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THE INFLUENCE OF A CrN+a-C:H:W COATING ON THE DEVELOPMENT
OF FRETTING WEAR IN A MODEL OF A WHEEL–AXLE PRESS-FIT JOINT
ON A WHEEL SET OF A RAILWAY VEHICLE

WPLYW POWŁOKI CrN+a-C:H:W NA ROZWÓJ ZUŻYCIA
FRETINGOWEGO W MODELU POŁĄCZENIA WTŁACZANEGO
KOŁO–OŚ ZESTAWU KOŁOWEGO POJAZDÓW SZYNOWYCH

Abstract

The tests were conducted on a wheel/axle press-fit joint model, which consisted of a shaft and a sleeve. Macrographic observations were demonstrated fretting wear on the shaft surface with and without coatings. In the case of the uncoated shaft, wear around the entire circumference of the axle seat was visible in the form of a peculiar ring of a specific width. The coated shaft surface was distinguished by a considerably smaller number of visible traces of wear. Wear was observed around the entire circumference of the axle seat, was spaced at random, and insignificantly sized areas each time. Micrographic observations with the use of a scanning microscope demonstrated that fretting was primarily comprised of the build-up of the material from both surfaces joined together. In addition to the build-up, surface micro-abrasion, micropits and microcracks are observed, albeit to a lesser extent.

Keywords: PVD coating, CrN+a-C:H:W, rotational bending, fretting wear, press-fit joint, wheel set

Streszczenie

Badania wykonano na modelu połączenia wtłaczanego koło–oś, który składał się z wału i tulei. Przeprowadzone badania makrograficzne wykazały występowanie zużycia frettingowego na powierzchni wału bez powłok i z powłokami. W przypadku wału bez powłoki zużycie widoczne jest na całym obwodzie podpięcia w postaci charakterystycznego pierścienia o określonej szerokości. Powierzchnia wałów z powłoką charakteryzowała się znacznie mniejszą ilością widocznych śladów zużycia. Zużycie obserwowane jest na całym obwodzie podpięcia rozmieszczone jest losowo i za każdym razem zajmuje niewielkie powierzchnie. Badania mikrograficzne z użyciem mikroskopu skaningowego wykazały, że na zjawisko frettingu składają się przede wszystkim nalepy materiału pochodzące z obu łączonych powierzchni. Obserwuje się także mikrowytarcia powierzchni, mikrowżery i mikropęknięcia.

Słowa kluczowe: powłoka PVD, CrN+a-C:H:W, zginanie obrotowe, zużycie frettingowe, połączenie wciskowe, zestaw kołowy

1. Introduction

Wheel systems are among the most important railway vehicle assemblies. Their task is to run the vehicle on the track; thus, wheel systems should be distinguished by appropriate durability and reliability. History has revealed many examples which show that even minor damage to them can be the cause of vehicle derailing – this carries financial implications related to damage to infrastructure and, in extreme cases, it results in casualties.

Wheel sets, in particular the wheel/axle joint, are the main elements determining the reliability of wheel systems. Difficult wheel set operational conditions result from a complex load state – this is comprised of the vertical load depending on the rail vehicle weight, lateral forces acting on the joint of the wheel edge and rail head during passage through a curve, and dynamic forces coming into being as a result of the rolling of the wheel set on a rail. The loads mentioned above may cause the development of fatigue wear, to which the wheel/axle push-fit joint zone is most susceptible. Those loads are a natural phenomenon accompanying railway vehicle operation, in relation to which we are unable to eliminate them. Therefore, other solutions should be sought which will prolong the life of wheel sets.

Railway vehicles are equipped with various kinds of wheel sets whose structures depend upon many factors. However, special steel with exceptionally high strength parameters is used for the construction of any wheel set, regardless of its structural details. Moreover, each wheel set is also subject to close technical inspections governed by standards and other discipline-specific regulations. This notwithstanding, damage and premature wear occurs.

Fretting wear occurring at the wheel/axle joint is one type of damage resulting from wheel set operation. This wear is counted among tribological kinds of wear. The complexity of physical and chemical phenomena accompanying fretting wear is the reason why the unambiguous definition of that kind of wear has not yet been provided. It is only known that the occurrence of oscillatory tangential displacement between mating surfaces pressed against each other with an appropriately high force is the necessary condition for the initiation of fretting wear. According to many scientists, the oscillation amplitude needed to initiate wear is in the range of 25–150 μm .

Fretting is found in almost all fields of technology in which mating elements meet the conditions listed above – elements of airplanes [1], medical implants [2, 3], and elements of nuclear power plants [4, 5] may be mentioned here.

It transpires from literature available to the author that few scientists are involved in investigating fretting wear in press-fit joints. This is probably related to the joint disassembly issue. Inappropriate joint disassembly may cause damage to or the deformation of the resulting wear image. This kind of joint does, however, accumulate in it all the conditions conducive to the development of fretting wear. There is a specific pressure between the surfaces of the connected elements, and the relative displacement of those surfaces occurs.

