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INVESTIGATION OF SURFACE AFTER EROSION USING OPTICAL PROFILOMETRY TECHNIQUE

Wojciech Tarasiuk1), Tadeusz Szymczak2), Andrzej Borawski1)

1) *Bialystok University of Technology, Faculty of Mechanical Engineering, ul. Wiejska 45A, 15-345 Bialystok, Poland*
(✉ *w.tarasiuk@pb.edu.pl*, +48 57 144 3038, *a.borawski@pb.edu.pl*)
2) *Motor Transport Institute, Centre for Material Testing, ul. Jagiellonska 80, 03-301 Warsaw, Poland*
(*tadeusz.szymczak@its.waw.pl*)

Abstract

The paper reports experimental results of the analysis of the 145Cr6 steel surface after erosion using the profilometrical technique by means of interferometry streaks. Erosive tests were carried out using abrasive containing quartz sand used in water jet cutting. Differences in the intensity of erosive wear were dependent on the angle of the abrasive stream (10°, 15°, 20°, 30°, 60°, 90°). In order to determine the characteristic features of the surface layer after the impact of the erosive stream, its characteristic parameters, such as roughness Ra and Sa for linear and field measurements, were analysed. Geometrical features of the regions investigated, such as shape, depth, angle of the abrasive stream, are presented. The analysis was carried out in two-dimensional (2D) and three-dimensional (3D) coordinate systems.

Keywords: optical profilometry, erosion, surface layer, roughness, 3D results.

1. Introduction

Profilometry is a measurement technique used to measure the surface topography. In most laboratories it is performed by using contact profilometers. They are operated by moving a measuring stylus attached to a high tilt sensitivity arm over a measured surface [1]. In effect, the measuring tip is moved laterally due to the shape of measured surface and vertically due to irregularities encountered on the analysed surface. The end result is an averaged roughness value determined for the distance the measuring stylus has traveled [2, 3].

Aside from the described measurement technique, the condition of a surface layer may be also measured using a non-contact technique, for example optical profilometry [4–6]. It is carried out by using the rules of streak interferometry where the polarized light is used to illuminate the surface and changes in interferential streaks, resulting from surface irregularities are tracked. The advantage of this method is the ability to obtain results images in *two-* (2D) or *three-dimensional* (3D) coordinate systems, along with surface parameters and digital files containing numerical values.

As literature data shows [7, 8, 15–17], streak interferometry technique in optical profilometry can be applied to both flat surfaces and spherical ones [6]. It is also used in quality control of microprocessor and solar panel surface manufacturing. In the area of technology and utilization research the aforementioned technique is used to determine the wear of cutting tools and to examine the condition of the surface after abrasion and corrosion tests [9–11, 13]. As can be readily seen, there are no results showing its application in the assessment of the condition of surface layers of materials subjected to erosion.

Erosive wear is a process occurring in many industries [10, 11, 14]. We can encounter it in pneumatic transport systems, air ducts, jet engine blades, mills, fans, and many other systems [11, 12, 14]. As the consequence of the influence of particles carried by a stream of air or liquid, a surface degradation occurs. It is much bigger and more irregular than that the degradation resulting from other wear mechanisms [10]. Additionally, the eroded area may cause a disturbed medium flow.

The main indicator we use to assess the wear intensity is the mass loss. However, in many applications the quality of the surface (*e.g.* roughness, wear depth) is an important factor. It affects how the particles of a transported medium accumulate, resulting in the areas which are hard to be cleaned, or even disturb the nominal transport of the medium [11, 12].

Therefore, the aim of this study is to examine the possibility and efficiency of using optical streak profilometry technique to determine the topography of the surface layer of a material subjected to erosion stream and determine the characteristics of the surface after erosion and correlate them with the values of the angle of abrasive stream.

