EFFECT OF TEST PARAMETERS ON ABRASION RESISTANCE OF COATINGS UNDER ABRASIVE WEAR CONDITIONS

GERHARD MITAL[1], TOMAS JEZNY[1], EMIL SPISAK[1]

[1]Technical University of Kosice, Faculty of Mechanical Engineering, Kosice, Slovakia

DOI: 10.17973/MMSJ.2024_12_2024114

gerhard.mital@tuke.sk

The article deals with the determination of the influence of the speed of hard metal layers welding, with a focus on the evaluation of the abrasive wear of the layers formed by the tubular wire welding technology. The layers were wound with filled wire manufactured by ESAB under the trade name Fluxofil 58. Two different winding speeds of v=125m/min and a speed of 18m/min were used to produce the samples. Subsequently, it was necessary to determine the dependence of abrasive wear on the different abrasive hardness.

The abrasives used in the experiment were SiO_2 (silica) and Al_2O_3 (alumina, also referred to as corundum). Abrasive wear resistance was determined from the mass loss determined by weighing the prepared specimens before the test and also after traversing the 420 m and 716 m sliding paths. The specimens were prepared in accordance with ASTM G 65/16. Subsequently, an analysis of the surface degradation after wear was carried out using a Neophot 21 optical metallographic microscope. S355J0 grade steel (11 523) was used as the substrate and therefore the base material. This is a structural unalloyed steel with prescribed mechanical properties and guaranteed carbon, sulphur and phosphorus levels.

KEYWORDS

analysis, abrasive, welding speed, resistance

1 INTRODUCTION

The service life of mechanical systems in operation depends on many factors such as the design, quality of manufacture, materials used, the action of the medium being processed and the operating conditions. Surface treatments allow the development of new technical-technological designs and the properties of the contacting pair are modified at a specific location and in a precisely defined quantity and quality. The base material is designed to meet the strength requirements, the coating - a layer on top of it - ensures its tribological or other function. Various surface treatments are used to increase the service life of mechanical assemblies, these allow the creation of a surface layer or coating with high wear resistance.

Surface treatments represent a wide range of surface layers and coatings created by different technological processes [Kuric 2011]. Many technological processes are now known for the creation of surface finishes that improve the reliability and lifetime of tools and machine parts [Zdravecka 2019, Slota 2022].

Surface treatments that improve the tribological properties of metallic materials can be divided into three basic groups: surface coatings, coatings, and duplex coatings. In the formation of surface coatings, the chemical composition, structure at the surface and in the subsurface layers of the material are altered. Towards the core, a gradient of physical-mechanical and chemical properties develops without abrupt change, with no interface between the surface layer and the core [Spisak 2016, Brezinova 2019, Husain 2021].

Coatings are applied to the surface of the material that have different chemical properties and structure than the base material. An interface is formed with a change in both physical-mechanical and chemical properties [Sundstrom 2001, Buchanan 2007, Tatickova 2023].

Duplex coatings combine surface modification with coating application. There is no change in the physical-mechanical and chemical properties from the surface to the core. Duplex processes require a combination of technological processes, which complicates and increases the cost of production [Rendon 2009, Budinski 2017]. High hardness favourably affects the surface layer and high hardness coatings, against erosive, abrasive, cavitation, fatigue and vibration wear [Wu 2009, Linghui 2013, Choteborsky 2013, Cacko 2014].

Soft and tough surface layers and coatings form the basic requirement for friction and wear, i.e., a positive gradient of physical-mechanical properties [Venkatesh 2020]. Shear deformation and failure of surface layers are localized to a thin layer with high plasticity. Below the surface layers, where the strength of the material is higher, the stress-strain field is modified and the development of plastic deformation and hence failure of the material is prevented to a greater depth. These surface treatments are mainly applied in adhesive and vibratory wear [Xu 2015, Winczek 2019, Olejarova 2021].

