ISSN 0208-7774 T R I B O L O G I A 4/2020 p. 37–49
DOI: 10.5604/01.3001.0014.5899

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THE MECHANISM OF OPERATIONAL WEAR OF SPINDLE-NECK COATING OF SPINNING SPINDLES MADE OF AlCu4Mg1 ALLOY DUE TO COOPERATION WITH A STREAM OF YARNS

MECHANIZM ZUŻYWANIA EKSPLOATACYJNEGO SZYJKI OKŁADZINY WRZECION PRZĘDZALNICZYCH ZE STOPU AlCu4Mg1 PRZY WSPÓŁPRACY ZE STRUMIENIEM WŁÓKIEN

Key words: spindle with collapse balloon crown, tribological combination: stream of yarns – coating from AlCu4Mg1 alloy, type of wear of the neck of coating.

Abstract: Results of the investigations of wear of spindle-neck coating with a collapse balloon crown of ring spinning frames, resulting from cooperation with stream of yarn within industrial conditions are discussed in the paper. The study have comprised measurements of the wear of spindle-neck coating made of EN AW-2024 (AlCu4Mg1) alloy after performed burnishing treatment in the course of cooperation with blend of 70 – 80% wool fibres with the addition of 30–20% polyester fibers, causing the greatest wear. Before and after the period of the operation, based on produced outlines of the roundness of the cylindrical part of the burnished neck of the coating, outlines of the cylindricity of the neck of the spindle have been drawn. Next, using the shape-meter, performed measurements were made of the wear on the spindle-neck coating having the form of a helical groove in the direction perpendicular to its run. There were also 2D measurements performed of the roughness on the neck of coating of spinning spindle, and photos were taken of side surface of the wear in form of helical groove, and one has an inserted EDS spectrum for the surface in the location of the precipitation (phase of AlCuFeMnSi type – point 2). Assessment of the surface in friction area between the spindle-neck coating and the stream of the fibres and the microphotography of side surface of the helical groove lead to the conclusion that the wear of the spindle-neck coating made of AlCu4Mg1 alloy, outside the deep grove, occurs as the result of abrasion, while inside the groove as the result of abrasion and oxidation.

Słowa kluczowe: wrzeciono z nasadką antybalonową, skojarzenie tribologiczne strumień włókien – okładzina ze stopu AlCu4Mg1, rodzaj zużycia szyjki okładziny.

Streszczenie: W artykule zamieszczono wyniki badań zużycia szyjki okładziny wrzecion z nasadką antybalonową przędzarki obrączkowej przy współpracy ze strumieniem włókien w warunkach przemysłowych. Badania objęły pomiary zużycia szyjki okładziny wrzecion wykonanych ze stopu EN AW-2024 (AlCu4Mg1) poddanych obróbce wykończeniowej przez nagniatanie przy współpracy z mieszanką włókien: 70÷80% włókien wełny z dodatkiem 30÷20% włókien poliestrowych powodującą największe zużycie. Wykonano zarysy okrągłości części walcowej szyjki okładziny, na podstawie których sporządzono zarys walcowości szyjki okładziny wrzeciona nagniatanej przed i po czasie eksploatacji. Następnie przeprowadzono pomiary zużycia szyjki okładziny w postaci rowka śrubowego w kierunku prostopadłym do jego przebiegu za pomocą kształtografu. Wykonano również pomiary chropowatości 2D powierzchni szyjki okładziny wrzecion przędzalniczych i zdjęcia powierzchni bocznej zużycia w postaci rowka śrubowego oraz zamieszczono widmo EDS dla powierzchni w miejscu wydzielenia (fazy typu AlCuFeMnSi – punkt 2). Ocena powierzchni obszaru tarcia szyjka okładziny–strumień włókien oraz mikrofotografii powierzchni bocznej rowka śrubowego skłaniają do stwierdzenia, że zużycie szyjki okładzin wrzecion ze stopu AlCu4Mg1, poza głębokim rowkiem, następuje w wyniku ścierania, natomiast w rowku w wyniku ścierania i utleniania.

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INTRODUCTION

The spindles of ring spinning frames, working in collapse balloon system, are mounted on a stable bed in a bearings having oil–spring damping. The yarn guides, changing their position in relation to the crown (rosette) of the spindle in a way synchronized with motion of the bed of spindle are cooperating with the spindles, and thus ensure almost constant tension of the yarn during spinning process. Properly shaped components like the neck of the coating and the crown mounted on the neck are largely contributing to maintaining the correct tension of stream of the fibres during the spinning process. Due to this system, it is possible to spin with good results on spinning frames with yarns made from good and poor quality raw materials **[L. 1]**. Working surfaces of the components being in direct contact with stream of the fibres, such as guides, collapse balloon crowns, and necks of the coating of the spindle, among others, are forming yarn with a combination of the moving stream of the fibres, yarn, or thread. In this combination, due to sliding friction, the metal part is undergoing wear in the form of pits (sometimes a groove). The change of mass and the change of the structure and physical properties of surface layers in the contact area occur in the processes of tribological wear, while the value of such wear depends on the types of processes of the wear **[L. 2–3]**.

Studies **[L. 4–5]** investigated the effects of the type of surface and finishing treatments on the wear of the spindle-neck coating collapse balloon crown of spinning frames produced from EN AW-2024 (AlCu4Mg1) alloy, in cooperation with blend of 70–80% fibres of wool with the addition 30–20% polyester fibres. In a successive study **[L. 6],** the type of the wear around circumference and along the generator line, in cooperation with blend of the fibers causing the highest wear, (70 – 80% wool fibers and 30 – 20% polyester fibers) was determined. Based on performed investigations and observations of the the wear of the spindle-neck coating collapse balloon crown of spinning frames in cooperation with stream of the fibres and operated within industrial conditions, it is possible to state that 5 to 7.5% of all spindles installed in ring spinning frames of PG-7A type undergo wearing in form of a helical groove **[L. 5]**.

The present article attempts to explain type of friction and wear in the tribological combination: moving stream of the fibres (being blend of 70–80% wool fibres and 30–20% polyester fibres) and the spindle-neck coating from AlCu4Mg1 alloy with a collapse balloon crown.

ASSESSMENT METHOD OF THE WEAR OF SPINDLE-NECK COATING WITH A COLLAPSE BALLOON CROWN OF RING SPINNING FRAMES

The observations were performed on two ring spinning frames of PG-7A type, and 320 pieces of spinning spindles had been installed on each spinning frame. The coating of the spindle together with the neck was produced from naturally precipitation hardened EN AW-2024 (AlCu4Mg1) alloy, and, after turning operation, the coating underwent finishing treatment by burnishing **[L. 7–8]**.

Investigations of the wear of spindle-neck coating with a collapse balloon crown of ring spinning frames in cooperation with stream of the fibres were performed with use of the metric method **[L. 3]** on ring spinning frames of PG7-A type in production conditions. Percentage composition and characteristics of the stream of the fibres processed on the ring spinning frames and percentage time-period of the processing are presented in the **Table 1**.

Measurements of roundness deviation (scanning of diameter of the neck of coating) were performed in order to assess the wear of the spindle-neck coating before and after an operational time equal to approximately 21600 man-hours. Measurements of the roundness deviation were performed at a distance of 1–16 mm from the crown at cross-sections made in steps of 0.5 mm before and after an operational time of the spindles. To perform the measurements, a Taylrond 365 roundness meter produced by the Taylor Hobson, equipped with measuring probe ended with ball having radius r_k = 0.50 mm was used. Next, as a result of the implemented measuring strategy of the outlines of roundness before and after the operating time, an outline of the cylindricity of the burnished neck of coating was generated **[L. 9]**.

