



Surface roughness and its structural orientation caused by internal microstructural changes in mechanically stressed copper conductors

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ABSTRACT

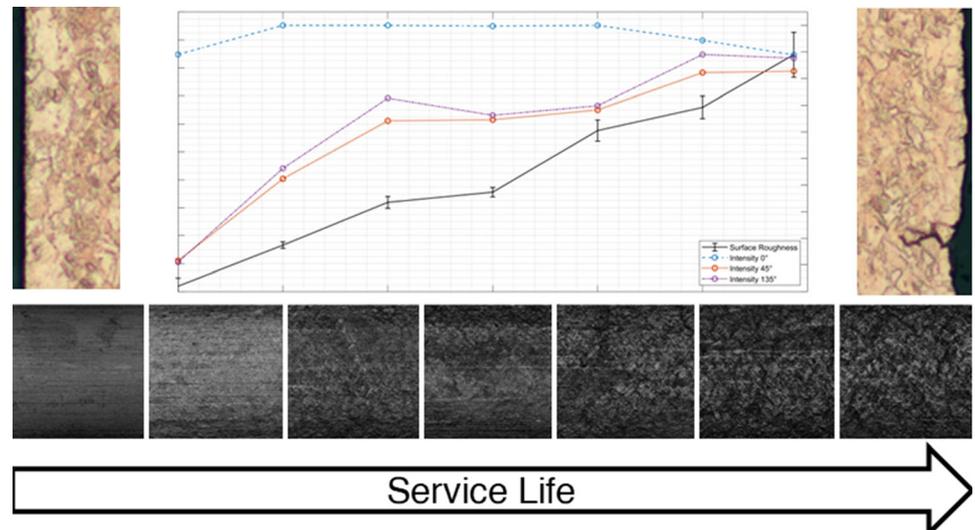
In this paper, the mechanical damage behavior is investigated based on the characteristic roughness on the surface and the orientation of superficial structures. The main goal is to explore the surface roughness on mechanically loaded copper conductors as a lifetime indicator. For this purpose, copper conductors are mechanically stressed in accordance with EN 50,396 and then examined metallographically and microscopically. The microstructure examination shows that the roughness is caused by material extrusion and cracks due to work hardening in the surface area. Using confocal microscopy, it is shown for the first time that significant formation of surface roughness takes place over the service life of copper conductors. The roughness increases monotonically, but not linearly with number of cycles, due to internal microstructural processes and can be divided into three sections. First inspections of the conductor surface over lifetime show a correlation between the intensity of structures orientated 45° to the loading direction and the roughness. This phenomenon, already known from microscopic slip lines, is thus also evident in macroscopic roughness formation and is well founded by the research theory on material extrusion along dislocation lines. In summary, a lifetime determination is possible based on its developing roughness which enables the utilization as a sensor element.

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GRAPHICAL ABSTRACT



Introduction

The copper material, which by today has been used in cables and wires exclusively for energy and data transmission, will in future be embedded into natural fiber composite materials and serve as an electromechanical sensor element for dynamic loading. This could enable continuous component monitoring and thus facilitate preventive action against sudden material failure. A crucial prerequisite for this is a fundamental understanding of the mechanical aging behavior of copper conductors under dynamic load. Little attention was paid to this in the past as the lack of recent publications shows. For the first time, mechanical investigations on stressed copper conductors were carried out during doctoral studies of Tobias Ehlenz between 2016 and 2019 at Trier University of Applied Sciences [1]. A core finding of his research is that copper conductors develop roughness on their surface due to dislocations caused by a bending load. Depending on the dynamic load duration or the load cycles, this roughness increases until the conductor breaks. [1, p. 77] As a potential effect for lifetime determination, the surface roughness of mechanically stressed copper conductors will be further investigated in this paper.

Our recent investigations show that all relevant load types (tension/compression, bending and torsion) produce characteristic surface roughness on copper conductors [2]. Surface roughness is thus a suitable wear indicator for copper conductors in moving applications. A special feature of the characteristic used is that a value measured at any point in time represents the entire load history (instead of an instantaneous value). As shown before by others, surface roughness has a significant impact on the propagation of radio-frequency (RF) waves in terms of transmission attenuation and phase [3–5]. For the first time this effect was mentioned in 1949 [6]. For an in situ measurement approach, RF current can hence be used to assess the conductors wear-level without the need to optically inspect the surface. However, the exact interaction with different forms of roughness is still widely unknown and must therefore be investigated in more detail.

Ehlenz already observed structures on the surface of dynamically loaded copper conductors [1, p. 102], which are reminiscent of the slip-lines known on ferrous materials [7]. These macroscopic images of the surface show in particular that the structures always form in an 45° angle to the direction of loading. [1, pp. 102–104]. Dislocation structures on the surface of dynamically loaded mono- and

polycrystalline face-centered cubic (fcc) copper have been investigated in the past [8, 9], and simulations have also shown a corresponding alignment of microscopic flow figures. However, these results only refer to monocrystals [8, 10], which are only partly comparable with the subject used in this work. Moreover, it remains to be shown how the microscopic structures are related to the macroscopic observations. In this paper, the relationship between the macroscopic surface roughness of the microscopic structure direction is shown for the first time.