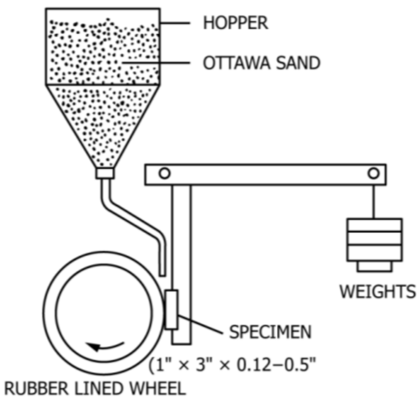

Figure 1. Schematic Diagram of Test Apparatus

2 MATERIALS AND METHODS

The specimens were wound on base material of steel grade 11 523 (S355J0) on test plates with dimensions 780mm × 360mm × 17.5mm. Specimens were then cut from the plates with dimensions of 70mm x 22mm x 6mm required for fixing into the test tribometer. The friction system (friction triplet) consisted of a coated specimen, a rotating disc with a rubber lining and abrasive particles sprinkled from a hopper (Fig. 1), which were of different hardness. The surface of the test specimens was milled and ground (Figs. 2 and 3) to a roughness of Ra=0.2 µm (primary surface profile) in subsequent steps.

The aim of the experiments was to compare the effect of the welding speed on the tribological properties of the layers under a load of 1000N (simulated conditions of components with a given weld working under abrasive wear conditions). The experimental part also evaluated the effect of the abrasive size on the wear resistance after traversing the sliding path by evaluating the coefficient of friction and wear.

Table 1 shows the parameters of the plate winding for 780mm × 360mm × 17.5mm plates. Fluxofil 58 with a wire diameter of Ø1.2mm was used as an additional material - a base tubular

wire for welding tough and abrasion resistant layers that are subject to wear such as parts of conveyors, crushing jaws, etc. The welded layers did not show cracks or pores. The cladding was carried out in two layers, the upper layer being structurally composed of columnar crystals. Chemical composition of the coating as indicated by the additive manufacturer: **C= 0.45%, Si= 0.6%, Mn= 1.6%, Cr= 5.5% a Mo= 0.6%.**
The application of the additive material to the base material was carried out in a protective CO2 atmosphere with a melting electrode (MAG-Metal active gas).

Table 1. Conditions for rolling experimental samples

Samples of series 2	Samples of series 3
Fluxofil 58	Fluxofil 58
Thickness 39mm	Thickness 40mm
Backing material sheet thickness 30 mm	Stainless steel base material 10mm
U= 28V, I= 282A	U= 23V, I= 200A
V= 18m/min	V=125m/min

Figures 2 and 3 show the fabricated surfacing samples for the abrasive wear resistance experiment.

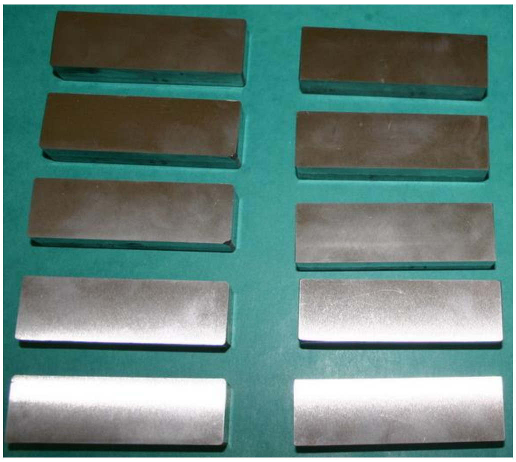

Figure 2. View of the ground surface of the test specimens before wear

Samples were labeled with number stamps as documented in Figure 3.

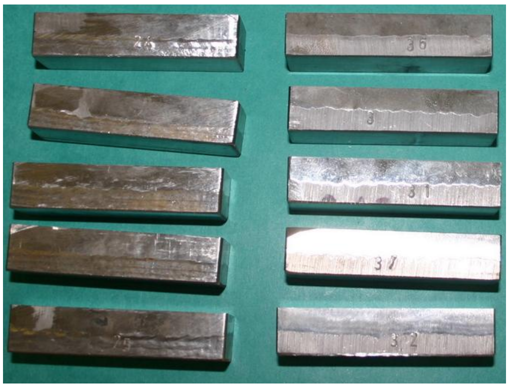

Figure 3. View of the cooked layers of the test samples

2.1 Abrasive materials used

In the use of machinery in industrial praxis, natural materials are often encountered, the hardest component of which is SiO_2 (~1000 HV).
It is therefore a given that materials with a hardness of 500 - 770 HV have a high wear resistance. Laboratory experiments have shown that even steels with a high proportion of hard complex carbides do not have constant values of abrasive wear resistance.