Table 1. Types of raw material spun on the ring spinning frames, their characteristics, and percentage time of their processing

Tabela 1. Rodzaje surowca przerabianego na przędzarce obrączkowej, ich charakterystyka oraz procentowy czas ich przerobu

Type of processed raw material	Linear mass of the yarn, tex	The number of yarn turns per 1 meter, 1/m	The number of spindle rotations, rpm	Percentage time of the processing, %
Polyester 30% + wool 70%	100; 125	390; 360	9500 – 10000	77.6
Polyester 20% + wool 80%	150	280	8500	22.4

Measurements of the helical groove, perpendicular to the direction of the run of the groove, were performed using the Form Talysurf 120 contour meter produced by the Taylor Hobson, equipped with a wide range measuring head equipped with a measuring tip having fillet radius of r_p = 20 µm. The outline of shape of the groove was determined at the following distances from face of the crown: 1.0 mm and next in intervals of length of the neck from 3.0 to 17.0 mm every 2.0 mm, and next at distances of 20.0, 25.0. 30.0, and 35.0 mm. The total depth of the groove was measured in microns for each outline of the shape, while the width of the groove was determined from the diagram.

Measurements of 3D surface parameters were not used due to shape and dimensions of the wear area having the form of helical groove. The following 2D parameters of surface roughness were measured directly after burnishing treatment: *Ra*, *Rq*, and *Rt*. After the operational time, i.e. after operation during 21600 man-hours, *Ra, Rq, Rp, Rv, Rz, Rc, Rt, Rsk, Rku, Rmr, and Rdc* were measured. A topographic map of the surface and the contour map were drawn for the surface of the neck of coating of spindle **[L. 10–13]**. Measurements of selected parameters of 2D surface roughness were done using the New Form Talysurf 2D/3D 120 contour measuring system made by the Taylor Hobson, making use of the Ultra Surface 5.21 and the TalyMap Platinium 5.1.1 computer software. In the course of the roughness measurements, the following sampling length was used: l_r = 0.25 or 0.80 mm (the sampling length was selected automatically by the software), number of recorded points N_x = 10000, sampling step Δ_x = 0.308 µm, fillet radius of the diamond gauging point r_{tip} = 2.0 µm, pressure of the gauging point F_{kp} = 1.0 mN, feed rate of the gauging point v_{os} = 1.0 mm/s, and the Gaussian filter.

Micro-hardness measurements were performed using Vickers method, on oblique micro-sections, on the Leitz Wetzlar micro-hardness tester, under an indenter load of 0,49 N.

Using a scanning electron microscope (SEM in short) *Jeol-J7*, traces of the wear on side surface of the helical groove have been observed. Next, using an X-ray analyser, the approximate chemical composition of the matrix and the precipitation in form of inter-metallic phases on side surface of the wear were determined.

ASSESSMENT OF TYPE OF THE WEAR IN THE COMBINATION: STREAM OF FIBRES – THE SPINDLE-NECK COATING DURING SPINNING PROCESS ON RING SPINNING FRAME

In course of rotational motion of the spindle with collapse balloon crown, in majority of the cases, the stream of the fibres moving with speed 0.42–0.58 m/s and maximal tension up to 37 cN (and fluctuating amplitude) rhythmically moves ("jumps over") from one notch to the successive notch of the crown, in the opposite direction to rotational motion of the spindle, which reduces its tension. The stream of the fibres wraps the lower part of the crown first, and next it wraps the spindle-neck coating **(Fig. 1)**. For the rotational speed from 8500–10000 rpm, in case of the spindles with collapse balloon crown with 10 teeth, the transition time of stream of the fibres from one groove to the successive groove amounts from 0.00060 to 0.000706 seconds. It can be assumed that this is the contact time of moving stream of the fibres with the crown produced from 100Cr6 steel first, and next with the neck of coating produced from AlCu4Mg1 alloy and having a hardness of the surface layer $\mu HV_{0,49}$ = 1300–1180 MPa and a depth of about 50 µm. The wear around its circumference and along its length occurs as a result of the local sliding friction of stream of the fibres against surface of the neck of coating. Such wear around the circumference of the neck of coating has a form of pits in quantity corresponding to number of the teeth (notches) on the crown. For the crown with number of teeth z = 10, the wear around the circumference of the neck of coating has form of ten pits with variable depth and width. The wear along length of the neck of coating is uneven, and the highest one is present at distance approximately 15.5 mm from face of the crown (i.e. at length of about 15.5 mm), in general, the value of the wear (depth of the pits) does not exceed 0.10 mm after a working time of more than 20 thousands man-hours.

As a result of improperly manufactured fillets on the edge of the teeth and the grooves of the crown, a "keeping in place" of the stream of the fibres by one tooth takes place, which results in the lack of the rhythmic movement of the stream from one notch to the next one (**Fig. 2**). Contact time of sliding stream of the fibres, in a selected area on the circumference of the neck of coating increases more than two times. During 8 hours, the stream of the fibres moving with maximal tension 37 cN, performs a repeating cycle from about 3.6 to about 4.3 million ultra-short time-periods of the friction against the neck of the coating. It leads to about 5 to 7.5% of the cases of catastrophic wear of the neck of the coating, having the form of a carved helical groove with depth of above 1.0 mm and a width from approximately 2.0 to approximately 3.0 mm, after a contact time with the stream of the fibres amounting to just over 20 thousands man-hours.

The grooves disable smooth sliding of stream of the fibres across the neck of coating, and the grooves lead to an increased number of the breakings.

The shape of the burnished cylindrical surface of the neck of coating of the spindle, located directly under the crown, before and after its operational time, is shown in the **Fig. 3.** Before usage, the cylindrical part of the neck of coating was characterized, in individual cross-sections, by the roundness deviation included within range 3.4–6.0 µm, while deviation of the cylindricity

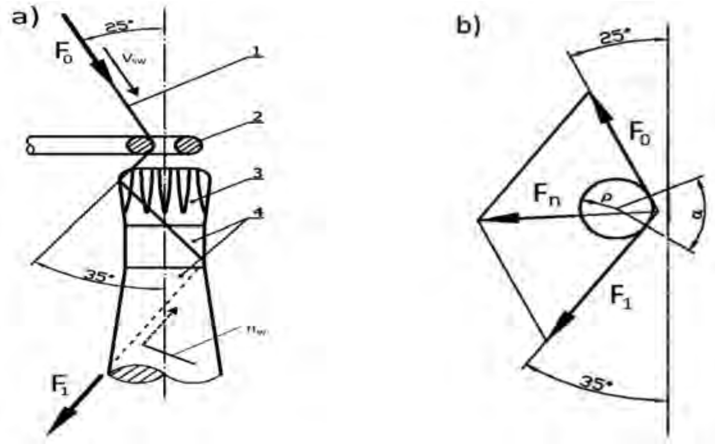

Fig. 1. The spindle-neck coating with mounted crown and guide (a) and tension of stream of the fibres (b): 1 – stream of the fibres, 2 – guide from 50Cr4 steel, 3 – crown, 4 – the neck of coating from AlCu4Mg1 alloy, $F_o \approx 30$ cN, $F_1 \approx 37$ cN, Fn ≈ 34 cN [L. 14]

Rys. 1. Szyjka okładziny wrzeciona z osadzona nasadką i prowadnikiem (a) oraz naciągiem strumienia włókien (b): 1 – strumień włókien, 2 – prowadnik ze stali 50Cr4, 3 – nasadka, 4 – szyjka okładziny ze stopu AlCu4Mg1 $F_o \approx 30$ cN, $F_1 \approx 37$ cN, Fn ≈ 34 cN **[L. 14]**