Among the publications on fretting wear testing in press-fit joints, those under [6–8] may be mentioned. These are mainly tests enabling the recognition of wear images or publications concerned with the description of the fretting wear development mechanisms. The influence of various factors on fretting wear intensity was tested – these

factors included roughness parameters of the top layer and the assembly technology. There are still too few tests concerning the mitigation of the development of wear in press-fit joints. In his previous research, the author of this publication suggested the modification of the top layer through the use of strengthening treatment: surface hardening, nitriding and finish rolling. Test results demonstrated an insignificant influence of those processes on the mitigation of the development of wear. In the case of finish rolling, the shaft surface affected by wear is considerably larger than in the case of shafts without additional top layer treatment. This stemmed from the fact that the finish rolling process led to the 'smoothing' of the surface. Mating surfaces with low roughness parameters are susceptible to the creation of adhesive bonds – this is why other processes must be sought. These other processes should be more effective in the mitigation of fretting on the one hand, and not too costly on the other. It seems that the use of coatings applied by means of the PVD method are a good solution.

Many pieces of literature can be found in which authors demonstrate good anti-wear properties of this kind of coatings, especially low-friction coatings. The authors of [9] tested the properties of a-C:H:W coatings applied over a steel base surface. They proved that gradient coating systems lead to better coating efficiency in macroscopic and microscopic tests. The authors also proposed a new wear model which enables a changing stress field. The authors of [10] tested coatings applied to a graphite base surface; they demonstrated that multi-layer a-C:H:Zr and a-C:H:W coatings are very hard and non-porous. The authors of [11] tested the tribological characteristics of Cr/CrN/a-C:H:W/a-C:H coatings in lubrication conditions demonstrating that FM and GMO greases reduce friction and thus the wear of the coating and of the mating element surface. The author of [12] tested the influence of TiN and CrN intermediate layers on the tribological properties of type DLC coatings and in doing so proved that the properties of these coatings depend on their chemical composition. It became apparent during the comparison of a-C:H:W and CrN+ a-C:H:W coatings that it is the former which have better properties in nanoscale tribological tests and the latter which have better characteristics in microscale and macroscale tests. Tests have confirmed the improvement of DLC tribological properties with the use of intermediate layers. Tests conducted by the authors of [13] concerned the influence of hydrogen content on the tribological properties of type nc-WC/a-C:H coatings. These tests revealed that the coefficient of friction, the microstructure and the kind of bonds between carbon atoms greatly depend upon hydrogen content. In their tests, they demonstrated that the tested coatings might be used to improve the tribological properties of hard steels and hardened titanium alloys.

With consideration to knowledge based on literature, the analysis of CrN+a-C:H:W coatings was performed in this article with regard to the occurrence of fretting in press-fit joints.

In view of the dimensions of a wheel set and the related difficulties with the construction of a fretting wear test station, these tests were conducted on a wheel/axle press-fit joint model. The dimensional analysis made by the author of [14] shows that the results of model testing may be referred to real wheel sets.

2. The characteristics of the top layers of tested models

Tests were conducted on samples in two alternatives of the top layer finish of the shafts. In the first group, there were uncoated shafts which had top layers with a hardness of 160 HB. Shafts of the second test group were provided with a CrN+a-C:H:W coating, the properties of which are shown in Table 1.

Table 1. Properties of the CrN+a-C:H:W coating according to the manufacturer's data

Coating material/coating structure	CrN+a-C:H:W
Micro hardness (HV 0.05)	1000–1500
Coefficient of friction (dry against steel)	0.1–0.2
Maximum service temperature (°C)	300
Coating temperature (°C)	< 250
Colour	Anthracite