Table 2. Comparison of different types of hardness of abrasives

Material	Hardness (HV)	Metal material	Hardness (HV)
limestone	110	Armco iron	90
glass	500	Stinging steel	100 - 250
feldspar	600 - 750	perlite steel	230 - 350
quartz	900 - 1280	steel for rolling bearings	700 - 950
WC	1900	tool steels	700 - 1000
corundum	2000	cemented steel	900
TiC	2450	nitrided steel	900 - 1250
SiC	2500	WC+Co	1400 - 1800

Based on the dependence of the mineralogical properties of the abrasives, where hardness and grain shape (macro and microgeometry) are important (Table 2), two types of abrasives were used for the experimental tests:

1. quartz - SiO_2 (Fig.4)
2. corundum - Al_2O_3 (Fig.5)

The following abrasive dimensions were used in the tests: 0.2 – 0.315 mm.

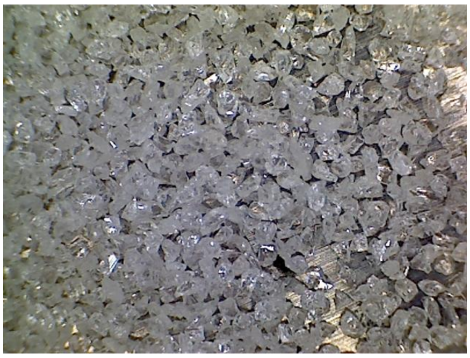

Figure 4. Abrasives SiO_2

Figure 5. Abrasives Al_2O_3

2.2 Experimental parameters for abrasive wear tests

According to the ASTM series, the recommended rotational speed of a 229 mm diameter disc is between 10 and 350 rpm and the load per specimen is in the range of 20 to 350 N. The specimens should be 25mm x 58mm x 6-16 mm in size. The double layer welds were carried out on S355J0 metal plates. The thickness of the specimens after welding exceeded the recommended values, which was beyond the capability of the testing equipment, and therefore the base material was machined by milling and the specimens had a final thickness of 20mm. Another reason for surface modification of the specimens was to ensure that the rubberised disc would sit full flat on the surface to be tested during the test, to avoid measurement errors based on variations in the size of the test areas when testing individual specimens, as the surface finish throws off the convexity and concavity of the surface and to make the surface flatness of the surface to be tested uniform, the surface needs to be further machined by milling and grinding. At the same time, a new specimen holder has been manufactured to allow different specimen thicknesses to be tested, so that the prescribed position of the specimen relative to the axis of the wheel is always ensured.

Table 3. Parameters of test ASTM G65/16

Disc diameter	229mm
Disc material	Rubber disc
Revolutions	287 RPM
Dimensions of the sample	70mm x 22mm x18mm
Load	1000N
Abrasive	Silica sand, white corundum
Glide path	420m, 716m

3 MEASUREMENT RESULTS

The evaluation of layers applied at different speeds showed that the wear rate increases with increasing winding speed. An increase in welding speed results in a decrease in wear resistance and is observed for abrasive particle wear SiO_2 as well as Al_2O_3.

Experimental tests at constant load with 420 and 716 m runways. Wear was determined based on the mass loss after traversing the 420m runway and traversing the 716m runway. Figure 6 shows the surfacing samples after testing for abrasive wear.

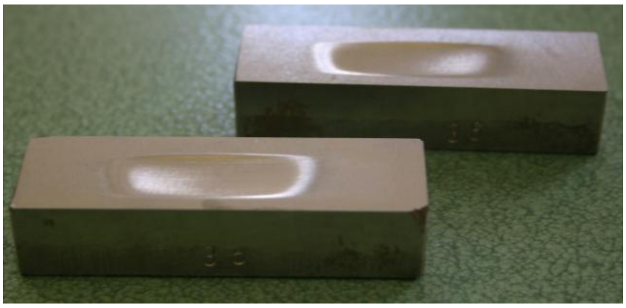

Figure 6. Appearance of samples after the test

The test specimens were weighed on precision KERN scales before and after the test with an accuracy of four decimal places. The test was interrupted, and the weighing was carried out after a sliding distance of 420m due to the temperature in the contact area reaching 80°C. Due to the effect of temperature, the ratios in the contact area of the specimen surface were changed, the gap between the specimen and the rubber disc was reduced. Achieving constant conditions in the contact area at a load of 1000N required the test to be aborted. The individual test results for Fluxofil 58 at 8m/min and using SiO_2 abrasive with a diameter of 0.2 - 0.315 mm are shown in Table 4 and Table 5.