2. Research methodology

The subject of the research was hardened tool steel 145Cr6 (NC6). This material is used in manufacture of cutting tools and working elements of machines operating in harsh environment and subjected to eroding factors. Research samples were cut from a 10 mm thick steel sheet using a water jet. The samples were cuboid-shaped with dimensions of $30\times30\times10$ mm. Before the heat treatment their walls were sanded to ensure equal quality of surfaces. Both biggest surfaces of the sample were subjected to erosive stream. The stream contained quartz sand used in the water jet cutting technique. The sand granulation was “mesh80”, which means grain size of 180 μm to 212 μm. The sand was carried by an air stream with the pressure of 0.5 MPa. The values of abrasive angle were 10°, 15°, 20°, 30°, 60° and 90°. The samples were weighed using a RADWAG electronic scales after every 30 seconds of impact from the stream of eroding particles. The wear was determined on the basis of based the mass loss. The measurements were performed with the accuracy of 0.0001 g. Due to the constant speed of the abrasive stream and the measurement frequency as well as their precision, the total time of an erosion test was no longer than 2.5 min. The nozzle distance from the sample was 15 mm. This approach allowed to recreate the operating work status of the analysed material under the laboratory conditions. A schematic of the test stand is shown in Fig. 1.

After being subjected to the abrasive jet the surface of a sample was examined using the optical profilometry technique based on streak interferometry principles. The measurements were performed using a Contour GT-K1 Brucker optical profilometer. It is equipped with a self-leveling table with four independent air bags whose pressure is automatically maintained by a compressor. Samples are placed on a measurement table equipped with a manual angular leveling function in two mutually perpendicular directions and an automatic traverse function for test areas defined with frames/measurement fields. The device is equipped with three lenses

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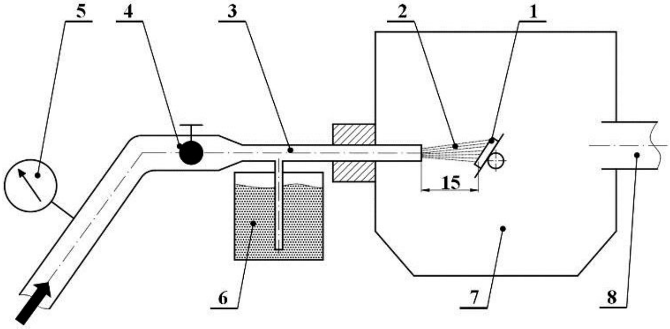


Fig. 1. A schematic of the test stand for erosional wear tests: 1 – a sample of the material tested, 2 – abrasive stream, 3 – nozzle, 4 – valve, 5 – manometer, 6 – send, 7 – chamber, 8 – outlet.

with magnifications of 5×, 20× and 50×. Together with an optical system, it allows the device to reach the magnifications of 70×; 300× and 700×. The profilometer was operated using a PC with Vision 64 software. The measurement results are represented in the form of 2D or 3D images along with a table containing the results of the surface topography analysis. The device allows examination of the condition of a surface layer with irregularities not bigger than 60 nm. Profilometric measurements were performed using the optical magnification of 5×. Before each examination, the sample was positioned using micrometer screws until the interference streaks were evenly distributed. Then were the measurements were performed using automatic and constant surface imaging based on the previously defined measurement field mesh the shape of a rectangle (measurement frame). For each sample, the field was defined individually using the wear trace symmetry axis. For this purpose an automatic field measurement technique using a predefined number of measurement fields in the range from 16 to 24 fields was used. For each of the fields, the topographic parameters were determined and combined into a wear zone image which is the final test result.

3. Results and analysis

The sample surfaces where the wear was present (Fig. 2) were subjected to hardness tests. Tests were performed using a Struers Duramin-500 metal durometer at in accordance with the Vickers method HV5 standard using a load of 49.03 N [18].

The results of the hardness test are shown in Table 1. They show the value of the abrasive stream angle which had the most negative impact on the designated mechanical parameter, *i.e.* 20°.

The performed tests provided us with the information at Table 2 regarding the mass loss in relation to the abrasion stream angle. The biggest mass loss was observed for the abrasion stream with the angle of 60°, whereas the smallest one was observed when angle was 10°. The analysis of the wear areas using optical profilometry also provided the additional data regarding the surface condition as shown in Figs. 5, 6. For comparison purposes, the wear trace depth and roughness parameters R_a and S_a, respectively, linear and superficial, were selected. A summary of the obtained values of analysed parameters is shown in Table 2.