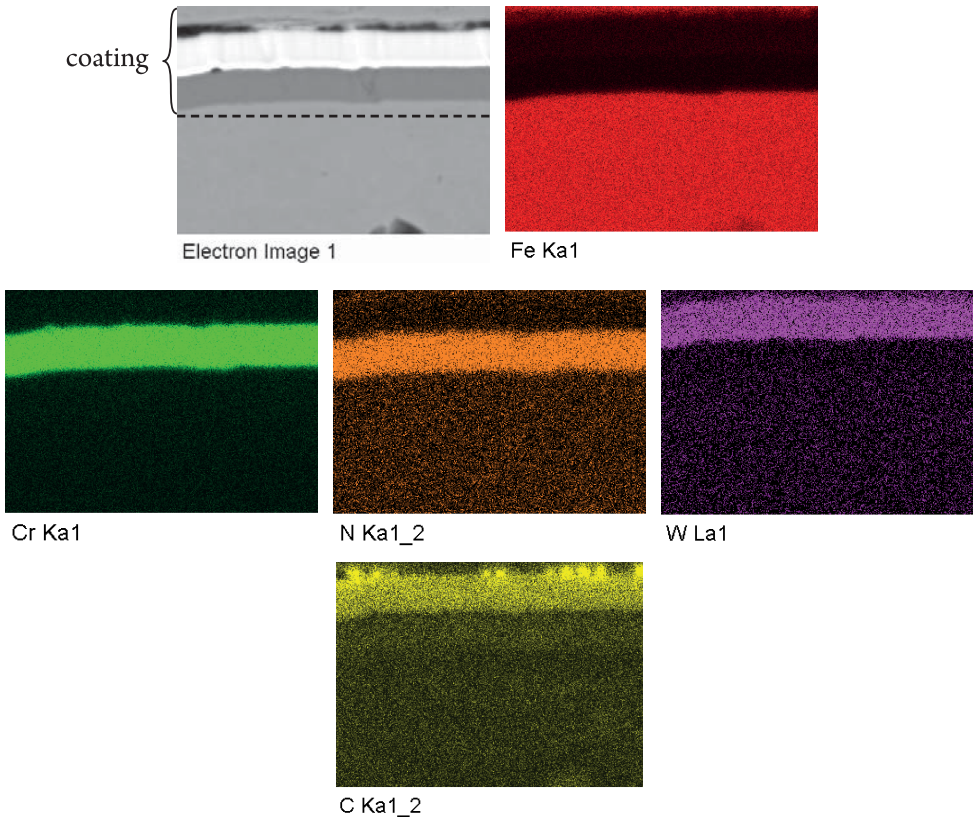


Fig. 1. Element distribution maps showing the chemical composition of the coating

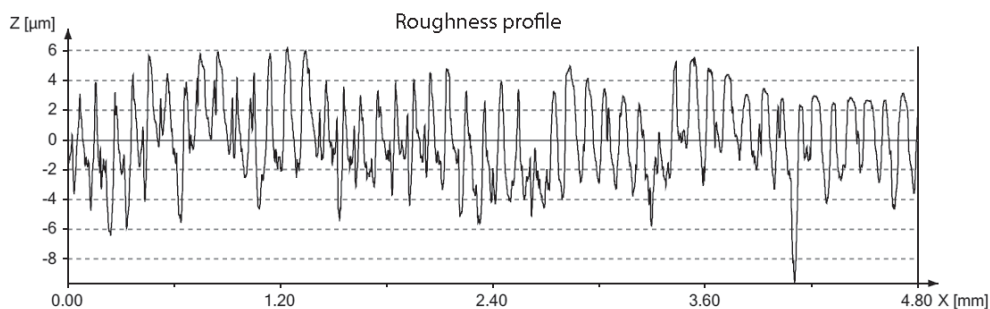
The coating was applied to the shafts by means of the reactive spraying method in a PVD process. The coating structure and chemical composition in the form of a chemical element distribution map is presented in Fig. 1. The coating consists of three layers and is colloquially called WC/C. The first layer is chromium nitride (CrN), the task of which is to improve coating adhesion to the surface of the steel base. The next layer is tungsten carbide (WC), which protects the surface of the base against abrasion and is responsible for the transfer of high pressures. The third layer, called the external layer, directly mates with the sleeve. According to literature, the atomic composition of this layer is as follows: 12% W, 70% C, 15% H, 3% Ni [15–16]. Nickel is an outcome of the coating generation process.

In the case of the tests of fretting wear in a press-fit joint, the appropriate hardness of the top layer and its roughness parameters prior to joint assembly play an important role. The roughness profile and selected parameters of the uncoated (a) and coated (b) top layer of the shaft are shown in Fig. 2.

The diagram showing shaft microhardness in the function of the distance from the surface is presented in Fig. 3.

a) uncoated shaft

Ra	2.06 μm	Rz	11.15 μm	Rmr(c=2.78 μm)	18.062 %
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b) coated shaft

Ra	1.68 μm	Rz	11.57 μm	Rmr(c=2.78 μm)	1.300 %
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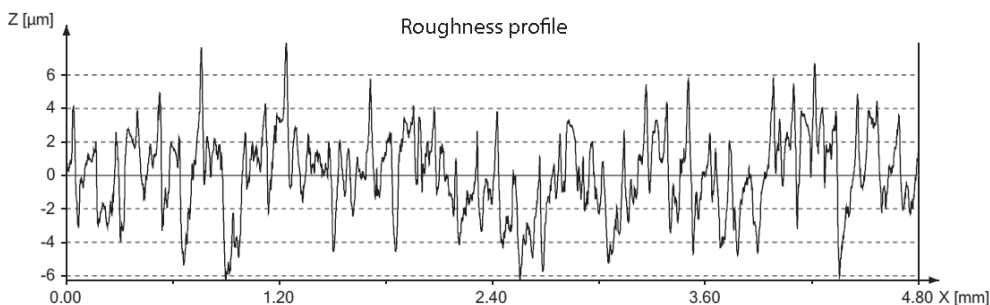