Table 4. Mass loss versus path for Fluxofil 58, v= 18m/min and abrasive used SiO_2 on average 0.2 - 0.315 mm

Marking of test samples	420[m]-Mass loss [g]	716[m]-Mass loss [g]	Mass losses [g/m]
S. 2.6	0.0996	0.1639	0.00021 g/m
S. 2.3	0.0858	0.1456	
S. 2.0	0.0880	0.1450	
Average value	0.09113	0.1515	

Table 5. Mass loss versus path for Fluxofil 58, v= 125 m/min and abrasive used SiO_2 on average 0.2 - 0.315 mm

Marking of test samples	420[m]-Mass loss [g]	716[m]-Mass loss [g]	Mass losses [g/m]
S.3.1	0.0947	0.1672	0.000 23 g/m
S.3.2	0.1004	0.1648	
S. 3.0	0.0998	0.1678	
Avg. value	0.0983	0.1666	

Figure 7 shows the dependence of the mass loss on the winding speed for the SiO_2 abrasive used. The winding speeds in this case were 18 m/min and 125 m/min. Where the pink colour is used to graphically indicate the dependencies of the mass loss on the winding speed for a sliding distance of 420m. The column marked in white indicates the mass loss dependencies on the winding speed for the 716 m sliding path.

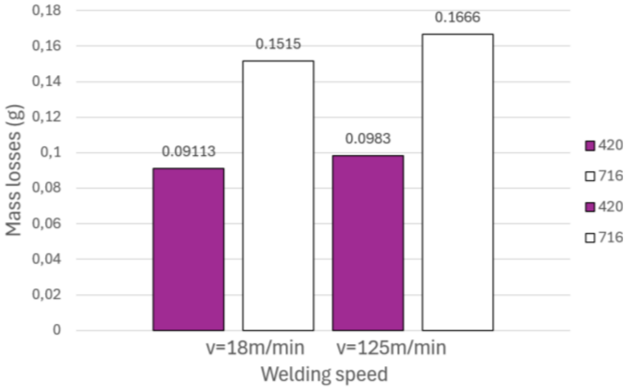

Figure 7. Mass loss in abrasive wear when using abrasives SiO_2 for layers wound at different speeds

Figures 8 and 9 document the surface of the specimens marked 3.1 and 3.2 after abrasive wear testing where there was a micro-cutting mechanism and therefore little abrasion of the material with the grooving effect of the abrasive Si02 harder than the test material.

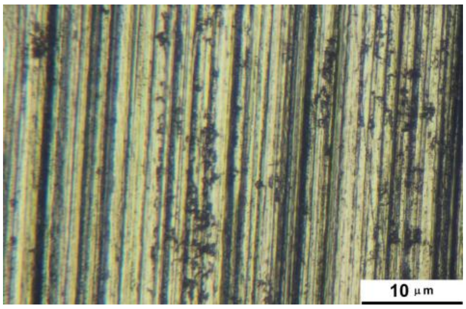

Figure 8. Surface morphology after specimen wear 3.1

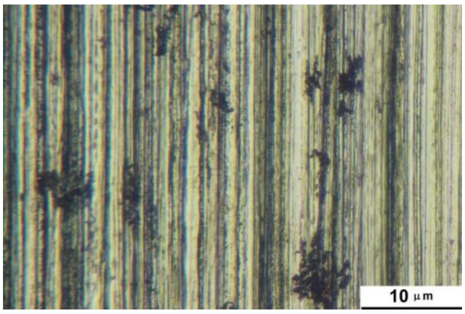

Figure 9. Surface morphology after sample wear 3.2

Individual test results for Fluxofil 58 at 18m/min and using abrasive Al_2O_3 with a diameter of 0,36 mm are given in Table 6 and Table 7.

Table 6. Mass loss versus path for Fluxofil 58, v= 18 m/min and abrasive used Al_2O_3 about the average 0.36 mm

Marking of test samples	420[m]-Mass loss [g]	716[m]-Mass loss [g]	Mass losses [g/m]
S. 2.5	1.0801	1.7493	0.000 23 g/m
S. 2.8	0.9818	1.6590	
S. 2.9	1.0202	1.6554	
Average value	1.0279	1.6879	

Table 7. Turbidity losses as a function of path for Fluxofil 58, v= 125 m/min and abrasive used Al_2O_3 on average 0.36 mm

Marking of test samples	420[m]-Mass loss [g]	716[m]-Mass loss [g]	Mass losses [g/m]
S. 3.5	1.0784	1.7041	0.000 24 g/m
S. 3.6	1.0686	1.7204	
S. 3.0	1.0695	1.7519	
Average value	1.07216	1.7255	

Figure 10 shows the dependence of the mass loss on the winding speed for the Al_2O_3 abrasive used. The winding speeds in this case were 18 m/min and 125 m/min. Where the pink colour is used to graphically indicate the dependencies of the mass loss on the winding speed for a sliding distance of 420m. The column marked in white indicates the mass loss dependencies on the winding speed for a 716 m sliding path.