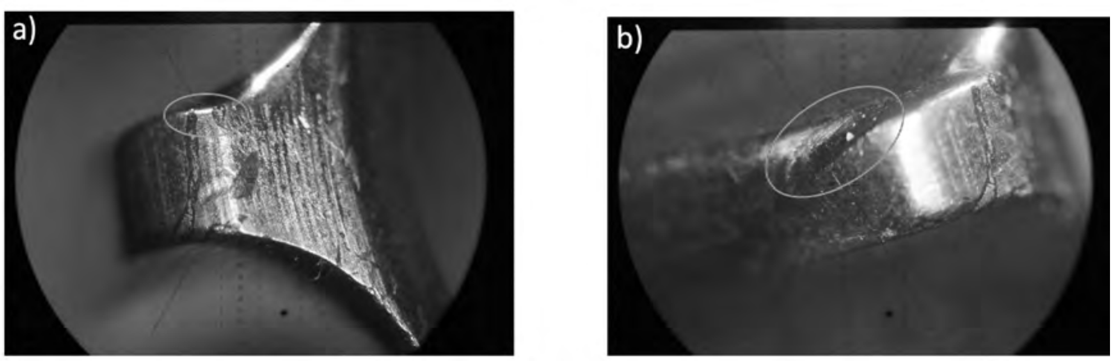

Fig. 2. Wear of tooth of the crown, resulting in holding of stream of the fibres: a) wear on edge of the tooth in form of a pit, b) wear of the tooth in form of a helical groove at the outer surface

Rys. 2. Zużycie zęba nasadki powodujące przytrzymywanie strumienia włókien: a) zużycie krawędzi zęba w postaci wgłębienia, b) zużycie zęba w postaci rowka śrubowego na powierzchni zewnętrznej

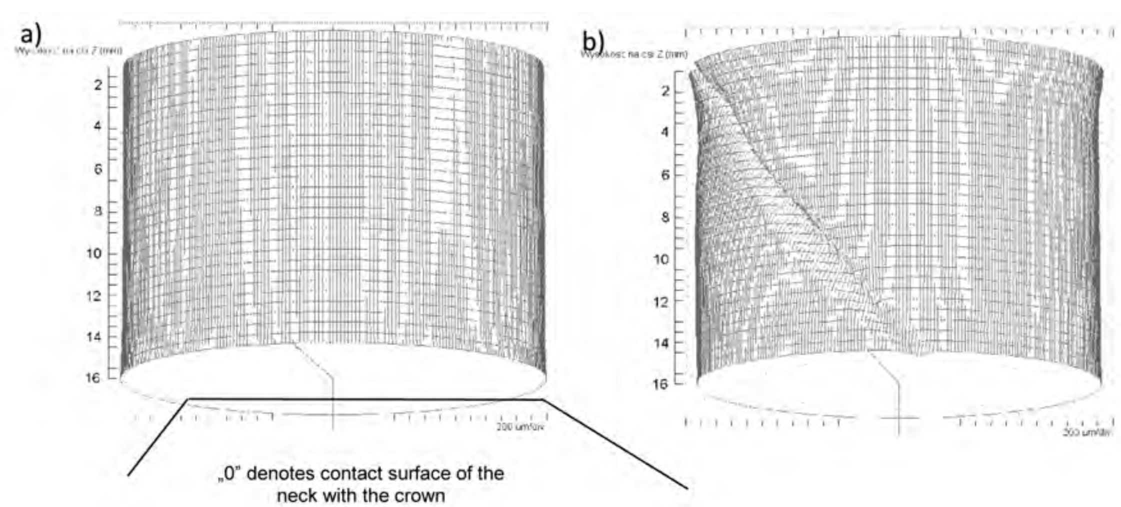

Fig. 3. Shape of cylindrical part of the neck of coating of spindle with collapse balloon crown after burnishing treatment: a) before usage, b) after operation time [L. 5]

Rys. 3. Kształt części walcowej szyjki okładziny wrzeciona z nasadką antybalonową po nagniataniu: a) przed eksploatacją, b) po eksploatacji **[L. 5]** amounted to 17.2 μm. After the operational time, the roundness deviation has increased along length of the neck of coating from approximately 19.4 to approximately 65.7 times, and it was included within the interval of 65.9–394.0 μm. The deviation of the cylindricity amounted to 435.0 μm.

The shape and value of roundness deviation in selected cross-sections of the neck of the coating of spindle after burnishing treatment, in brand new condition and after the operational time, is presented in **Fig. 4**. In practice, values of roundness and cylindricity deviations would be much greater due to the fact that the measuring probe of the roundness meter ended with ball with radius of r_k = 0.50 mm could not touch the bottom of the groove.

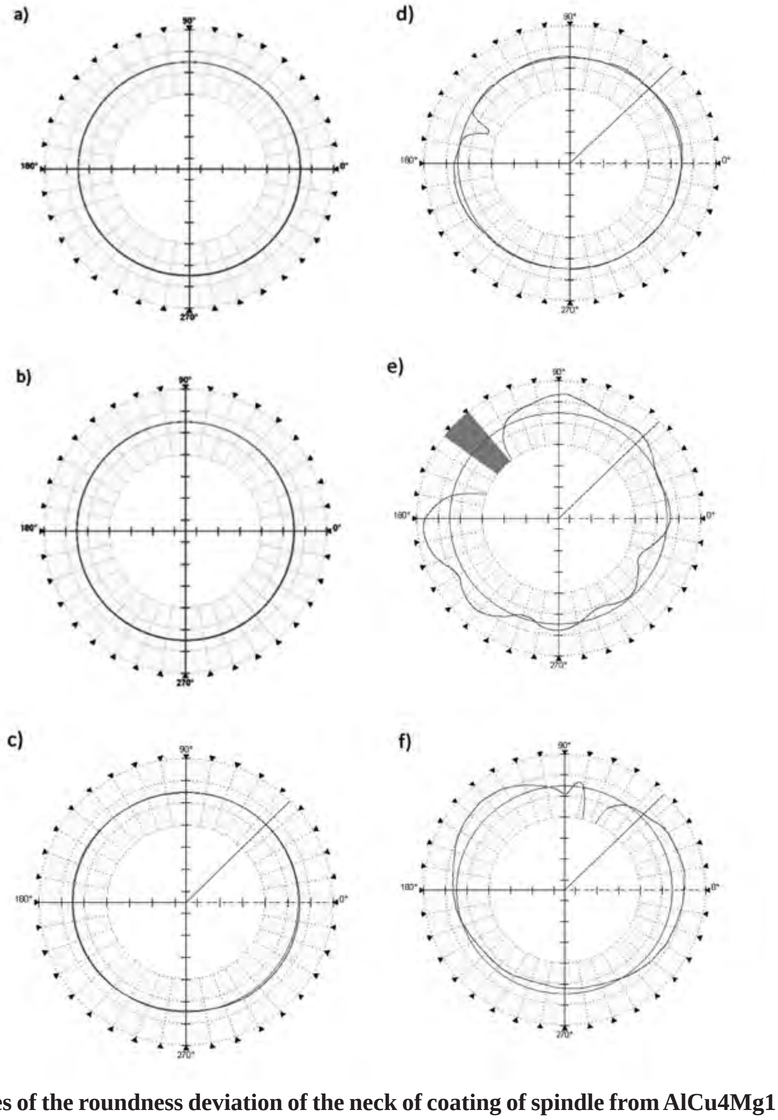

Fig. 4. Shape and values of the roundness deviation of the neck of coating of spindle from AlCu4Mg1 alloy after burnishing treatment at distances approximately 1,0 and 9,0, and 16,0 mm from face of the crown: before the operation (Fig. a; b and c) and after operational time of about 21600 man-hours (Fig. d; e and f)

Rys. 4. Kształt i wartości odchyłki okrągłości szyjki okładziny wrzeciona ze stopu AlCu4Mg1 po nagniataniu w odległościach około 1,0 i 9,0 oraz 16,0 mm od podstawy nasadki: przed eksploatacją (rys. a; b i c) oraz po czasie eksploatacji wynoszącym około 21600 roboczogodzin (rys. d; e i f)