Fig. 2. Roughness profile of the shaft surface

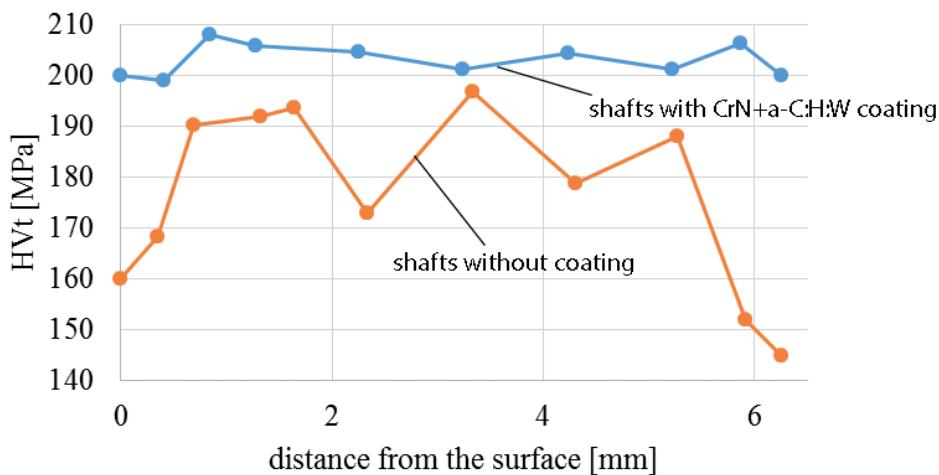


Fig. 3. Microhardness distribution

3. Test methodology

Wear tests were conducted on a model of a wheel/axle push fit joint of a railway vehicle wheel set. The model consists of a sleeve forced onto a shaft with 0.02 mm negative allowance.

Model elements were made of the same materials as those from which a wheel and axle of a wheel set are made. The sleeve was made of P58 steel, and the shaft was made of C45 steel.

The model was designed in such a manner that the dimensional similarity to the real wheel set is retained. Retained – this primarily concerned the shaft and sleeve connection zone. The shaft length and diameter were dependent upon the fatigue testing machine structure. The diagram of the sample with dimensions is presented in Fig. 4.

As mentioned previously, two model groups were used in the fatigue tests. The first group contained base samples in which the top layer of the shaft was not additionally improved. The samples of that group were used as a point of reference for the assessment of the top layer wear

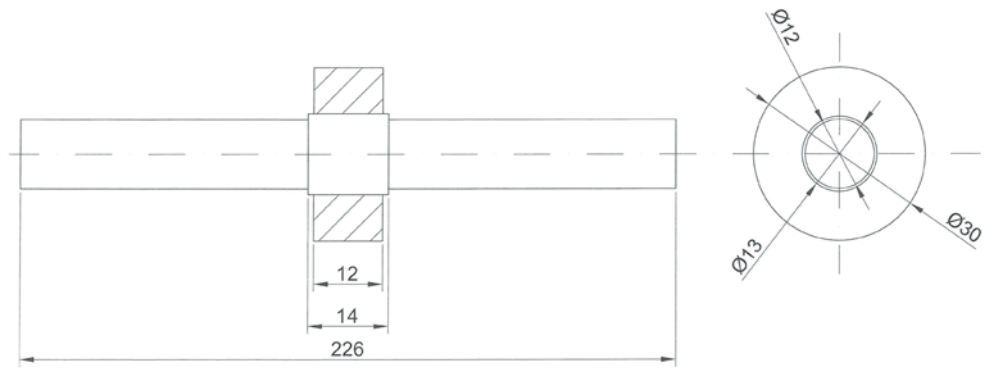


Fig. 4. Diagram of the test model with dimensions

intensity in the second group samples. In the second group of models, a Cr+a-C:H:W coating was applied to the top layer of the shaft.

In addition to an appropriate test model, the selection of a wear test station – which will, to the maximum extent, reflect the wheel set operational conditions described in the introduction – is an important issue. Primarily, the test station should enable the oscillatory tangential displacement of the mating surfaces. One such machines which meets the criteria is a MUJ fatigue testing machine, the structure of which is presented in Fig. 5.

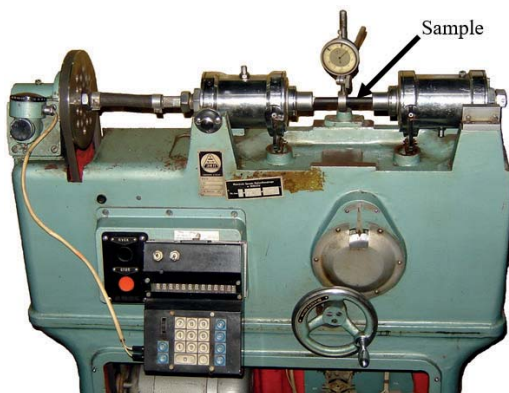


Fig. 5. The structure of a fatigue testing machine

The machine structure enables the generation of a periodically variable load with pure bending of a rotating model. Railway vehicle wheel sets rolling on a straight track (a situation when a railway vehicle does not move on a bend and hunting oscillation does not take place) are subjected to similar conditions. A situation in which a vehicle is on a bend was not covered in the tests.

The FEM analysis performed in the ANSYS software permitted the selection of the maximum value of a force which causes shaft deflection without leading to plastic deformation. The assumed 550 N force causes the maximum stresses to be reduced to 356 MPa (Fig. 6) and leads to maximum sample deflection, which is 0.52 mm. The most important parameters of wear tests are summarised in Table 2.

