EVALUATION OF TRIBOLOGICAL CHARACTERISTICS OF MATERIAL PREPARED BY DMLS TECHNOLOGY

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DOI: 10.17973/MMSJ.2021_10_2021039

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The method of producing molten metal powder according to the European laser sintering system (EOSINT) was used to prepare the experimental material. The used powder metal material was designated EOS Maraging Steel - MS1. It is a steel powder, which is optimized especially for processing in EOSINT M 280 systems. The measurement of tribological characteristics of prepared materials was performed using the standard STN ISO 20808: 2004. The ball-on-disc dry sliding friction and wear experiments have been made on prepared materials in contact with steel ball. For the experiment, there were determined the following conditions: the value of normal load 5 N, the sliding radius 2 mm. Wear testing was carried out at room temperature 25°C using the ball-on-disc technique. Wear behaviour of the prepared material was studied in dry sliding; relative humidity was 26-28%. The normal load of 5 N; and sliding speed of 0.1 m/s was applied. The total sliding distance was 1000 m. The worn surface was analysed by confocal microscope and scanning electron microscope.

KEYWORDS

laser, sintering, powder, maraging, friction

1 INTRODUCTION

Today's industry is conditioned by a rapid process of adaptation in the market and flexible responses to customer requirements. One of the ways to ensure these attributes is to create space to shorten product development time to eliminate costs, for example by using unconventional production technologies. One of the possibilities is the implementation of Rapid prototyping technology, specifically Direct Metal Laser Sintering, through which it is possible to create plastic and metal components. To improve production processes and eliminate their cost, it is necessary to test, analyse and evaluate the materials created in the field of research and development, for example from a tribological point of view. The analysis issue of the properties of components created by DMLS technology researched not only in practice but also in laboratory conditions is addressed at the global level, as evidenced by publications published in journals and conferences, such as a paper published in the Journal of Materials Engineering and Performance, describes the analysis of hardness, microstructures and tribological characteristics of aluminium alloy AlSi10Mg-TiB 2 composites produced by DMLS [Lorusso et al. 2016]. Complex mechanical property, assessment of microstructure and tribological properties were also inferred in a study by Hussain et al., which assessed cBN particulates SS316 alloy. From the achieved results of the realized study, general conclusions and recommendations for practice were created [Hussain et al. 2017]. The issue of examining surface properties was also addressed by the authors Zebrowski and Walczak, who examined the surface properties and tribological characteristics of titanium alloy. The specimens have been subjected to profilometric analysis, SEM examinations, microhardness tests and tribological tests on ball-on-disc stand in Ringer fluid environment [Zebrowski and Walczak 2019]. Similar studies have been carried out in publications [Amanov et al. 2013, Kim and Cho 2014, Subrahmanyam et al. 2020, Ralls et al. 2021], focusing on the evaluation of properties, structure, production, and the like for components produced by DLMS technology.

Direct Metal Laser Sintering - DMLS was developed by EOS GmbH, Rapid Product Innovations (RPI) as the first commercial method of a rapid prototype for the production of metal parts. Using this manufacturing method, a metal powder with a diameter of 20 µm, without a binder, is completely melted by a high-power laser beam to form a part with the properties of the original material [Mancanares et al. 2015, Gaspar et al. 2014, Krehel et al. 2013]. Removal of the polymeric binder prevents the firing and infiltration step and produces a 95% dense steel part compared to a density of 70% selective laser sintering (SLS) [Panda et al. 2017, Salokyova 2014, Torok et al. 2020]. Another advantage of the DMLS process compared to SLS is the higher resolution of details due to the use of thinner layers allowed by a smaller powder diameter. This capability provides more complex parts of shapes. Material options currently offered include alloy steel, stainless steel, aluminium, bronze, cobalt chrome, and titanium. In addition to functional prototypes, DMLS is often used to make high-speed instruments, medical implants, and aircraft parts for high thermal applications [Panda et al. 2013, Murcinkova et al. 2020].