By analysing the obtained results we can identify the abrasive angles resulting in the mass wear. This angles are 30° and 60°. These values were also accepted as limits of the biggest range

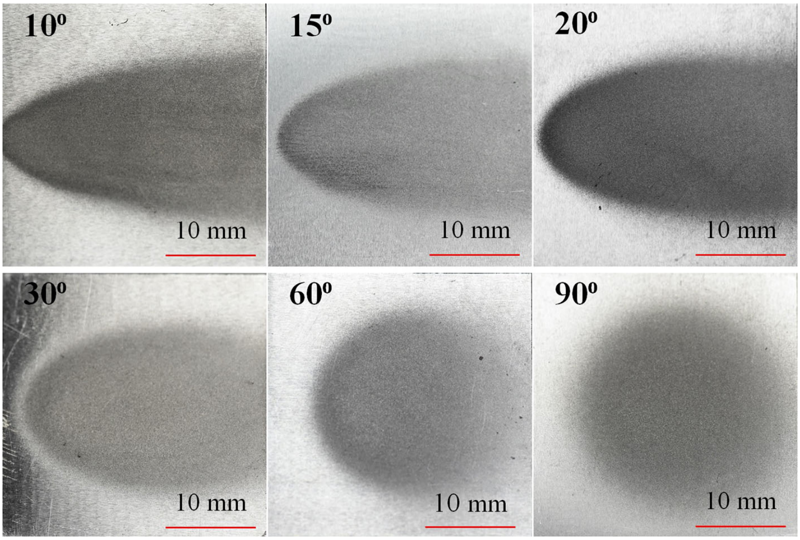


Fig. 2. NC6 steel samples after the erosive wear test; angles of incidence of abrasive stream from 10° to 90°.

Table 1. Hardness test results for steel 145Cr6 (NC6) subjected to erosion.

Abrasive stream angle	Method of measurement (scale)	Hardness values					Average hardness [MPa]
		Measurement 1 [MPa]	**Measurement 2 [MPa]**	**Measurement 3 [MPa]**	**Measurement 4 [MPa]**	**Measurement 5 [MPa]**	
10°	HV5	765	745	719	735	727	738 ± 23
15°	HV5	765	745	719	735	727	738 ± 23
20°	HV5	714	701	719	676	662	694 ± 29
30°	HV5	729	748	745	686	679	717 ± 36
60°	HV5	719	774	743	751	774	752 ± 27
90°	HV5	724	727	737	757	757	740 ± 22

Table 2. Summary of parameters characterizing the surface of hardened steel 145Cr6 (NC6) samples subjected to an abrasive stream at various angles.

The angle of incidence of the abrasive stream	**10°**	**15°**	**20°**	**30°**	**60°**	**90°**
Wear [mg]	32.6	42.6	52.5	67	68.6	52.6
The depth of the trace of wear [µm]	25.4	41.2	61.4	113.7	179.6	128.5
Roughness parameter R_a [µm]	5.4	10.2	17	28.6	53.2	40.4
Surface roughness parameter S_a [µm]	3.6	7.2	12.2	23.1	46.5	29.6

of the abrasive angle for the biggest mass loss of the analysed material as shown in Fig. 3a. It is worth pointing out that the mass wear for abrasive stream angle of 20° and 90° was almost equal.