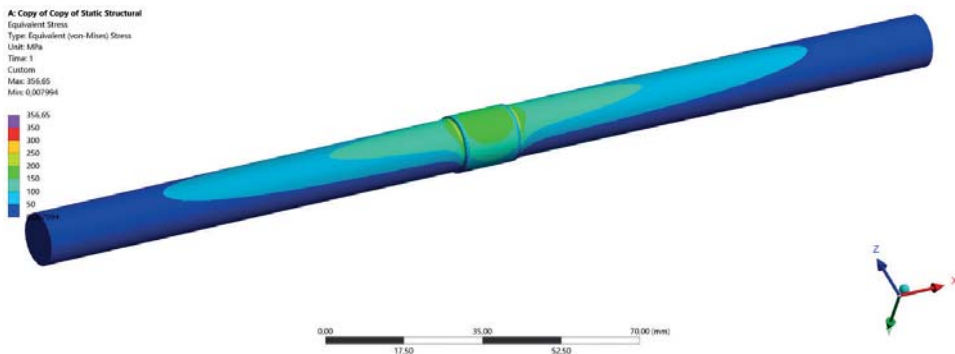


Fig. 6. Distribution of reduced stresses

Table 2. Summary of wear test parameters

Parameter	Value obtained
maximum force necessary to force the sleeve onto the shaft	4800 N (the uncoated shaft)
	6600 N (the shaft with a Cr+a-C:H:W coating)
test model load	550 N
normal stress	118 MPa (for the 13 mm DIA shaft section)
	93 MPa (for the 12 mm DIA shaft section)
number of cycles	8×10^6
number of revolutions	1360 rpm

After the wear tests were completed, the test model was cut in such a way that the arising wear image was not damaged. The joint was cut parallel to the shaft symmetry axis. As a result of this procedure, three samples for further testing and observation were obtained.

The observations and surveys of the shaft top layer aimed at determining its actual condition after wear tests and the influence of the tested coatings on fretting development and intensity. For this purpose, macrographic tests enabling the determination of the condition of the top surface of the shaft and fretting intensity were performed. Micrographic tests with the use of a scanning microscope provide an answer to the question as to which kinds of wear are comprised of fretting for the assumed wear test methodology. Analysis of the chemical composition by mean of the x-ray microanalysis in the EDS method enabled the determination of, among other things, the percentage share of elements in wear products.

4. Analysis of laboratory test results

Macrographic observations (Fig. 7) of the uncoated shaft surface confirm the test results obtained by the authors of [6, 17, 18], which show that fretting occurs at joint edges in the case of press-fit joints.

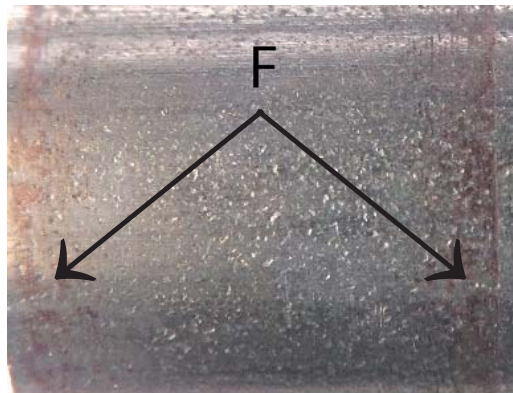


Fig. 7. The macrographic image of the shaft surface, F – fretting wear

In the case under analysis, fretting wear occurs around the entire circumference of the shaft axle seat. The width of the ring affected by wear reaches 2-3 mm and is the same on each side of the axle seat. Wear occurs at a distance of 2-5 mm from the axle seat edges. The tests of the topography of the top layer at the place of fretting wear indicates a considerable increase of the roughness parameters. The probable cause of the roughness increase is the wear products.

Microscopic observations with the use of an SEM confirm that the responsibility for the increase of roughness parameters rests to a large extent with material build-up at the shaft surface in the fretting wear zone visible in Fig. 8. Further observations show occasional occurrences of microcracks and micro-abrasion.