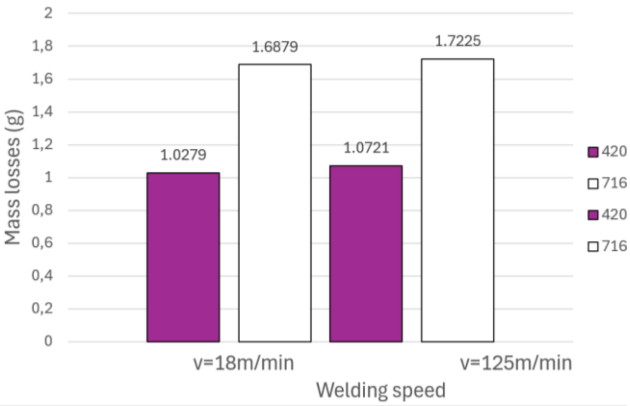

Figure 10. Dependence of abrasive wear mass loss when using abrasives Al_2O_3 for layers wound at different speeds

Figures 11 and 12 document the surface of the specimens marked 3.5 and 3.6 after abrasive wear testing where there was also a micro-cutting mechanism and therefore little material removal with the grooving effect of the abrasive Al_2O_3 harder than the test material.

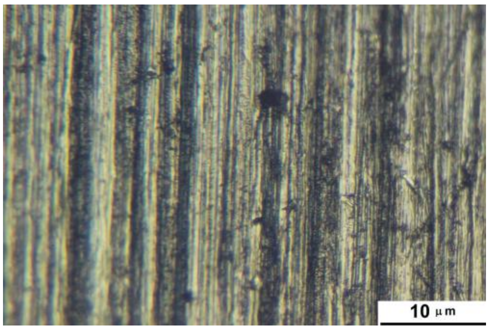

Figure 11. Surface morphology after sample wear 3.5

In order to compare the parameters and measurement agreement of the experimental equipment, tests were performed on the rubber disc equipment for test specimens 1 and 2 as well as for the 210 m runway as a supplementary measurement.

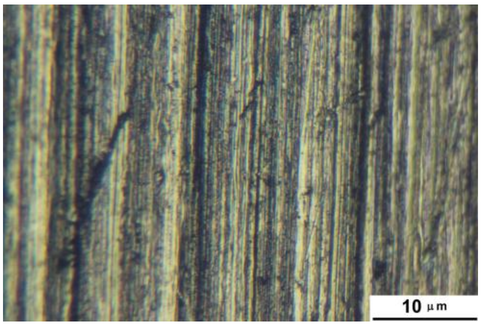

Figure 12. Surface morphology after sample wear 3.6

The results are correlated for wear with the layers (Table 4, Table 5) for the abrasives SiO_2 with diameter 0,2 – 0.315 mm. Also, the regression analysis documents a relatively high degree of adequacy of the mathematical model in the setting of the experiment itself. The regression analysis shows that the coefficient of determination and the setting of the dependent and independent variables within the values being compared exhibit a high degree of interdependence between the variable values.

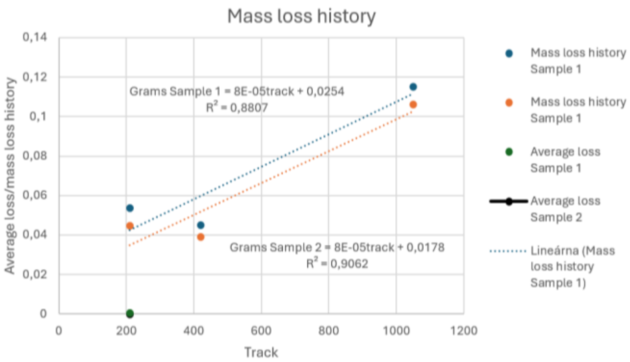

Figure 13. Mass loss and abrasive wear history when using abrasives SiO_2 Fluxofil 58, v= 18 m/min in the upper part and table of used values in the lower part

3.1 Abrasive wear of a sprayed overmoulded coating

WC-based materials are also among the materials that resist abrasive wear very well. For this reason, NP60WC50% material was used in the experiment for comparison. This material is used for pump shafts, taps, blades used in the energy, chemical and food industries, etc. The deposited layer can only be machined by diamond grinding and can only be turned with boron nitride tools. Maximum carbide content: 45 %. Coating was carried out by welding the powder material with an oxy-acetylene flame.