In the case of wear depth and surface roughness (R_a and S_a), the differences between the values of the aforementioned quantities, depending on the abrasive stream angle, were much

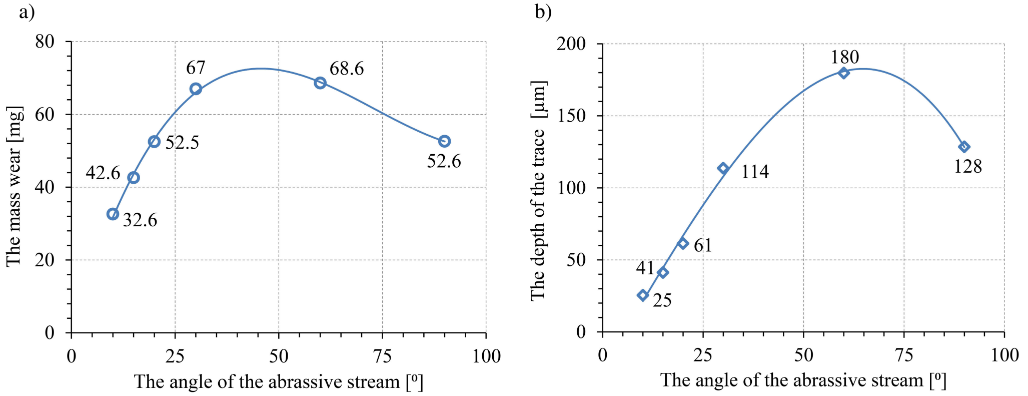


Fig. 3. The mass wear (a) and the depth of the trace (b) as a function of the angle of the abrasive stream.

bigger as shown in Figs. 3b and 4. The depth of the profile increased as the abrasive stream angle increased to 60°, Fig. 3b which is 7 times bigger than the result obtained for the smallest abrasion angle value tested.

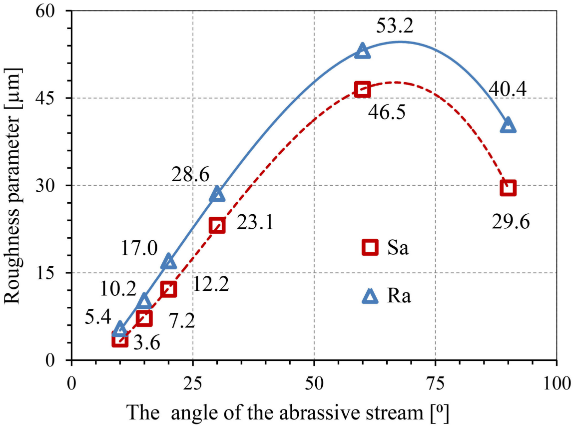


Fig. 4. Roughness parameter versus the angle of the abrasive stream.

As regards surface roughness defined by R_a, the measurement result for abrasive stream angle of 10° was almost 10 times smaller than that for the erosive stream angle of 60°. The measurement results in the form of roughness surface parameter (S_a) also indicated significant differences in the quality of the examined areas depending on the angle of the abrasive stream operating.

As it comes to after-erosion surface topography acquired using optical profilometry, a much wider spectrum of parameters characterizing the examined surface layer was obtained, as shown in Figs. 5, 6. Figure 5 shows the 2D surface topography of samples subjected to an abrasive stream acting at different angles.

The result of erosive stream angle impact was clearly visible in 3D topography images of the examined surfaces, as shown in Fig. 6. They reveal regions with different erosion levels, *i.e.* from the stream impact area, through influence and confluence areas.