For example, **Fig. 5a** presents the neck of coating of spindle together with the crown and marked wear having form of helical groove. **Fig. 5b** presents the neck of the coating together with the shape of the groove in a selected cross-section, which is shown in the expansion (at 8x magnification). Performed measurements of the shape of the groove using as instrument to measure the profile equipped with a measuring probe having fillet radius of r_p = 20 μm have allowed proper assessment of the depth and the width of the wear groove. The outline of the groove, performed perpendicularly to its run, was set in the following distances from face of the crown:

1,0 mm and next within the range of length of the neck from 3.0 to 17.0 mm every 2.0 mm, and next at distances of 20.0, 25.0, 30.0, and 35.0 mm (**Fig. 5b**). As can be seen, at the distance of 1 mm from face of the crown, the depth of the groove is g_{r1} = 423 µm, whereas the width amounts to s_{r1} = 2.8 mm. As you move away from face of the crown, the depth of the groove increases, and, at distance 9 mm, it reaches the highest value g_{r9} = 1333 µm and the width of about s_{r9} = 2.3 mm. Next, together with increasing distance from face of the crown, the depth of groove of the wear decreases and, at distance 17 mm, reaches a value of g_{r17} = 729 µm and a width of about s_{r17} = 2,1 mm. At a distance of 30 mm, the depth of the groove of the wear amounts to g_{r30} = 88 µm, while the width amounts to about s_{r30} = 2.2 mm.

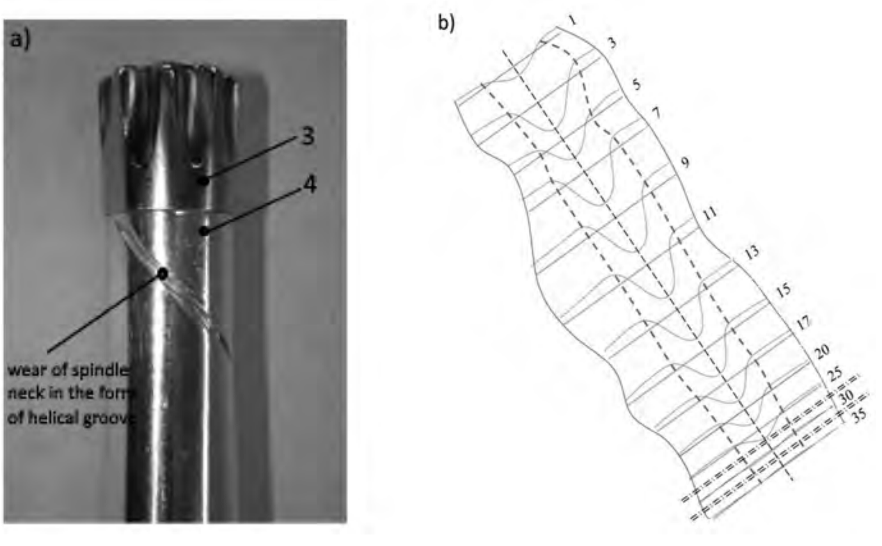

Fig. 5. End part of the coating from AlCu4Mg1 alloy with the crown of spinning spindle: a) wear of burnished neck of coating of spindle, having form of helical groove, after operational time of about 21600 man-hours: 3 – crown, 4 – the neck of coating of spindle from AlCu4Mg1 alloy; b) shape, depth and width of the groove in perpendicular sections at distances approximately 1; 3; 5; 7; 9; 11; 13; 15; 17; 20; 25; 30 and 35 mm from face of the crown

Rys. 5. Końcówka okładziny ze stopu AlCu4Mg1 wraz z nasadką wrzeciona przędzalniczego: a) zużycie szyjki okładziny wrzeciona nagniatanej, w postaci rowka śrubowego, po okresie eksploatacji równym około 21600 roboczogodzin: 3 – nasadka, 4 – szyjka okładziny wrzeciona ze stopu AlCu4Mg1; b) kształt, głębokość i szerokość rowka w przekrojach prostopadłych w odległości około 1; 3; 5; 7; 9; 11; 13; 15; 17; 20; 25; 30 i 35 mm od podstawy nasadki

In the next step, a topographic map of the surface and a contour map were drawn as result of 3D surface measurements taken in position, where the groove was deep enough that it still allowed the measurement (i.e. at distance approximately 35 mm from face of the crown) and in an area where the groove has disappeared (i.e. at distance approximately 40 mm from face of the crown).

Figure 6a presents the shape and dimensions of the pit (groove) resulted from the friction of the stream of the fibres against surface of the neck of coating at the distance approximately 35 mm. **Figure 6b** presents the shape at the distance of approximately 40 mm. It can be noticed that stream of the fibres at a distance of 35 mm and a higher from face of the crown carves two diverging grooves with significantly smaller depth: s_{r35} = 54 µm and s_{r40} = 216 µm and a width of about s_{r35} = 2.3 mm and s_{r40} = 2.5 mm. It should be assumed that such phenomenon occurs when stream of the fibres is moving away from the neck through the beginning of the bobbin, and in particular, when bed of the ring spinner is in its upper position and is shaping the top of yarn-beam. Then the wrapping length of the neck of coating by stream of the fibres decreases, and the change of tension amplitude of the stream contributes to the change of its contact position, which contributes to the change of the wear having the form of two diverging grooves (**Figs 6a** and **6b**).

To explain type of the wear in the tribological combination: the neck of coating made of AlCu4Mg1 alloy – stream of the fibres, 2D profiles of the roughness were produced and measured the following roughness parameters: *Ra*, *Rq*, *Rp*, *Rv*, *Rz*, *Rc*, *Rt*, *Rsk*, *Rku*, *Rmr,* and *Rdc* on bottom of the groove (area A – **Fig. 7a**) and outside the groove (area B – approximately 2 mm outside the groove – **Fig. 7b**) at distance approximately 35 mm from face of the crown.

Based on results of the measurements of surface profile parameters, it can be seen that vertical parameters (concerning height of peaks and dales of the profile) on bottom of the groove are significantly higher from 1.25 to 2.47 times than the values of the analogous parameters of the surface roughness measured outside the groove. Whereas, values of the amplitude parameters, such as *Ra* and *Rq*, are also higher from approximately 2.17 to 2.50 times. Values of the asymmetry coefficient (skewness) of the profile *Rsk* are slightly higher, which proves the similar direction and values of the shift of the distribution mode of the ordinates of profile relative to the mean line. Values of the concentration coefficient (kurtosis) of the profile *Rku* amount to 4.25 for the bottom surface the groove and are more than 3 times lower comparing to values of this coefficient calculated outside the groove. Thus, it can be said that the distribution of the ordinates of the profile for the bottom surface of the groove is similar to the normal distribution, while the distribution of the ordinates for the profile of the roughness outside the groove is characterized by much lower degree of "fuzzying," i.e. values of the ordinates are mostly concentrated around the mean value. In turn, the material share of the profile for the bottom surface of the groove amounts to 94%, and for the surface outside the groove amounts to 100%.