Tribological properties of NP 60WC45 and abrasive wear resistance were tested under the same conditions as the guides (Table 8). The coating formed by flame spraying of NP60WC45 powder is one of the materials that are resistant to all kinds of wear. Thermal flame spraying produces a coating on the surface of the coated part from the fused particles, which is subsequently reflowed by flame using an oxy-acetylene flame. This is the flame coating of metal powder by so-called two-step technology. The coatings created by the so-called "two-step technology" are thus created by adding powder which is injected in small doses into the molten bath, where it melts and forms a compact coating highly resistant to abrasive wear. The coating was applied to a plate preheated to 90°C. The spraying of the metal powder was followed by flame remelting of the coating.

Experimental tests of NP60WC45 were carried out using an abrasive Al_2O_3, due to the fact that it is a very hard coating.

Table 8. Mass loss versus path for Fluxofil 58, v= 125 m/min and abrasive used Al_2O_3 on average 0.36 mm

Marking of test samples	420[m]- Mass loss [g]	716[m]- Mass loss [g]	Mass losses [g/m]
S. 1 WC-Co	0.2215	0.7041	0.000 98 g/m
S. 2 WC-Co	0.2019	0.6904	
S. 3 WC-CO	0.2406	0.7119	
Average value	0.2213	0.7023	

The highest wear resistance of the two layers studied was achieved by the NP 60 WC 45 layer. The increase in abrasive wear resistance is associated with the carbide particle content.

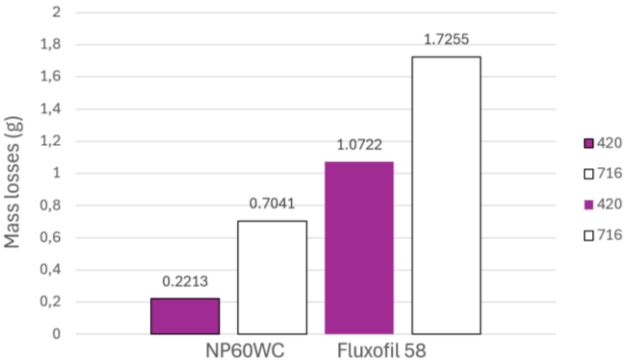

Figure 13. Comparison of mass losses of NP60WC and Fluxofil 58 using abrasive Al_2O_3

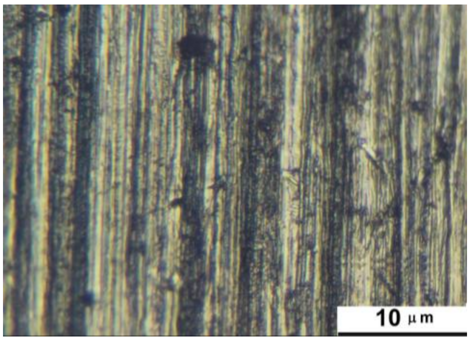

Figure 14. Wear surface - Fluxofil 58 - abrasive Al_2O_3

The surface after wear of Fluxofil 58 exhibits a micro-cutting mechanism with the grooving effect of a hard abrasive. The post-wear surface of NP50WC 45 (Figure 15) documents the sliding of abrasive grains over hard carbide particles. The cobalt matrix was preferentially worn away. The highest abrasion resistance of the NP50WC 45 two-step abrasive is associated with the high proportion of hard carbide particles in the cobalt matrix.