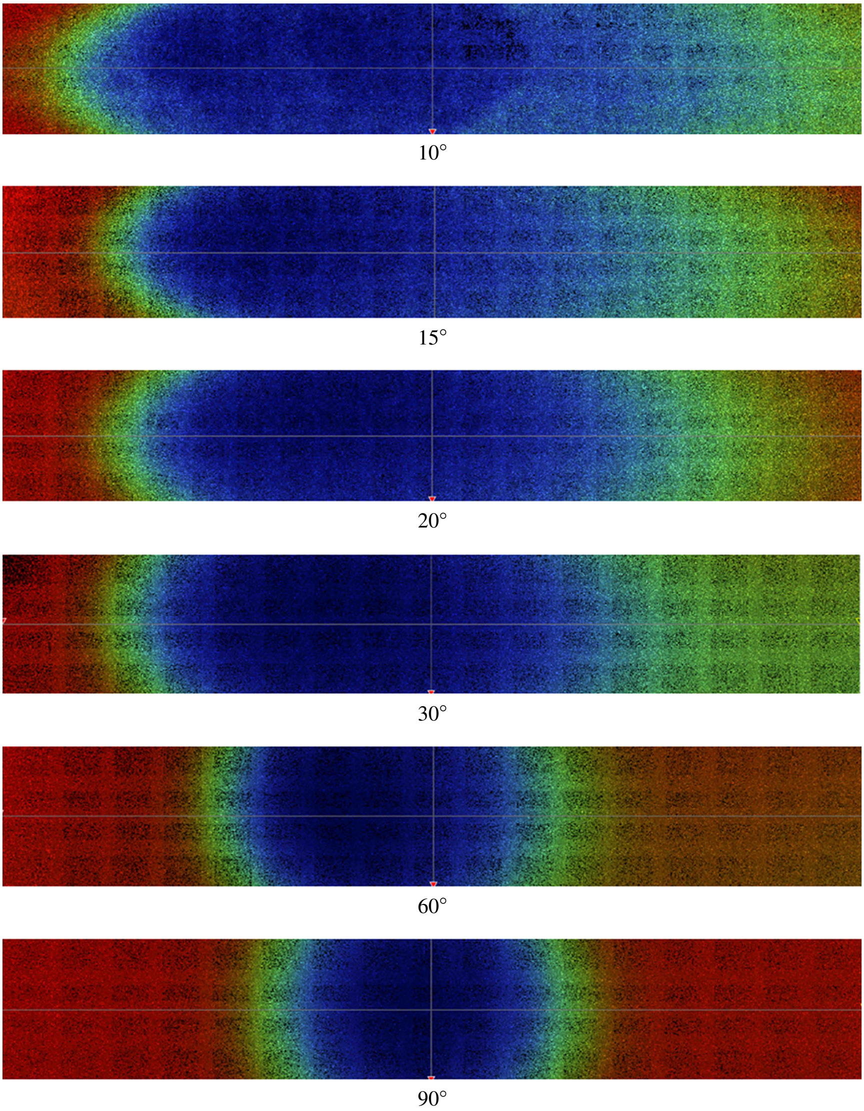
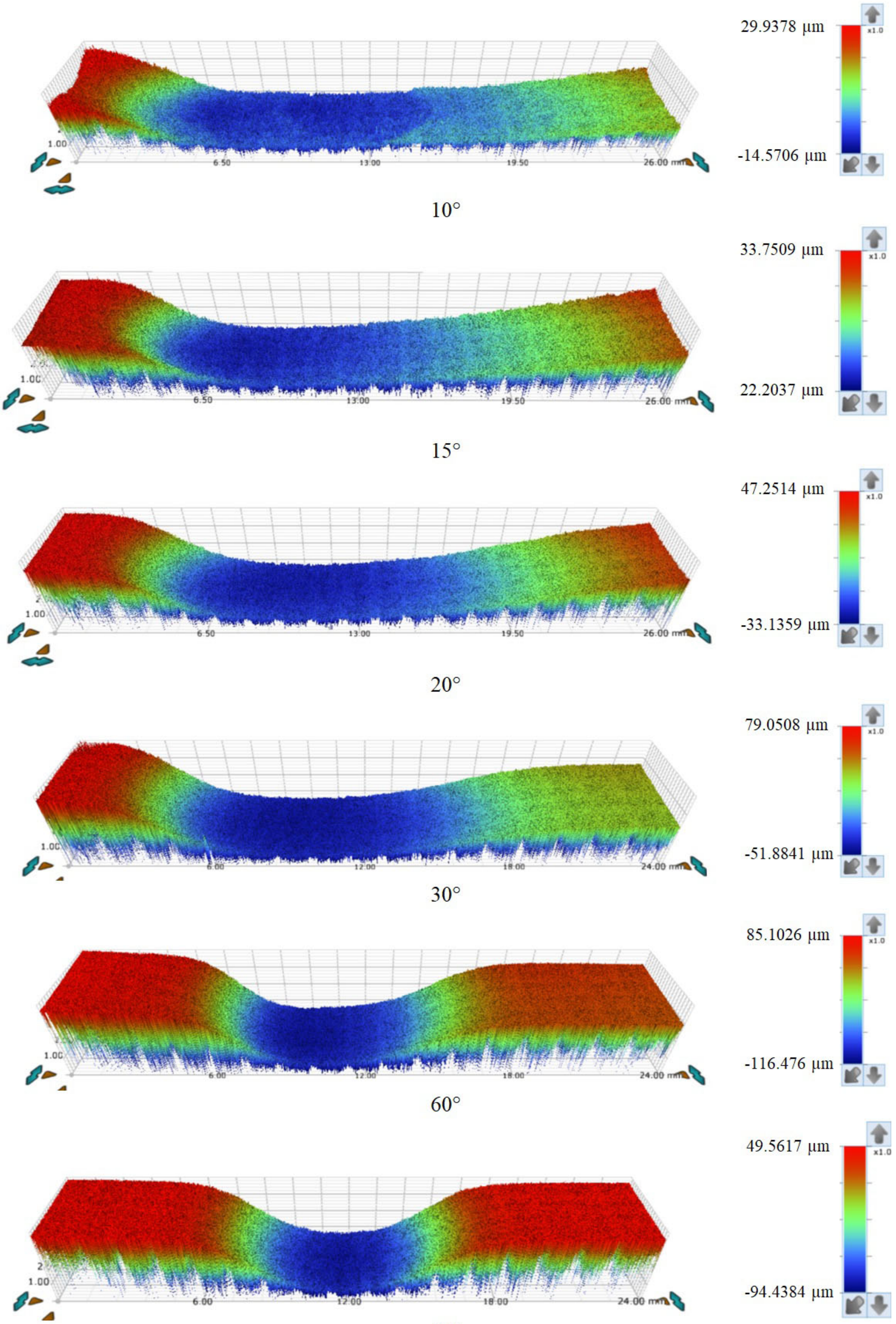