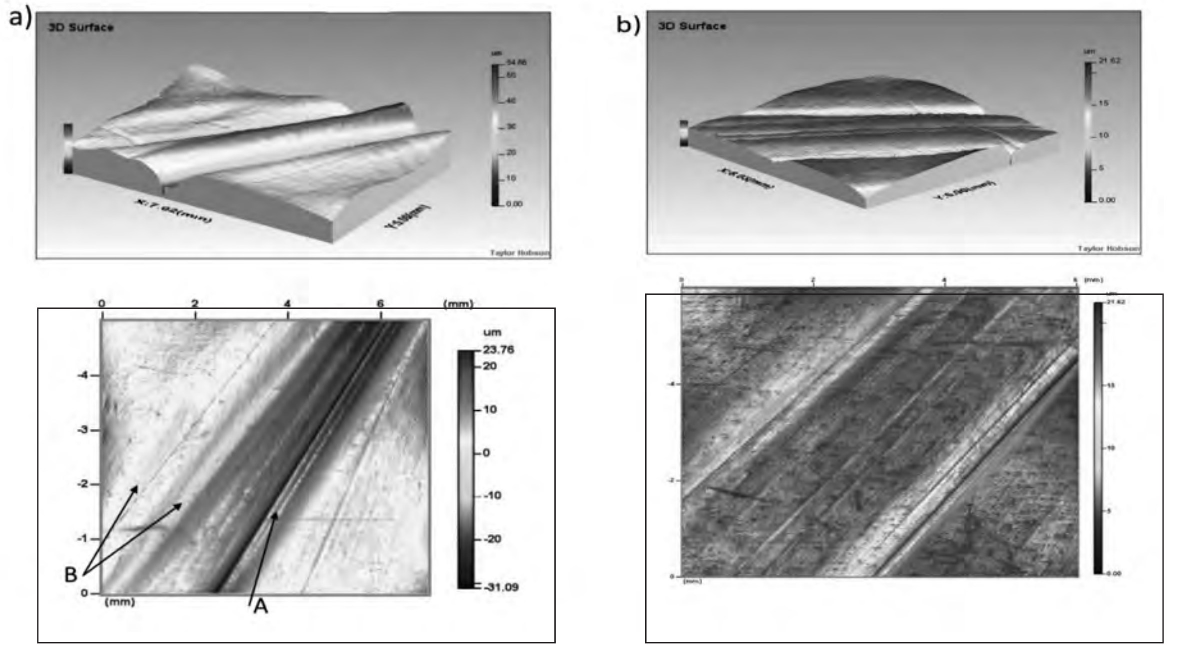

Fig. 6. Topographic and contour maps of 3D surface of the wear of the neck of coating in form of groove carved due to sliding friction against stream of the fibres: a) at distance approximately 35 mm from face of the crown; b) at distance approximately 40 mm from face of the crown

Rys. 6. Topograficzna i warstwicowa mapa 3D powierzchni zużycia szyjki okładziny w postaci rowka w wyniku tarcia ślizgowego strumienia włókien: a) w odległości około 35 mm od podstawy nasadki; b) w odległości około 40 mm od podstawy nasadki

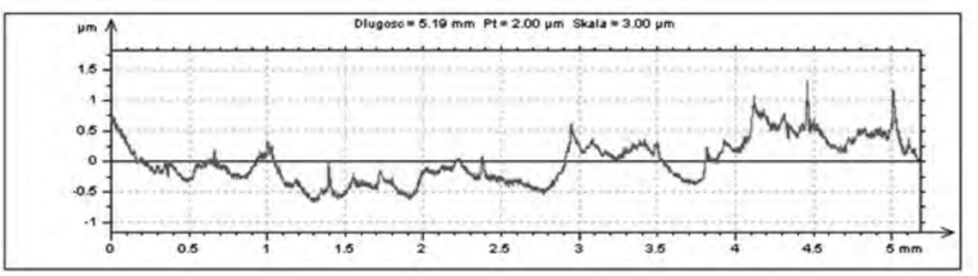

Fig. 7a. Profile of the surface roughness inside (on the bottom) worn helical groove at distance approximately 35 mm from face of the crown (area A): *Ra* = 0.10 µm, *Rq* = 0.13 µm, *Rp* = 0.47 µm, *Rv* = 0.25 µm. *Rz* = 0.72 µm, *Rc* = 0.25 µm, *Rt* = 1.07 µm, *Rsk* = 0.68, *Rku* = 4.25, *Rmr* = 94.5%, and *Rdc* = 0.21 µm

Rys. 7a. Profil chropowatości powierzchni wewnątrz (na dnie) wytartego rowka śrubowego w odległości około 35 mm od podstawy nasadki (obszar A): *Ra* = 0,10 µm; *Rq* = 0,13 µm; *Rp* = 0,47 µm;*Rv* = 0,25 µm; *Rz* = 0,72 µm; *Rc* = 0,25 µm; *Rt* = 1,07 µm; *Rsk* = 0,68; *Rku* = 4,25; *Rmr* = 94,5% i *Rdc* = 0,21 µm

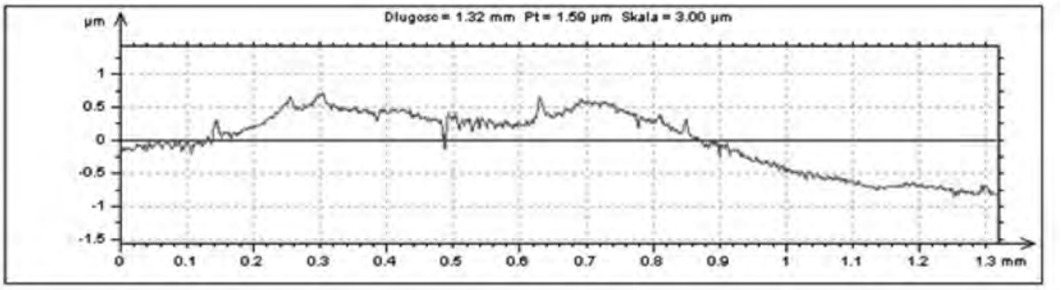

Fig. 7b. Profile of the surface roughness in immediate vicinity of the helical groove at distance approximately 35 mm from face of the crown (area B): *Ra* = 0.04 µm, *Rq* = 0.06 µm, *Rp* = 0.19 µm, *Rv* = 0.20 µm, *Rz* = 0.39 µm, *Rc* = 0.14 µm, *Rt* = 0.69 µm, *Rsk* = 0.57, *Rku* = 11.90, *Rmr* = 100%, and *Rdc* = 0.07 µm

Rys. 7b. Profil chropowatości powierzchni w bezpośredniej bliskości rowka śrubowego w odległości około 35 mm od podstawy nasadki (obszar B): *Ra* = 0,04 µm; *Rq* = 0,06 µm; *Rp* = 0,19 µm; *Rv* = 0,20 µm; *Rz* = 0,39 µm; *Rc* = 0,14 µm; *Rt* = 0,69 µm; *Rsk* = 0,57; *Rku* = 11,90; *Rmr* = 100% i *Rdc* = 0,07 µm

Directly after burnishing treatment, selected parameters of the profile of the roughness were included within the following ranges: *Ra* = 0.18–0.23 µm, *Rq* = 0.22–0.30 µm and *Rt* = 1.01–1.42 µm. In relation to values of these parameters after the time of operation of the spindle, a decrease of the roughness parameter *Ra* from 4.50 to 5.75 times occurred, and the parameter *Rq* changed from 3.67 to 5.0 times, and the parameter *Rt* changed from 1.46 to 2.06 times. However, the moving stream of the fibres causes distinctly less smoothing of the surface at bottom of the groove: the parameters *Ra* and *Rq* undergo a reduction from 1,80 to 2,30 times, while the parameter *Rt* remains at the same level, or undergoes a reduction of approximately 1.30 times. It is possible, therefore, to say that moving stream of the fibres causes significant smoothing of the surface of the neck of coating outside the groove. On the other hand, the profile of the roughness on the bottom surface of the groove is characterized by sharp peaks and adjacent significant pits, which proves a different course of the wear.