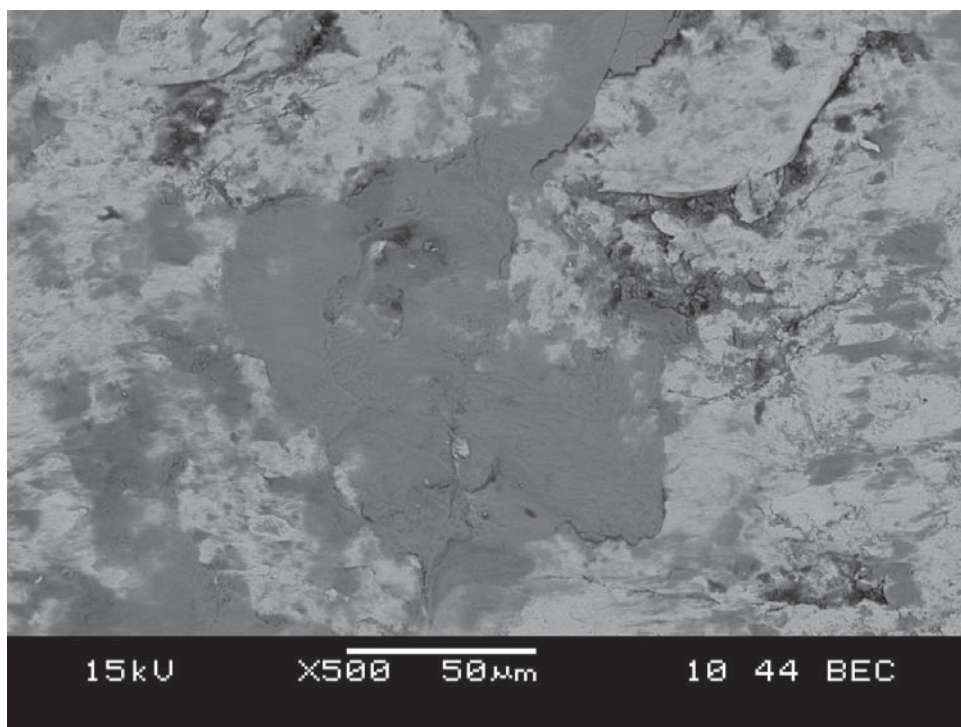
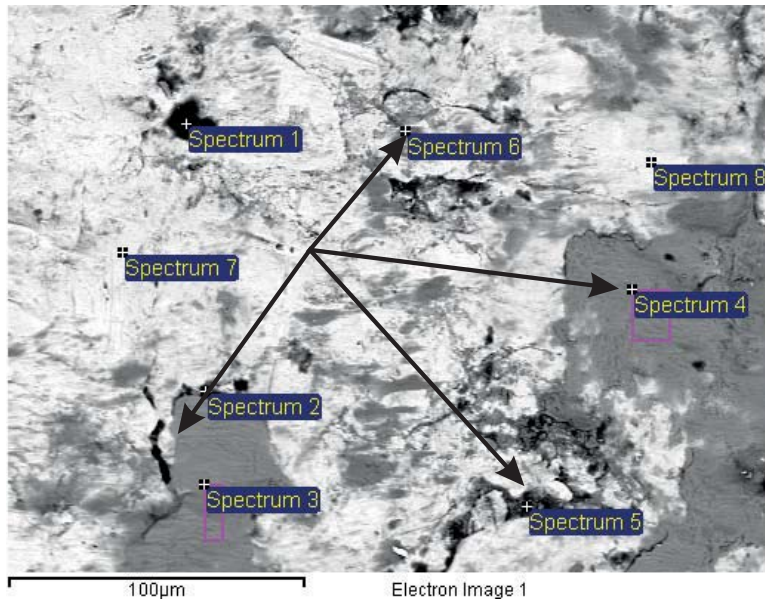


Fig. 8. The SEM image of the shaft surface in the fretting wear zone

The deformations of the top layer of the elements being connected result from the joint assembly process. The magnitude of these deformations depends upon the top layer's parameters such as roughness and hardness. These deformations cause the surface contact over the length of the joint to be heterogeneous. In the case under analysis, the mating surfaces have similar input parameters. The tangential force occurring in this case causes the mutual shearing of microprojections on both surfaces, thus creating wear products in the form of fine particles of the material, which will subsequently form material build-up at the top layer.



Spectrum	Fe	O	C	Na	Si	S	Cl	K	Ca	Mn	Total
Spectrum 1	21.8	13.2	59.2	1.3	0.8	0.9	1.2	0.6	1.0	–	100.0
Spectrum 2	51.4	16.7	26.4	1.4	1.3	0.5	0.8	0.5	0.5	0.4	100.0
Spectrum 3	64.4	34.8	–	–	0.3	–	–	–	–	0.5	100.0
Spectrum 4	60.7	38.5	–	–	0.4	–	–	–	–	0.4	100.0
Spectrum 5	56.2	27.7	14.7	–	0.3	–	–	0.2	0.4	0.5	100.0
Spectrum 6	61.9	31.6	3.7	–	1.7	–	–	0.5	–	0.5	100.0
Spectrum 7	99.3	–	–	–	–	–	–	–	–	0.7	100.0
Spectrum 8	99.4	–	–	–	–	–	–	–	–	0.6	100.0

All results in weight%

Fig. 9. EDS analysis of the elements at the shaft surface in the fretting wear zone

A peculiar feature of fretting damage is the brown colour typical of steel corrosion. This follows from the fact that wear products damage that has come into being as a result of adhesive bonds and, subsequently, plastic deformation, are susceptible to oxidation. This fact is confirmed by the EDS analysis of the chemical composition of wear products in the place of fretting wear. In Fig. 9, places marked with arrows show fretting damage in the form of material build-up. These places have an oxygen content from 27% to 40%; therefore, iron oxides come into being. The remaining measured places also contain oxygen, but its concentration is considerably lower.