Fig. 5. 2D surface topography of profilometric measurements of samples subjected to an abrasive stream acting at an angle in the range from 10° to 90°.

On the basis of the obtained result, we can determine the ratio between the wear area and its depth, while it cannot be determined through regular photos or 2D images. Additionally, we can determine the shape of the abrasive stream impact zone. Such a result can also be used to determine the direction of abrasive incidence. It is worth noting that standard examination of the wear areas does not allow us to unequivocally investigate the wear depth and surface condition, which is very important in the case of numerous types of machines due to operational reasons. The measurements performed using optical profilometry enable obtaining precise and reliable information on the condition of the examined area and may be used in the diagnostics of machine parts subjected to erosive wear.



10°

15°

20°

30°

60°

90°

Fig. 6. 3D surface topography of profilometric measurements of samples subjected to an abrasive stream acting at different angles.

4. Conclusions

Optical streak profilometry technique can be successfully applied to measure representative regions of erosive wear areas. It allows to determine the topography of the wear areas resulting from an erosive stream impact with different parameters. The obtained results are analysed with regard to changes of different parameters.

The advantage of such measurements is obtaining a substantially number of parameters by doing only one surface measurement.

Based on the erosive wear results and images obtained using optical profilometry it can be concluded that:

- mass wear of hardened steel 145Cr6 (NC6) was the biggest for the abrasive stream angle of 60° and smallest for that of 10°,
- mass loss for abrasion stream angle of 10° was almost two times smaller as compared to that at the angle of 60°,
- depth of the wear traces for abrasive stream for angles of 60° and 10° had a 7-fold difference assuming higher values for the former of the aforementioned angles,
- depth of wear for the abrasive stream angle of 10° is 25.4 µm, and for that of 60° (the largest mass loss) is 179.6 µm,
- surface roughness parameters R_a and $S_a$for the abrasive stream angle of 60° were almost 10 times bigger than that for the angle of 10°,
- surface roughness parameter R_a equals 5.4 for the abrasive stream angle of 10° and 53.2 for that of 60°,
- surface roughness parameter S_a equals 3.6 for the abrasive stream angle of 10° and 46.5 for that of 60°.