Figure 8 presents a diagram of the roundness deviation produced in area outside the wear having the form of helical groove at a distance of approximately 9.0 mm from face of the crown. Next, measurements of the arithmetic mean of the ordinates of the profile *Ra* were made in different locations around the circumference of the neck of coating. The measurements taken on surface of the neck have shown that the surface roughness defined by the parameter *Ra* was included within range *Ra* = 0.04–0.16 µm. Unfortunately, the imperceptible height of peaks and dales present on the surface did not allow finding a clear link of obtained values of the roughness parameter *Ra* with the location of the measuring point on the peak or in the dale of measured outline. To relate, at least partially, values of selected surface roughness parameters with value of the wear, a measurement of shape of the outline along its generator line was performed on the surface of the neck of coating (**Fig. 9**). The measurement has revealed areas on the surface that were located at different heights (at different diameters) where the generator line was not a straight line, which verify the different values of the wear along the length of the neck of the coating. Next, measurements of selected parameters of the roughness were performed at distances approximately 2.5 mm, 15.5 mm, and 22.5 mm from face of the crown (**Figs 10a, 10b,** and **10c**). As can be seen from the measurements of selected parameters of the surface roughness, such as *Ra*, *Rq* and *Rt* among others, the lowest surface roughness occurred at a distance of approximately 22.5 mm from face of the crown (in area C of generator line of the outline of the neck), and a slightly higher value was in the area of the highest wear, i.e. at distance of approximately 15.5 mm (in area D). For instance, the value of the parameter *Ra* in the area C has amounted to 0.03 µm, while, in the area D, it was 0.05 µm, whereas, the values of the parameter *Rt* in both these areas were identical and were equal to 0.56 µm. Moreover, the value of the parameter *Ra* at distance approximately 2.5 mm from face of the crown was more than fourfold higher and amounted to *Ra* = 0.14 µm, while of the parameter *Rt* was approximately 1.9 times higher and amounted to *Rt* = 1.06 µm. Values of the asymmetry coefficient (skewness) of the profile *Rsk*, at distance approximately 15.5 and 22.5 mm from face of the crown are negative, which proves the left sided oblique distribution of the ordinates of the profile in relation to the mean line and that the modal value is bigger than the median and mean value of the ordinates of the profile. Such characteristics feature surfaces with a flat-top profile or similar to it, characterized by curve of material ratio with progressive character, and by high share of carrying capacity near surface of the top layer. Such surfaces are formed during abrasive wear as a result of the friction of stream of the fibres against surface of the metal, and are characterized by significant smoothing of the unevenness. Whereas, values of the asymmetry coefficient of the surface at a distance of approximately 2.5 mm from face of the crown are positive – *Rsk* = 0.57, which proves the right sided oblique distribution of ordinates of the profile. Values of the concentration coefficient (kurtosis) of the profile *Rku* for the area C and D are higher than 3 and are equal to 15.0 and 4.26, respectively, which proves the high concentration of the ordinates of the profile near the mean value. Whereas, values of the concentration coefficient for the surface located at a distance of approximately 2.5 mm from face of the crown (area E) are equal to *Rku* = 2.74; thus, it can be said that distributions of the ordinates of the profile are close to the normal distribution. A higher values of the surface parameters *Ra, Rq,* and *Rt* on the neck of coating near to face of the crown can be explained by a lower pressing force of the stream of the fibres, resulting from diameter of the neck being smaller by 0.10 mm, compared to the diameter of the face of the crown.

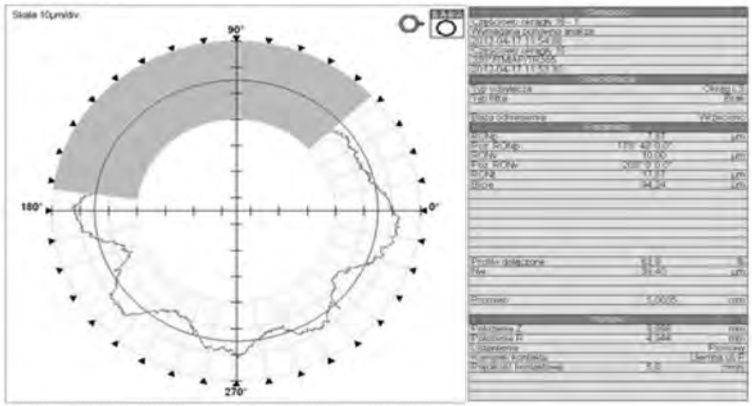

Fig. 8. Diagram of the roundness deviation performed in area outside the wear at distance approximately 9.0 mm from face of the crown

Rys. 8. Wykres odchyłki okrągłości wykonany w obszarze poza zużyciem w odległości około 9,0 mm od podstawy nasadki

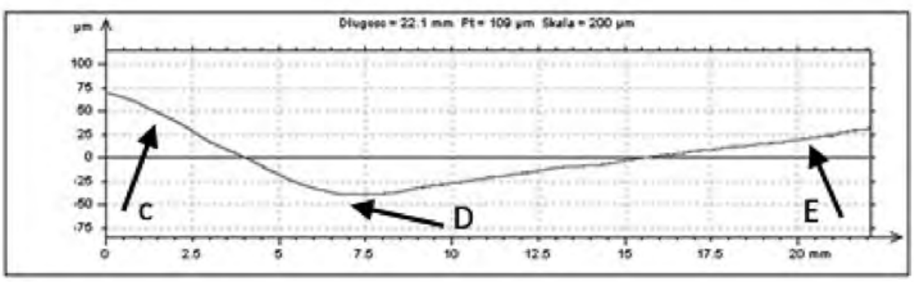

Fig. 9. Shape of the outline along the generator line of the spindle-neck coating with collapse balloon crown

Rys. 9. Kształt zarysu wzdłuż tworzącej szyjki okładziny wrzeciona przędzalniczego z nasadka antybalonową

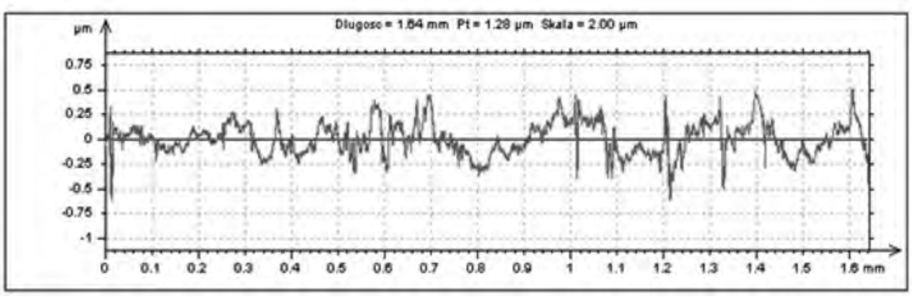

Fig. 10a. Profile of the surface roughness and values of the parameters at distance approximately 22.5 mm from face of the crown (area C on generator line of the neck): *Ra* = 0.03 µm, *Rq* = 0.05 µm, *Rp* = 0.16 µm, *Rv* = 0.38 µm, *Rz* = 0.54 µm, *Rc* = 0.17 µm; *Rt* = 0.56 µm, *Rsk* = -2.53, *Rku* = 15.0; *Rmr* = 100% and *Rdc* = 0.06 µm

Rys. 10a. Profil chropowatości powierzchni i wartości parametrów w odległości około 22,5 mm od podstawy nasadki (obszar C na tworzącej szyjki): *Ra* = 0,03 µm; *Rq* = 0,05 µm; *Rp* = 0,16 µm; *Rv* = 0,38 µm; *Rz* = 0,54 µm; *Rc* = 0,17 µm; *Rt* = 0,56 µm; *Rsk* = -2,53; *Rku* = 15,0; *Rmr* = 100% i *Rdc* = 0,06 µm

