samples made with DMLS technology was 232HV0.5, which is comparable to what the manufacturer EOS GmbH claims. The highest average hardening was obtained for surfaces treated with ceramic beads, which resulted in an increase in hardness of ~138.8% (for peening pressure of 0.6 MPa). At the same time, these results are very similar for surfaces treated with steel shot - an increase of approx. ~137% relative to the reference surface. There were no statistically significant differences in hardness for surfaces treated with CrNi shot and ceramics, but it should be noted that hardness values for surfaces treated with ceramic beads were obtained using about 2÷3 smaller size shots. The strengthening of the material occurs as a result of plastic deformation in the surface layer, the density of dislocations then increases, and the remnants of the hard shot are compressed (driven in) causing a pointwise (or localized) significant increase in hardness [5].

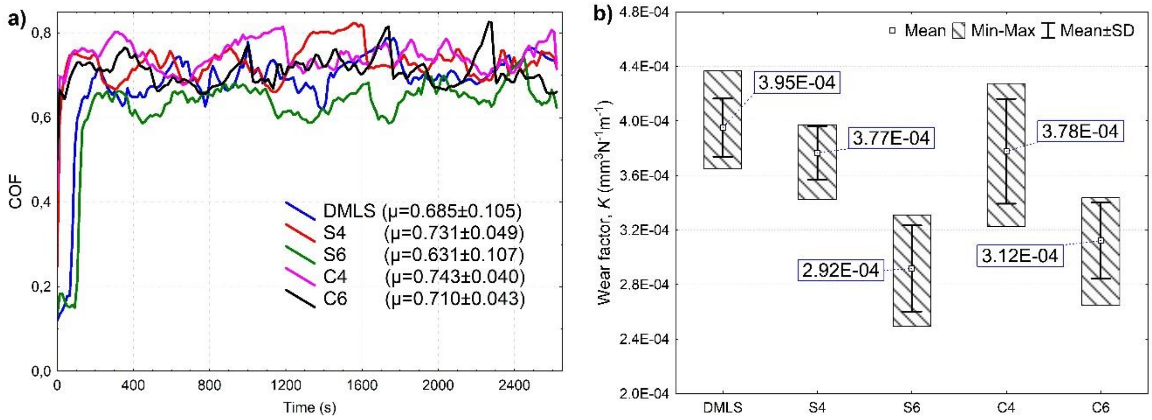

Figure 3 Result of the wear test sliding: a) coefficient of friction with regard to time and b) wear factor

The analysis of the friction coefficients (**Figure 3a**) showed that the lowest values (while very close when taking into account the standard deviation) of the friction coefficient were recorded for the reference and S6 surfaces. It is likely that this situation is influenced by the unmelted metal powders on the DMLS specimen. A decrease in average COF values was observed with an increase in peening pressure which, in turn, is associated with a decrease in surface roughness (Ra). Comparing surfaces treated with steel shot and ceramics, slightly higher average COF values are observed for the same peening pressure. This can be explained by the plated residues of hard ceramic particles, which generate higher COF values [2, 5, 6]. However, all the average COF values are in the range μ=0.631÷0.743 and, taking into account the standard deviation, it can be concluded that the differences are not statistically significant. On the other hand, **Figure 3b** shows the results of the wear coefficient of the peened surfaces. For all modified surfaces, an increase in wear resistance was observed with an increase in peening pressure. The wear factor value is related to hardness and COF. High hardness and low COF correspond to higher wear resistance. The highest wear resistance under technically dry friction conditions was recorded for the S6 surface and, when compared to the DMLS surface, has a nearly 26.1% lower wear factor.

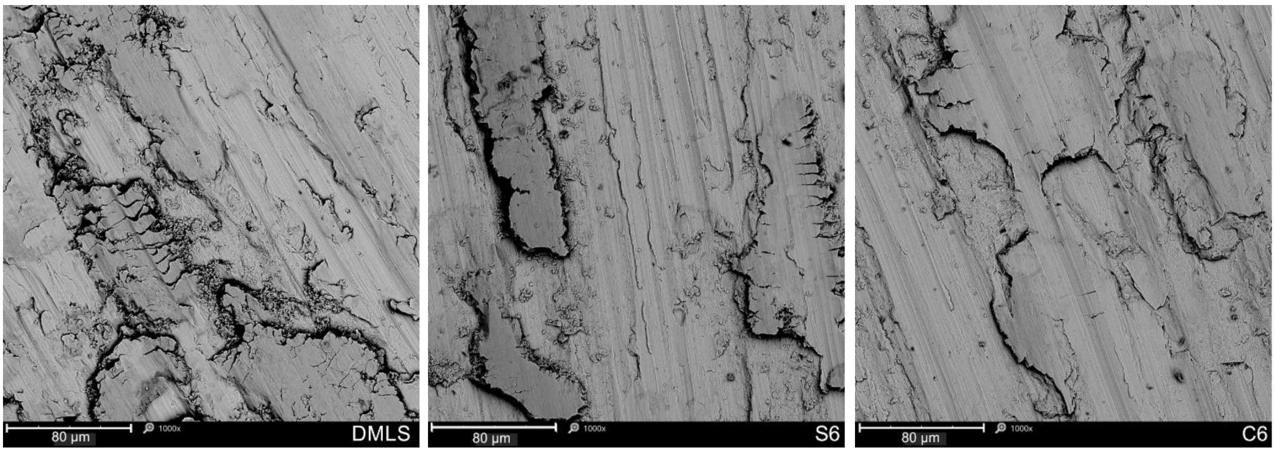

Figure 4 Representative SEM micrographs of worn surfaces

On all analyzed surfaces of wear traces (**Figure 4**), the predominant abrasive wear mechanism was observed (it was determined by long parallel grooves) and, in parallel, the fatigue wear mechanism, which led to the formation of micro-cracks, spreading perpendicular to the direction of movement of the counterspecimen. Wang et al. [10] indicate that at loads below 4 N, the dominant wear mechanism is typically abrasive manifested by micro-cutting and parallel grooving, and with increasing load (6 and 8 N) the dominant abrasive wear mechanism changes to fatigue surface cracking leading consequently to the surface spalling off. While Sanjeev et al. [8] for wear tests under 10N and 30N load indications of adhesive and scuffing wear, observed by the smearing patterns. At the same time, they indicate that in the case of samples created by additive technology, there may be a weakness in the bond between the layers, which accelerates to the fatigue.

4. CONCLUSION

On the basis of the conducted research, it was found that:

- Increasing the peening pressure results in lower surface roughness (Ra) compared to the reference surface - DMLS.
- The peening with CrNi steel shot and ceramic balls increases the hardness of the treated surface as the peening pressure increases.
- For all peened surfaces, a decrease in average COF values was observed with an increase in peening pressure which can be associated with a decrease in the roughness (Ra) of these surfaces. Comparing surfaces treated with steel shot and ceramics, slightly higher average COF values are observed for the same peening pressure.
- For all treated surfaces, there was an increase in wear resistance with the increase in peening pressure. High hardness and low COF correspond to higher wear resistance.
- SEM analysis of the surfaces after wear tests showed that two main types of wear, abrasive and fatigue, dominated in parallel in all the surfaces tested.

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