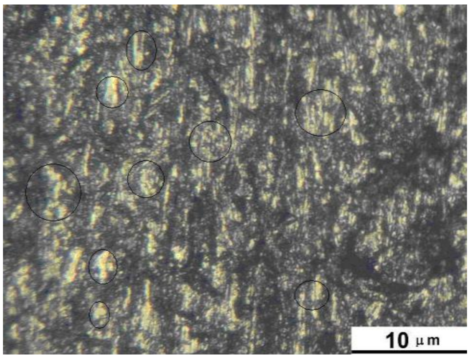

Figure 15. Wear surface NP50WC 45 - abrasive Al_2O_3

From the point of view of experimental tests in laboratories, it can be stated that the results used in friction and wear research can be applied to practical possibilities of investigating surface and subsurface indentations or thick surfacing layers as in this case. The measured experimental results show that hard and sharp particles Al_2O_3 create a micro-cutting effect on the surface. Most of the particles interfere with the tribocontact, which increases the surface wear associated with the striations of the material (Fig. 8-12, Fig. 14).

The results show a significant effect of abrasive hardness on the wear of materials. Very intense wear occurs if the abrasive used is harder (Al_2O_3) whereby the particles more intensively etch the surface of the material. The presence of a relatively softer abrasive (SiO_2) results in low shear deformation of the surface layers under the applied particle, i.e., less wear (approx. 0.00023 g/m) compared to wear with abrasive particles Al_2O_3 (approximately 10 times higher i.e. 0,00024g/m).

The silica sand and corundum used in the abrasive wear experiment showed that, as well as the surface characteristics of the layers, the type of abrasive itself is a significant factor affecting wear, and hence the conditions and type of particles acting on the surface of the material are another important evaluation criterion for the use of the abrasive in practice.

The results of laboratory tests depend on their ability to simulate the conditions in the tribology system and in obtaining the necessary data for making decisions on the choice of materials or surface treatment. The benefit of our facility is the testing of a variety of materials and consequently more realistic testing on fewer samples under conditions closer to those of real-world operation.

4 CONCLUSIONS

Abrasive wear resistance tests are an effective tool for evaluating materials and coatings. In the first stage of the experiment, technical modifications were made to the test rig for the effectiveness of simulating the surface layers of coatings under abrasive wear conditions. In the next part of the work, experimental measurement and assessment of wear resistance of materials - surfaces and assessment of the influence of surfacing parameters with determination of the surfacing speed limit were carried out. The used welding technology is still a developing field and can be applied relatively quickly and easily in operation.

In the next part of the work, experimental tests were carried out on a series of headers. In each series, the sliding distance was between 420m and 716m at a load of 1000N and a rubber disc rotation speed of 287 rpm. Ensuring the service life of the individual components and the wear process is linked to the refurbishment of the working parts of the machinery and equipment. One of the options is winding. The results obtained show that the wear resistance of the formed layer may not increase with increasing winding speed. This is related to the knowledge that it is not hardness but technological parameters, and therefore the resulting structure of the coating, that is the indicator that influences wear resistance. The highest resistance to abrasive wear was obtained by the surfacing made with the two-step technology NP50WC45, which is related to the high proportion of hard carbide particles in the cobalt matrix.

The experimental part of the work includes the study of the influence of abrasive hardness on the resistance to abrasive wear of welds. The evaluation of layers applied at different speeds showed that the wear rate increases with increasing winding speed. An increase in the winding speed results in a decrease in the wear resistance as documented by the measured data and the graphical dependence of the mass loss on the applied winding speed.

ACKNOWLEDGMENTS

This research was funded by the grant KEGA 018TUKE-4/24.

REFERENCES

[Brezinova 2019] Brezinova, J., et al. Evaluation of the influence of the welding current on the surface quality of spot welds. Metals, 2019, Vol. 9, No. 11.

[Buchanan 2007] Buchanan, V.E., Shipway, P.H., McCartney, D.G. Microstructure and abrasive wear behaviour of shielded metal arc welding hardfacings used in the sugarcane industry. Wear, 2007, Vol. 263, pp. 99-110. https://doi.org/10.1016/j.wear.2006.12.053.

[Budinski 2017] Budinski, K.G., Budinski, S.T. On replacing three-body abrasion testing with three-body abrasion testing. Wear, 2017, Vol. 376-377, pp. 1859-1865. doi.org/10.1016/j.wear.2017.01.001.

[Cacko 2014] Cacko, P., Krenicky, T. Impact of lubrication interval to operating status of bearing. App. Mech. and Mater., 2014, Vol. 616, pp. 151-158. doi.org/10.4028/www.scientific.net/amm.616.151.

[Choteborsky 2013] Choteborsky, R. Effect of heat treatment on the microstructure, hardness and abrasive wear resistance of high chromium hardfacing. Res. Agric. Eng., 2013, Vol. 59, pp. 23-28.