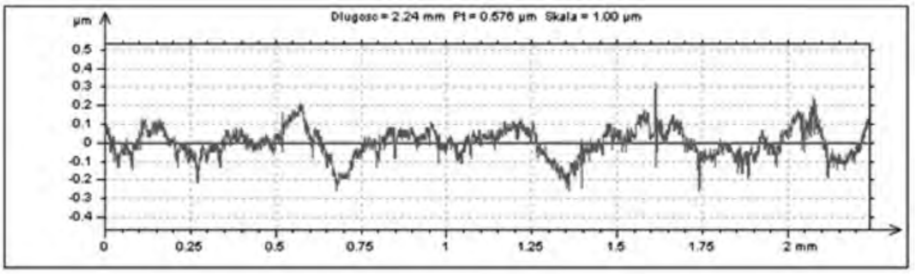

Fig. 10b. The profile of the surface roughness and values of the parameters at a distance of approximately 15.5 mm from face of the crown (area D on generator line of the neck): *Ra* = 0.05 µm, *Rq* = 0.07 µm, *Rp* = 0.19 µm, *Rv* = 0.24 µm, *Rz* = 0.43 µm, *Rc* = 0.14 µm, *Rt* = 0.56 µm, *Rsk* = -0.36, *Rku* = 4.26, *Rmr* = 100% and *Rdc* = 0.10 µm

Rys. 10b. Profil chropowatości powierzchni i wartości parametrów w odległości około 15,5 mm od podstawy nasadki (obszar D na tworzącej szyjki): *Ra* = 0,05 µm; *Rq* = 0,07 µm; *Rp* = 0,19 µm; *Rv* = 0,24 µm; *Rz* = 0,43 µm; *Rc* = 0,14 µm; *Rt* = 0,56 µm; *Rsk* = -0,36; *Rku* = 4,26; *Rmr* = 100% i *Rdc* = 0,10 µm

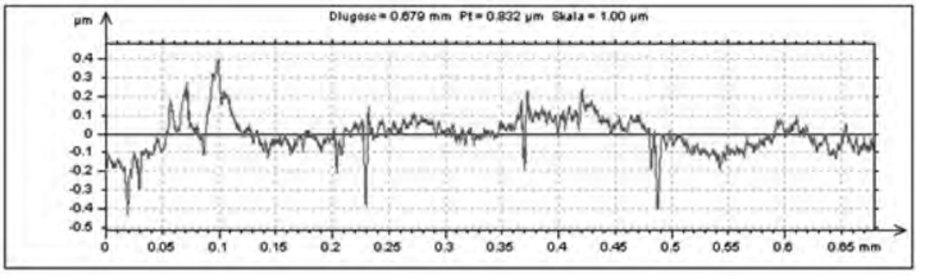

Fig. 10c. Profile of the surface roughness and values of the parameters at distance approximately 2.5 mm from face of the crown (area E on generator line of the neck): *Ra* = 0.14 µm, *Rq* = 0.17 µm, *Rp* = 0.46 µm, *Rv* = 0.38 µm, *Rz* = 0.85 µm, *Rc* = 0.40 µm, *Rt* = 1.06 µm, *Rsk* = 0.57, *Rku* = 2.74. *Rmr* = 99.7% and *Rdc* = 0.29 µm

Rys. 10c. Profil chropowatości powierzchni i wartości parametrów w odległości około 2,5 mm od podstawy nasadki (obszar E na tworzącej szyjki): *Ra* = 0,14 µm; *Rq* = 0,17 µm; *Rp* = 0,46 µm; *Rv* = 0,38 µm; *Rz* = 0,85 µm; *Rc* = 0,40 µm; *Rt* = 1,06 µm; *Rsk* = 0,57; *Rku* = 2,74; *Rmr* = 99,7% i *Rdc* = 0,29 µm

Microphotography of side surface of the wear, after the friction (at a distance of approximately 9.0 mm from face of the crown), is shown in **Fig. 11**. The photo shows layering of the matrix and precipitations in form of bright areas of metallic phase, as well as scratches in moving direction of stream of the fibres. **Fig. 12** shows exemplary EDS spectrum for the surface in the location of the precipitation (phase of AlCuFeMnSi type – point 2). **Table 2** contains the specified percentage contents of the elements Al, Cu, Fe, Mg, Mn, and Si in a selected location of the matrix (point 1), and in the metallic phase (in point 2). In the AlCuFeMnSi phase, there is approximately 37% less aluminium, approximately 85% more copper, 98% more iron, 79% more manganese, and 1,08% more silicon, in relation to the contents of these elements in the matrix.

In the combination: stream of the fibres – the neck of coating had occurred limit sliding friction, because an oiling agent was on the wool fibres, providing suitable adhesiveness of the fibres and giving a slip, and acting to reduce static. In vast majority of the cases, the stream of the fibres moving on the neck of

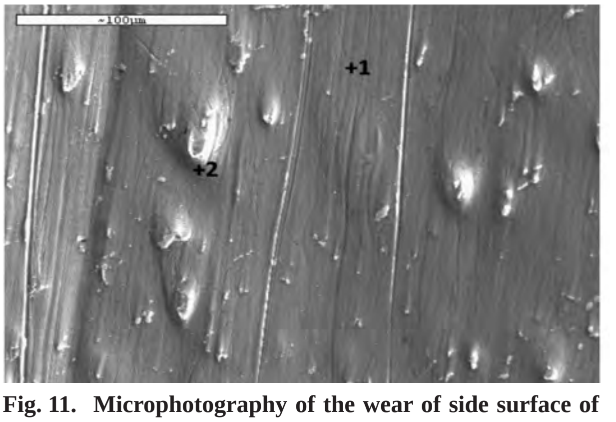

Fig. 11. Microphotography of the wear of side surface of helical groove (at distance approximately 9.0 mm from face of the crown)

Rys. 11. Mikrofotografia powierzchni zużycia ścianki bocznej rowka śrubowego (w odległości około 9,0 mm od czoła nasadki)

the coating of the spindle during ultra-short contact, ranking from 0.00060 to 0.000706 seconds, depending on rotation speed of the spindle, causes slight wear of the neck. Such wear is manifested through formation of pits around circumference of the neck of the coating with a changing depth from about 20 to approximately 100 µm in a quantities corresponding to number of teeth of the crown. The loss of the material in top layer of the neck is caused by the separation of the particles due to micro-cutting, because, in friction areas of the mating elements a dead particles (grass, tree bark, straw), glued to stream of the fibres can be met, and not infrequently, micro-grains of a dust stuck to the wool fibres are acting as localized micro-blades **(Fig. 13)**. These particles are pressed down with variable force against surface of the neck of the coating due to the changing tension of stream of the fibres caused by its cyclical entering and exiting from notches of the crown, and due to the variable position of the axis of the spindle ending with the crown occurring in course of its rotational movement. By analogy to grinding operation with abrasive paper which unwinds from a roll, it can be possible to assume that the solid particles are acting as localized micro-blades, which, during a long period of time, can cause the formation of pits of varying depth. The stream of the fibres, during rotary motion of the spindle, and thus the crown, changes its position, "jumping over" from one notch to the next one. When the stream of the fibres is located on one from the teeth of the crown, and hence at the greatest distance from axis of the spindle, then pressure of this stream on the neck of coating is the lowest. In the case when stream of the fibres is in notches of the crown, and more closely wraps and sticks to surface of the neck of the coating, the pressure of the yarn on surface of the neck becomes distinctly greater. As a result of varying tension of stream of the fibres, reaching a maximal value up to approximately 37 cN, irregular abrasive wear of the neck of the coating occurs, both around the circumference and along the axis of the spindle. Such wear is generally manifested through a significant reduction of surface roughness and its shining.