2 MATERIAL AND METHODS

The samples were made on the EOSINT M280 - 3D printer. This printer is used to produce metal parts directly from CAD data. The form of material is a powder - EOS maraging Steel MS1 with a chemical composition corresponding to the classification according to USA: 18% Ni Maraging 300, European Standard 1.2709 [EOS 2021]. The material is characterised by good mechanical properties and good heat treatment using a thermal curing process to obtain excellent hardness and strength [Palermo 2019]. The chemical composition of the material is presented in Table 1.

Table 1. Chemical composition of the samples

Elements	w [%]	Elements	w [%]
Ni	17-19	**Cr, Cu**	≤ 0.5
Co	8.5-9.5	**C**	≤ 0.03
Mo	4.5-5.2	**Mn, Si**	≤ 0.1
Ti	0.6-0.8	**P, S**	≤ 0.01
Al	0.05-0.15	**Fe**	res.

Two series of samples were tested to evaluate the tribological characteristics of the material. The first batch was produced by 3D printer. The second batch was printed and heat-treated at 490°C for 6 hours with the subsequent cooling in air. Production of testing samples are presented in Figs. 1 and 2.

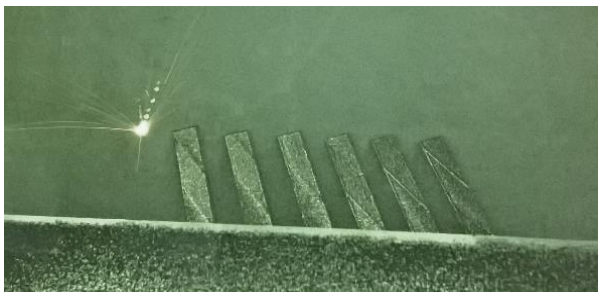

Figure 1. Production of samples using DMLS technology, on samples for the toughness test - laser sintering process

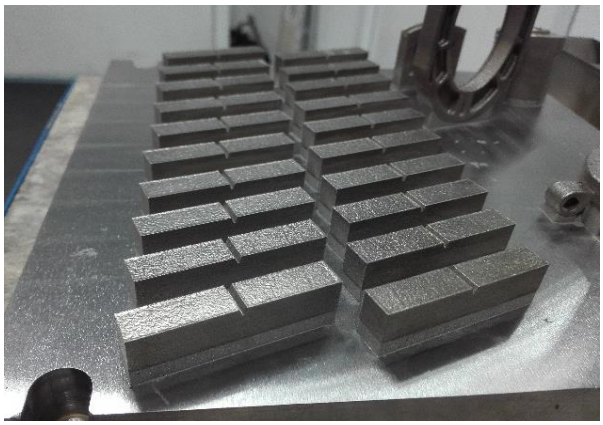

Figure 2. Production of samples using DMLS technology, on samples for the toughness test - method of storage of samples on the plate

The process of measuring tribological characteristics was performed at room temperature on a tribometer (Bruker UMT-3 Heavy Duty Tribometer) according to the standard STN ISO 20808: 2004 [STN ISO 20808:2004]. The standard contains information and instructions for performing wear test and sliding friction test using „ball-on-disc" method. The sliding speed was 0.1 ms^{-1} and the sliding distance was 1 000 m. The test was performed at room temperature 25 °C and a dry friction relative humidity of 26-28%. The measurement program was set to evaluate measurements every 15 seconds. Before the wear test, the surfaces were carefully prepared by polishing down to surface roughness below 0.05 microns where possible. After clamping the test ball - steel 100 Cr6 into the holder, the current parameters and test conditions were set and recorded. The measurement was started automatically after the device was started, the Viewer program evaluated the recording of the values of the friction coefficient and the averages of the friction coefficient deviations automatically. The friction coefficients were continually recorded and wear volume on each specimen was calculated from the surface profile traces across the wear track and perpendicular to the sliding direction using the confocal microscopy (SENSOFAR). The measurement was performed according to ISO 208 08: 2004 (E). Subsequently, we investigated the mechanisms of wear and local chemical composition in traces of wear on an Auriga Compact FIB-SEM electron microscope. The worn volume of the sample was calculated according to the following equation [STN ISO 20808:2004]:

$$V_{disc} = \frac{\pi \cdot R(S_1+S_2+S_3+S_4)}{2} \quad (1)$$

where

V_{disc} – sample wear volume [m^3], R- skiding radius [m],

S1-S4 – represents the cross-sectional areas at four points on the wear track [m^2];