Macroscopic observations of the coated top layer of the shaft after wear tests demonstrated fretting wear traces (the 'F' in Fig. 10). As in the previous case, these are located by both joint edges. The first traces appear 2 mm from the edge. Wear affects is randomly located at the axle seat circumference. The smallest surface area affected by wear is 0.5 mm², and the largest is approximately 14 mm². The width of the 'strip' affected by wear is different on each side.

Fretting comprises, to a large extent, material build-up most probably originating from the tearing off of the sleeve top layer micro-irregularities (Fig. 11). The inferior properties of the sleeve hub top layer in relation to the coated shaft axle seat cause precisely the sleeve hub surface to be susceptible to damage during joint assembly.

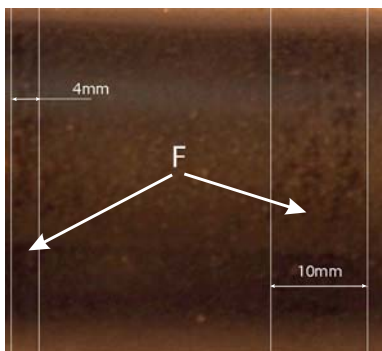


Fig. 10. The surface of a shaft with a CrN+a-C:H:W coating after wear tests

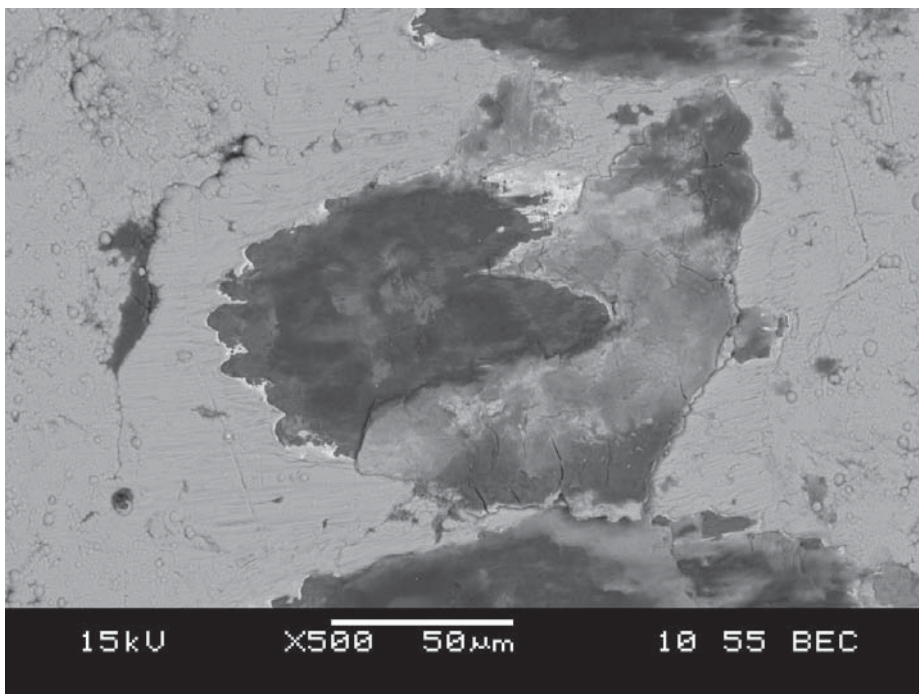
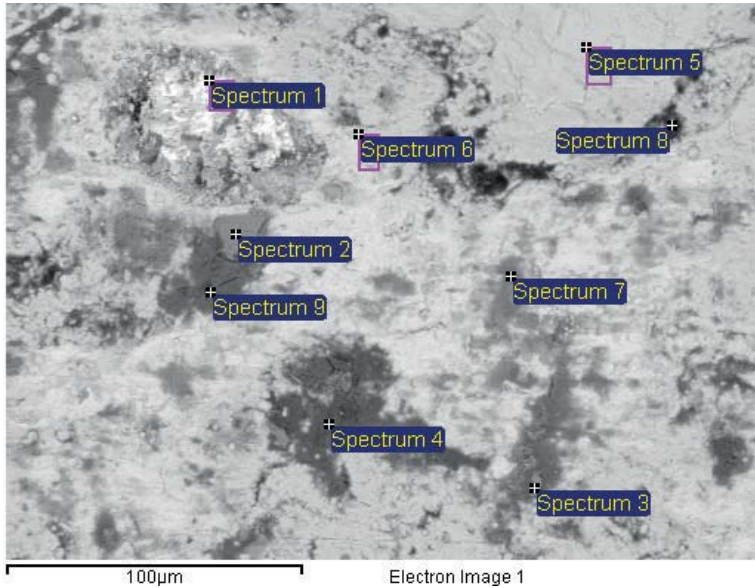


Fig. 11. Fretting in the form of material build-up on the coated shaft surface

This assumption is confirmed by the analysis of the elements occurring on the shaft surface in the fretting wear zone. The results of the analysis of the chemical composition at selected points of the shaft surface within the fretting zone are presented in Fig. 12.