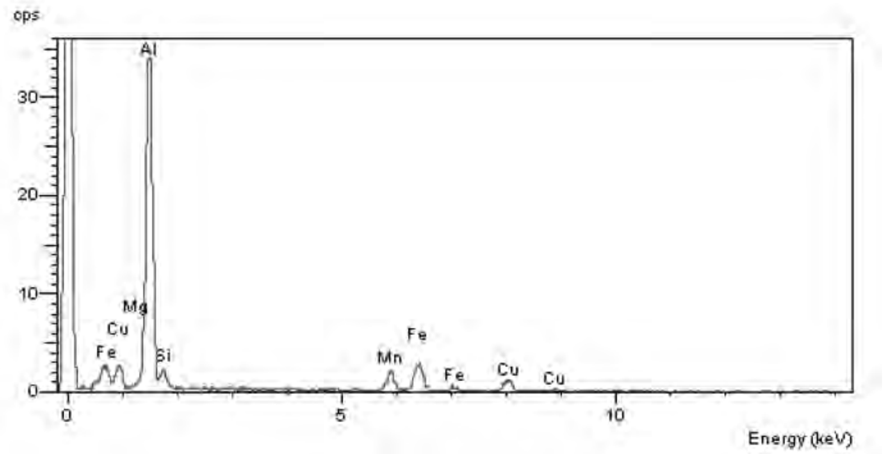

Fig. 12. Exemplary distribution of the elements: Al, Cu, Fe, Mg, Mn, Si in the AlCuFeMnSi phase (point 2) on wear surface of side wall of the helical groove of the neck of coating from AlCu4Mg1 alloy after operational time of approximately 21600 man-hours (after time of cooperation of stream of the fibres being blend of: 70–80% wool fibers +30–20% polyester fibres with the neck of coating)

Rys. 12. Przykładowy rozkład pierwiastków: Al, Cu, Fe, Mg, Mn, Si w fazie AlCuFeMnSi (punkt 2) na powierzchni zużycia ścianki bocznej rowka śrubowego szyjki okładziny ze stopu AlCu4Mg1 po czasie eksploatacji wynoszącym około 21600 roboczogodzin (po czasie współpracy strumienia włókien będącego mieszanką: 70÷80% włókien wełny +30÷20% włókien poliestrowych z szyjką okładziny)

Table 2. Percentage contents of the elements Al, Cu, Fe, Mg, Mn, Si in a selected locations of the wear on side surface of the helical groove of the neck of coating of spinning spindle made of AlCu4Mg1 alloy

Tabela 2. Zawartość procentowa pierwiastków Al, Cu, Fe, Mg, Mn, Si w wybranych miejscach zużycia powierzchni bocznej rowka śrubowego szyjki okładziny ze stopu AlCu4Mg1 wrzeciona przędzalniczego

	Al %	Cu %	Fe %	Mg %	Mn %	Si %
Matrix (Point 1)	93.65	3.82	0.13	1.45	0.95	–
Phase (Point 2)	58.92	25.24	10.04	0.14	4.58	1.08

However, in result of improperly manufactured fillet on one from teeth of the crown, stream of the fibres is "held" by this tooth, and as result, there is no rhythmic transition from one notch to the next one. The time period of the friction of the sliding stream of the fibres, in a selected area along the circumference, of the crown first, and of the neck of coating next, increases more than twice. As result, in the first succession, attrition (carving) of a pit on the edge of the tooth occurs (**Fig. 3a**) and attrition of a helical groove having

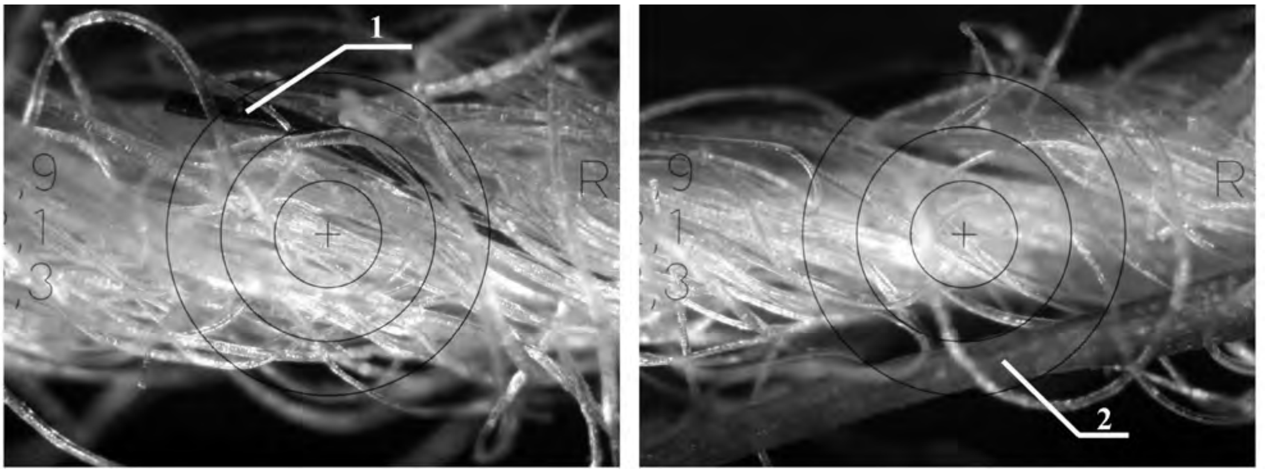

Fig. 13. Picture of the yarn with inclusions of the dead particles: 1 – grass, 2 – straw, magnification 100x
Rys. 13. Widok przędzy z wtrąceniami cząstek martwych: 1 – trawa, 2 – słoma, pow. 100x

slight depth on side surface of the crown (**Fig. 3b**). The number of the pits around circumference of the neck of the coating, at some distance from face of the crown, is smaller by one or two pits. The authors, based on analysis of the literature **[L. 3]** among others, and long-lasting observations of surfaces of the wear, have put a hypothesis that discontinuous limit sliding friction is present in the combination: rotating neck of coating – moving stream of fibres. The work caused by the limiting friction force in a unit of time is converted into frictional heat, which is distributed between surfaces of the both mating elements, causing an increase of temperature, mainly on the contact surface of the neck of the coating with the stream of the fibres. The increase in temperature increases the rate of oxygen diffusion to the AlCu4Mg1 alloy and the simultaneous formation of very thin layers of chemically absorbed oxygen on the friction surface, which results in the formation of aluminium oxides. In turn, ultra-microscopic layers of these oxides are removed from the surface, chipping off from the surface, both under the effect of frictional forces, and due to loss of adhesion with core of the neck of coating from AlCu4Mg1 alloy, due to increasing volume of aluminium oxides in relation to the volume of initial aluminium alloy.

SUMMARY

The most probable hypothesis seems to be such that loss of the material around the circumference and along the generator line of the spindle-neck coating with collapse balloon crown in form of pits with shape of helical line and size of the order of hundredths of a millimetres is caused by the separation of ultra-microscopic volumes of material in the frictional area due to micro-cutting. The separation of the material occurs as a result of cyclically interrupted action of the stream of the fibres, in particular, of solid particles in form of grass, tree bark, straw, and due to not infrequently present micro-grains of dust located in moving stream of the fibres, which are acting as micro-blades. According to the authors, the abrasive wear has a dominant importance in separation of the material during the limit sliding friction of stream of the fibres against surface of the neck of coating of collapse balloon spindle.

On the other hand, in case of faulty manufactured crowns, most often, an incorrectly manufactured fillet on one of the teeth and prolonged friction of the stream of the fibres against the neck of coating occurs. The authors have put a hypothesis that, as a result of the above, an increase in temperature occurs and the diffusion rate of oxygen to AlCu4Mg1 alloy in area of the limiting sliding friction between stream of the fibres and the neck of coating increases, which is manifested through the formation on the friction surface of very thin layers of chemically absorbed oxygen producing aluminium oxides **[L. 3]**. The loss of the aluminium-copper-magnesium alloy occurs as a result of the removal of ultra-microscopic layers of aluminium oxide from surface of the friction. These layers are chipping off from the surface both under the influence of acting friction forces, as well as due to loss of the adhesiveness with core of the alloy, because of the increasing volume of aluminium oxides, compared to the initial alloy (The Pilling-Bedworth rule for the aluminium). It is therefore presumed that catastrophic wear of the neck of coating of spindle with collapse balloon crown, having the form of helical groove with considerable depth, generally not exceeding 1.5 mm and width of a few millimetres, occurs as the result of the synergy of abrasive wear and by the oxidation.

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