The specific wear rate of the area sample was obtained from the equation:

$$W_{s(disc)} = \frac{V_{disc}}{F_p \cdot L} \quad (2)$$

where

$W_{s(disc)}$- specific wear rate of sample (mm^3/Nm), Fp – applied load [N], L- sliding distance [m];

3 RESULTS AND DISCUSSION

The calculation of the worn volume of the sample V_{disc} was determined as a relation from the values of the areas of the cross-section profiles (S1-S4). For the pattern, a calculation was used measured values from the printed and hardened sample after wear test. Pattern values are R= 2 mm = 0.002 m, areas (S1-S4) in Table 2.

Table 2. Measured values of cross-sectional profile areas (S1-S4), printed and hardened sample

	µm²	mm²
S1	19050.9	0.019051
S2	13046.5	0.013047
S3	21079.1	0.021079
S4	15496.8	0.015497

$$V_{disc} \frac{3.14 \times 2mm \times (0.019051\,mm^2 + 0.013047\,mm^2 + 0.021079\,mm^2 + 0.015497\,mm^2)}{2} = 0.215634162mm^3 \quad (3)$$

The measured values of all profiles on all samples are presented in Table 3.

Table 3. Measured values of worn volume V_{disc}

Samples, plane	only printed, B	printed and hardened, T
R [mm]	2	2
S1 [mm²]	0.047386	0.019051
S2 [mm²]	0.033064	0.013047
S3 [mm²]	0.028586	0.021079
S4 [mm²]	0.057232	0.522082
V_{disc} [mm³]	0.015497	0.215634

For calculating the specific wear of the sample Ws(disc) were used calculated values of Vdisc parameter. The formula for the calculation is given above. For example, the calculation of the Vdisc sample, V_{disc}=0.522082 mm^3.

$$W_{S(disc)} = \frac{0{,}522082mm^3}{5N \times 1000m} = 10{,}44164E-5mm^3/Nm \quad (4)$$

Results of specific wear of samples Ws(disc) are presented in Table 4.

Table 4. Results of specific wear of samples $W_{s(disc)}$

Samples, plane	only printed, B	printed and hardened, T
F [N]	5	5
L [m]	1000	1000
W_s [mm³/Nm]	1.044 E-05	4.31E-05
V_{disc} [mm³]	0.522082	0.215634

Calculation of the coefficient of friction from the applied load and average value of friction force using equation [10]:

$$\mu = \frac{F_t}{F_p} \quad (5)$$

where:

μ -coefficient of friction,

F_t – the average value of friction force [N],

F_p – applied force [N];

The measurement of friction coefficient was evaluated automatically during ball-on-disc method. Measured data after wear test (ball-on-disc method) coefficient of friction (maximal, minimal), the average coefficient of friction and offset friction coefficient are stated in Table 5.

Table 5. Measured values of the coefficient of friction

Samples, plane	only printed, B	printed and hardened, T
Minimal coefficient of friction	0.02	0.03
Maximum coefficient of friction	0.91	0.98
Average coefficient of friction	0.75	0.80
Offset ± coefficient of friction	0.17	0.09

Materials that were hardened by aging at 490 °C for 6 hours showed higher wear resistance. These materials achieved significantly higher values of hardness. This change in hardness is related to the change in microstructure after heat-treatment [Turtelli et al. 2006]. The surfaces of the samples after tribology evaluation were worn, without significant cavity cracks or other irregularities. Figures 3 and 4 show worn surfaces of samples on samples after the wear test observed with SEM.