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References

[1] Werner, A., Poniatowska, M. (2009). Coordinate measurements of complex-shape surfaces. *Proc. of XIX IMEKO World Congress Fundamental and Applied Metrology*, Lisbon, Portugal, 1815–1820.

[2] Rudnicki, Z. (2010). *Metody komputerowej analizy obrazów w badaniach tribologicznych*. Kraków: Wydawnictwo Akademii Górniczo-Hutniczej. (*in Polish*).

[3] Wieczorowski, M. (2009). *Wykorzystanie analizy topograficznej w pomiarach nierówności powierzchni*. Poznań: Wydawnictwo Politechniki Poznańskiej.

[4] Pawlus, P., Reizer, R., Wieczorowski, M. (2017). Problem of non-measured points in surface texture measurements. *Metrology and Measurement Systems*, 24(3), 525–536.

[5] Petzing, J., Couplnad, J., Leach, R. (2010). *The measurement of rough surface topography using coherence scanning intereferometry*. Measurement Good Practice Guide No. 116, London: National Physical Laboratory.

DOI: 10.24425/mms.2020.132773

[6] Szymczak, T., Brodecki, A., Eminger, A., Kowalewski, Z.L., Rudnik, D. (2016). Experimental assessment of ball joints operation using servo-hydraulic testing systems. *Solid State Phenomena*, 240, 232–237.

[7] Pawlus, P., Reizer, R., Wieczorowski, M. (2018). Comparison of results of surface texture measurement obtained with stylus methods and optical methods. *Metrology and Measurement Systems*, 25(3), 589–602.

[8] Niemczewska-Wójcik M., Sładek, J., Tabaka M., Wójcik, A. (2014). Product quality assessment – measurement and analysis of surface topography. *Metrology and Measurement Systems*, 21(2), 271–280.

[9] Lu, Z., McKellop, H.A. (2014). Accuracy of methods for calculating volumetric wear from coordinate measuring machine data of retrieved metal-on-metal hip joint implants. *Proc. of the Institution of Mechanical Engineers, part H*, 228(3), 237–49.

[10] Krupicz, B., Liszewski, M., Tarasiuk W. (2016). Mechanical properties of materials and their erosive wear. *Tribologia*, 5, 85–94.

[11] Kosarac, A., Sikuljak, L., Salipurevic, M., Mladenovic, C., Zeljkovic, M. (2019). Prediction of self-excited vibrations occurance during aluminium alloy AL 7075 milling. *Proc. of the 18th International Symposium INFOTEH-JAHORINA*, East Sarajevo, Bosnia and Herzegovina.

[12] Tarasiuk, W., Piwnik, J., Węgrzyn, T., Sietelski, D. (2016). Wear Resistance of Steel 20MnCr5 after Surfacing with Micro-jet Cooling. *Archives of Foundry Engineering*, 16(3), 121–124.

[13] Węgrzyn, T., Piwnik, J., Wszołek, Ł., Tarasiuk, W. (2015). Shaft wear after surfacing with micro-jet cooling. *Archives of Metallurgy and Materials*, 60(4), 2625–2630.

[14] Łukaszewicz, A. (2019). Nonlinear Numerical Model of Friction Heating during Rotary Friction Welding. *Journal of Friction and Wear*, 39(6), 476–482.

[15] Borawski, A. (2016). Suggested research method for testing selected tribological properties of friction components in vehicle braking systems. *Acta Mechanica et Automatica*, 10(3), 223–226.

[16] Babicz, S., Stawarz-Graczyk, B., Wierzba, P. (2018). Phase object observation system based on diffraction phase microscopy. *Metrology and Measurement Systems*, 25(1), 213–221.

[17] Hawryluk, M., Ziemba, J., Dworzak, Ł. (2017). Development of a method for tool wear analysis using 3D scanning. *Metrology and Measurement Systems*, 24(4), 739–757.

[18] PN-EN ISO 6507-1:2018-05. Metals-Vickers hardness measurement. Part 1. Test method.