[Husain 2021] Husain, H., Hazdra, Z., Kudlacek, J., Kuchar, J. Risk factors for B4C composite utilization in tribological processes. In: Metal 2021 - 30th Anniversary Int. Conf. on Metallurgy and Materials, Conference Proceedings. Brno, 26-28 May 2021. Ostrava: Tanger Ltd., 2021, pp. 801-806. ISBN 978-80-87294-99-4. DOI: 10.37904/metal.2021.4186.

[Kuric 2011] Kuric, I. New methods and trends in product development and planning. Quality and Innovation in Engineering and Management, 2011, pp. 453-456.

[Linghui 2013] Linghui, S.W., Linghui, S., Qiao, S.Y., Min, M. Effect of Carbide Orientation on Impact-Abrasive Wear Resistance of High-Cr Iron Used in Shot Blast Machine. Tribol. Lett., 2013, Vol. 50, pp. 439-448.

[Olejarova 2021] Olejarova, S. and Krenicky, T. Experimental Verification of the Input Factors Variation Influence on the Generated Vibration Levels and Frequency Spectra. Materials, 2021, Vol. 14, 4281. https://doi.org/10.3390/ma14154281.

[Rendon 2009] Rendon, J., Olsson, M. Abrasive wear resistance of some commercial abrasion resistant steels evaluated by laboratory test methods. Wear, 2009, Vol. 267, No. 11, pp. 2055-2061. https://doi.org/10.1016/j.wear.2009.08.005.

[Slota 2022] Slota, J., Kubit, A., Gajdos, I., Trzepiecinsky T., Kascak, L. A comparative study of hardfacing deposits using a modified tribological testing strategy. Lubricants, 2022, Vol. 10, No. 8, 187. https://doi.org/10.3390/lubricants10080187.

[Spisak 2016] Kascak, L. Spisak, E. The Analysis of Plastic Strain of Single and Double Reduced Tinplates. The International Journal of Engineering and Science, 2016, Vol. 5, No. 12, pp. 32-37. ISSN 2319-1805.

[Sundstrom 2001] Sundstrom, A., Rendon, J., Olsson, M. Wear behaviour of some low alloyed steels under combined impact/abrasion contact conditions. Wear, 2001, Vol. 250, pp. 744-754.

[Tatickova 2023] Tatickova, Z., Kudlacek, J., Zoubek, M., Kuchar, J. Behaviour of Thermochromic Coatings under Thermal Exposure. Coatings, 2023, Vol. 13, No. 3, 642. https://doi.org/10.3390/coatings13030642.

[Venkatesh 2020] Venkatesh, B., Sriker, K., Kumar, M.A. Wear characteristics of multi layer hardfacing alloys. AIP Conf. Proc., 2020, Vol. 2259, 020020. DOI: 10.1063/5.0017689.

[Winczek 2019] Winczek, J., Gucwa, M., Mician, M., Konar, R., Parzych, S. The evaluation of the wear mechanism of high-carbon hardfacing layers. Arch. Metall. Metals, 2019, Vol. 64, pp. 1111–1115.

[Wu 2009] Wu, C. S., Hu, Z. K., Zhang, Y. M. Suppression of weld-bead defects and increase in the critical welding speed during high-speed arc welding 2009. In: Proc. of the Institution of Mech. Eng., Part B: J. of Engineering Manufact., 2009, Vol. 223, Iss. 6. https://doi.org/10.1243/09544054JEM136.

[Xu 2015] Xu, X., van der Zwaag, S., Xu, W. A novel multi-pass dualindenter scratch test to unravel abrasion damage formation in construction steels. Wear, Vol. 322-323, pp. 51-60. http://dx.doi.org/10.1016/j.wear.2014.10.011.

[Zdravecka 2019] Zdravecka, E. and Slota J. Mechanical and Microstructural Investigations of the Laser Welding of Different Zinc-Coated Steels. Metals, 2019, Vol. 9, No. 1. https://doi.org/10.3390/met9010091.

CONTACTS:

Ing. Gerhard Mital, PhD.
Ing. Tomas Jezny, PhD.
Technical University of Kosice
Faculty of Mechanical Engineering
Department of Mechanical Engineering Technologies and Materials
Masiarska 74, 040 01 Kosice, Slovakia
gerhard.mital@tuke.sk