Heat-treated materials after hardening showed a lower degree of surface wear, compared to only printed samples without heat-treatment (here volume of removed material was smaller). Samples only printed without heat-treatment had more pronounced locations of material particles, especially in the central part of the tribological trace [Cacko et al. 2014]. A detailed analysis of the worn surfaces of the evaluated material revealed that the most common mechanism of wear in both of type samples was adhesive wear.

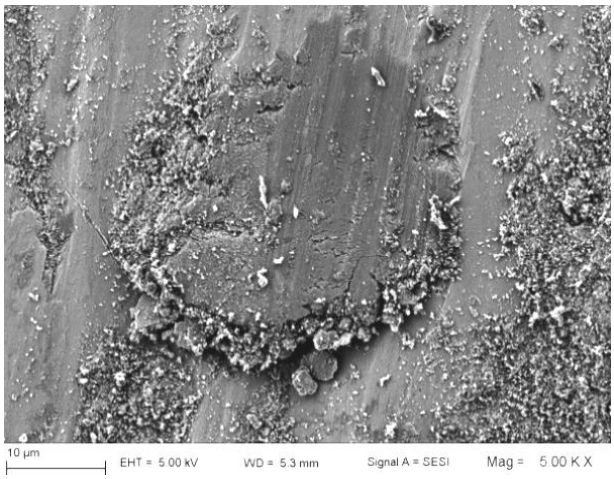

Figure 3. SEM worn surface of only printed sample

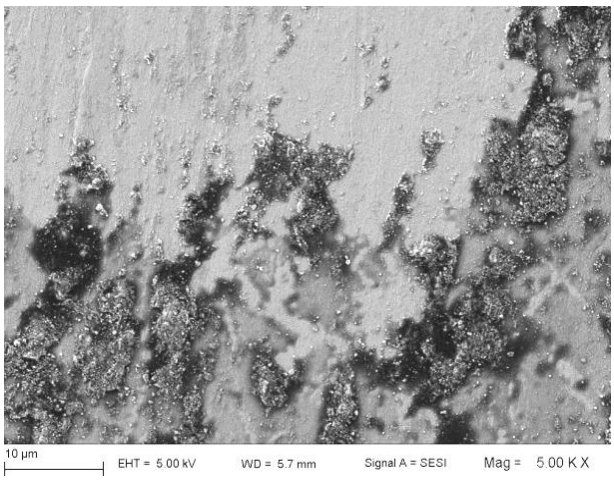

Figure 4. SEM worn surface of printed and hardened sample

Figure 5 and 6 show traces of worn surface after ball-on-disc wear test observed at 100x magnification. The area values of the cross-sectional profiles (S1-S4) were measured using a confocal microscope. During adhesive wear the particles of material separated and moved at the interface. The free particles were then oxidized with atmospheric oxygen and accumulated on the worn surface, which locally caused abrasive wear of the samples. The presence of abrasive wear confirmed the occurrence of scratches and wear debris in the samples of material without heat-treatment.