Spectrum	Elements related to the coating and sleeve structure					Elements related to the process of sample preparation for laboratory tests				Total
	Fe	O	C	W	Cr	Si	Ca	Mn	Ni	
Spectrum 1	7.1	5.4	19.4	53.7	10.6		–		3.8	100.0
Spectrum 2	94.6	–	3.4	–	0.9	0.4	–	0.7	–	100.0
Spectrum 3	93.8	–	4.1	–	1.0	0.4	–	0.7	–	100.0
Spectrum 4	41.2	26.5	–	29.5	1.0	–	–	–	1.7	100.0
Spectrum 5	0.6	1.0	26.1	66.8	0.9	–	–	–	4.6	100.0
Spectrum 6	3.1	20.1	–	71.0	1.0	–	–	–	4.8	100.0
Spectrum 7	40.3	29.1	6.2	21.9	1.3	–	–	–	1.2	100.0
Spectrum 8	15.0	15.1	48.6	17.7	2.6	–	0.4	–	0.5	100.0
Spectrum 9	42.4	26.1	–	28.5	1.0	–	0.5	–	1.6	100.0

All results in weight%

Fig. 12. EDS analysis of the elements on the shaft surface in the fretting wear zone

During the analysis of the chemical composition for a selected area affected by wear, macroscopic observations have demonstrated that wear is random in nature and is not continuous. This is proved by the chemical composition at the survey points 'Spectrum 1' and 'Spectrum 5'. It is mainly the elements related to the coating structure (carbon and tungsten) that occur there. In the case of the 'Spectrum 1' survey point, a small amount of chromium is also observed. This is caused by the micro-abrasion of the working part of the coating, which led to the uncovering of the first coating layer containing chromium. The total destruction of the coating did not, however, take place. Iron occurring at that point probably originates from the sleeve hub. Nickel occurring in that part is an effect of the manufacturing process of the coating.

The survey points 'Spectrum 2' and 'Spectrum 3' are the proof of the shearing of the micro-irregularities on the top layer of the sleeve hub during joint assembly. During forcing, torn-off micro-irregularities creating the so-called 'third body' were moving along the joint and filling the natural microcavities in the coating. Hence, the chemical composition in these places is primarily iron. These wear products did not undergo plastic deformation and were not oxidised. They did not take part in the rise of fretting, either.

The remaining survey points demonstrate the occurrence of fretting wear. In the case of the 'Spectrum 6' survey point, material build-up mainly consisting of tungsten is observed. This is evidence of the tearing off of micro-irregularities of coating as a result of adhesion, and of the creation of build-up which underwent plastic deformation during the latter part of assembly or operation. This deformed build-up was oxidised, hence the analysis of the chemical composition also showing the occurrence of oxygen. The 'Spectrum 8' survey point also signifies damage to the coating. Material build-up at this point is composed of carbon and tungsten (i.e. elements related to the coating structure) and of a small amount of iron. This build-up also underwent plastic deformation and, at a further stage, oxidation.

Wear products see above note analysed at the 'Spectrum 4', 'Spectrum 7' and 'Spectrum 9' survey points are the material build-up in which chemical composition is a mixture of elements originating from the top layer of the sleeve hub and of the coating. However, the occurrence of iron is noted in the vast majority of cases – this means that mainly the sleeve top layer was damaged. During operation, this build-up gradually underwent plastic deformation and oxidation. The analysis of the chemical composition in these survey points showed the presence of the same or similar amount of oxygen to that of tungsten. The presence of carbon is not noted.

Trace amounts of chromium observed in the 'Spectrum 2' to 'Spectrum 9' survey points originate from the local microdamage of the working part of the coating. The remaining chemical elements – such as silicon, calcium, manganese and nickel – are the result of the surface preparation for laboratory tests or the outcome of the coating production process.

5. Conclusion

The aim of this article was to present the results of tests of fretting wear in a press-fit joint and an assessment of the possibilities of using a CrN+a-C:H:W coating to reduce such wear.

The tests demonstrated that in the case of a joint in which the shaft top layer was not covered with the relevant coating, fretting wear occurs around the entire circumference in the form of a ring, the width and distance of which from the joint edge are different at each side. Fretting wear, of considerably lower intensity, however, was also observed on the surface of the coated shafts. Fretting wear occurred over the entire circumference, covered small areas of various shapes, and was spaced at random.

Test results confirmed the tests conducted by other authors specifically that input parameters of the top layer of the elements being connected have significant influence on the development of fretting wear. Appropriate roughness and hardness parameters reduce wear intensity. Tested coatings have, indeed, slightly lower roughness parameters in comparison with the uncoated shaft, but increasing top layer hardness by 25% proved sufficient for the reduction of adhesion and also of fretting wear.

Fretting in press-fit joints is a complex phenomenon. Irrespective of the kind of top layer, material build-up is the dominant kind of wear comprised of fretting. In addition to the build-up, but to a lesser extent, microcracks, micro-abrasion and abrasive wear are observed. The main factor responsible for these kinds of wear in press-fit joints is adhesion.

Study sponsored by grant no PB.S01-1/2017 obtained from State Higher Vocational School in Nowy Sącz

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