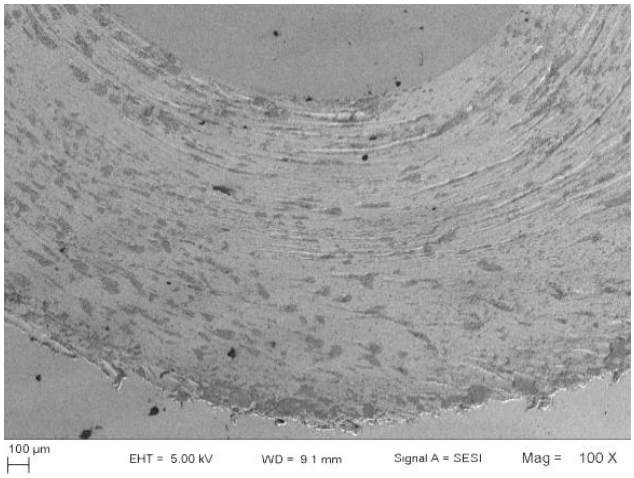

Figure 5. Trace of worn sample area, only printed

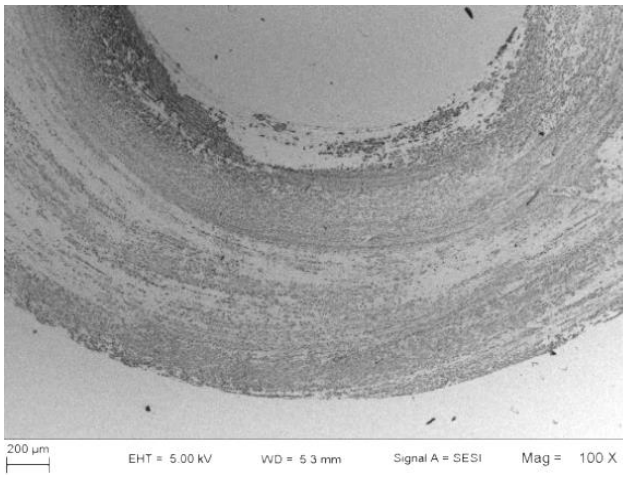

Figure 6. Trace of worn sample area, printed and hardened

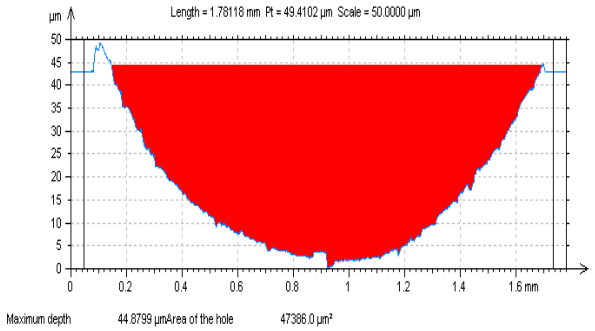

Figure 7. Measurement of trace of worn sample area, only printed

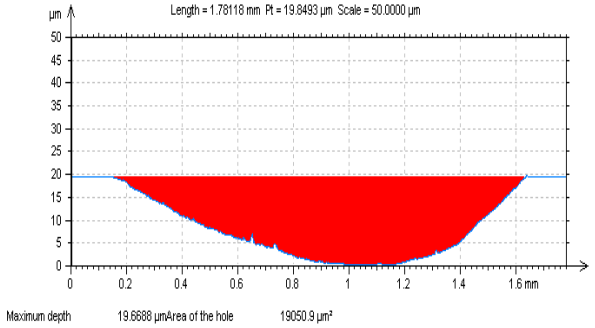

Figure 8. Measurement of trace of worn sample area, printed and hardened

4 CONCLUSIONS

The measured values of the friction coefficients appeared to be independent of the heat treatment used. The values of the average coefficient of friction ranged from 0.8 for heat-treated samples, while it was 0.75 for slightly uncoated materials. However, a more significant effect of heat treatment was found in determining the specific wear rate of materials. The wear rate for heat-treated samples ranged from $3.92x10^{-5}$ to $6.18x10^{-5}$ (mm^3 / Nm). Higher wear rates were achieved by steels without heat treatment, from $6.25x10^{-5}$ to $1.044x10^{-4}$ (mm^3 / Nm). Materials that were cured by aging at 490 °C for 6 hours showed higher wear resistance, at the same time these materials also achieved significantly higher hardness values.

A detailed analysis of the worn surfaces of the evaluated material revealed that the most common mechanism of wear in both types of samples was adhesive wear, where separate particles of material moved at the point of their contact surfaces. The presence of abrasive wear confirmed the occurrence of scratches and wear debris, which prevailed in samples without heat treatment.

ACKNOWLEDGMENTS

The authors would like to thank the grant agency for supporting research work and co-financing of the projects KEGA 018TUKE-4/2021 and Vega 1/0431/21.

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