For this purpose, the characteristics of structures and roughness development of a mechanically stressed copper conductor are presented as a function of the load or service life and its potential cause. The focus is on the developing surface roughness, since this is a measure of the mechanical aging of a copper conductor [2]. For this purpose, metallographic examinations are carried out before (“as-new condition”) and after mechanical loading. The expected microstructural changes are used to proof the cause(s) of the roughness formation. Subsequently, the surface roughness measured over the lifetime of a mechanically loaded conductor is presented. The quantitative analysis of the surface structures provides new insights into the roughness formation and thus into the aging behavior of a mechanically loaded copper conductor. Here, not only empirical results are presented, but also hypotheses are put forward on how this material behavior can be reasoned.

Methods

Copper (Cu-ETP, CW004A) cables of type H07V-U with a cross section of 1.5 mm^2 are used as test specimens for the mechanical tests. Due to its property of most commonly used conductor material in combination with the insulator PVC (polyvinyl chloride), this is a representative test subject and provides reproducible results in mechanical, metallographic and optical investigations [2].

Mechanical stress

The mechanical aging of the copper conductor is performed by a “two-pulley flexing test.” The two-pulley apparatus loads the conductors cyclically until they break and is carried out in accordance with EN 50,396. This standard describes “non-electrical test

methods for low-voltage energy cables” [11, pp. 11–16]. Since single-core conductors are not considered in the standard, the following parameters have been defined: roller diameter 80 mm (material polyoxymethylene “POM”), load weight 2 kg, load current 20 mA (for continuity measurement only). The combination of POM roll and PVC insulation ensures that there is no negative influence on the surface by the testing machine.

By alternately bending the copper conductor cyclically through two rollers, the controlled mechanical aging of the copper conductor until breakage can be reproducibly realized. For this publication, the conductors are only loaded in bending, since this load type consists of tension/compression components [12, p. 169] and is thus the representative load type for later applications. Furthermore, it was found in recent investigations that bending loads show the most characteristic and reproducible damage pattern [2]. Thus, test subjects can be created for further investigation which possess the characteristic damage features in the form of surface roughness.

Metallographic examination of copper conductors

Metallographic examinations are made to visualize the dislocation formation on the conductor surface. These serve to reveal the metallic microstructure. For this purpose, the copper conductors are embedded in CEM1000 [13] cold mounting resin longitudinally to the direction of loading. The cold mounting process was specifically chosen to show the damage behavior at the surface, since recrystallization processes already take place in the microstructure of copper materials at temperatures above approx. 150°C , and the mechanical damage pattern would therefore be distorted in the case of hot mounting [14]. Subsequently, the specimens are mechanically ground with silicon carbide (SiC) abrasive paper with grain sizes 800, 1000, 1200 and 2000. Then, samples were polished with 1-Step- (Festool MPA 5010) and fine sanding polish (Festool MPA 9010). This provides a smooth surface necessary for optical inspection. To make the microstructure and especially the grain boundaries visible, a microscopic etching with ammonium persulfate is carried out [15, p. 107]. The etched sample surface is then examined with the Carl Zeiss “Scope A1” microscope, the “AxioCam 208

color” camera and a $50\times$ lens resulting in $500\times$ magnification.

In addition, the grain size of the microstructure will be investigated. For this purpose, the software μ Grain is used, which allows an automated grain size determination with the line intersection method according to ASTM E112. The grain boundaries are detected automatically with the aid of the watershed (image processing) algorithm based on local extreme values in the gray scale. The result of the analysis is the ASTM grain size number G . This number is calculated by the following equation [16]:

$$N_{AE} = 2^{G-1}$$

N_{AE} describes the number of grains per square inch at a magnification of $100\times$. The ASTM grain size number G thus indicates the number of grains per area. The aim of this parameter is to evaluate grain sizes independently from the utilized magnification.

Surface analysis via confocal microscopy

The surface roughness formed on mechanically loaded copper conductors was measured and analyzed using the Confovis Toolinspect S confocal microscope. The roughness is given by the root mean square (RMS) roughness Sq , which is calculated according to EN ISO 25178–2 as follows:

$$Sq = \sqrt{\frac{1}{A} \iint_A z^2(x, y) dx dy}$$

The area-related roughness value Sq is preferred over the line-related roughness value R_q , since the influence of suboptimally selected measuring areas can be minimized. The three-dimensional resolution of the object via the confocal microscope allows the calculation of an angular power spectrum from the surface data. This spectrum shows the intensity of structures over an angular range from zero to 180° degrees. It should be noted that due to the ambiguity of the zero-reference position, structures at 45° are equivalent to 135° structures and vice versa. Calculations of the RMS roughness as well as the angular power spectrum are performed with MountainsMap software from Digital-Surf based on the unfiltered raw data of the confocal microscope.

Results and discussion

Below figure shows the results of the investigation of mechanically aged copper conductors obtained with the above-mentioned methods.

Surface roughness formation due to material extrusion and cracks on the conductor surface

Figure 1a shows the surface of a new copper conductor and (b) a copper conductor loaded to 587 bending cycles until breakage. The images were obtained with a confocal microscope. The image area is $630\ \mu\text{m} \times 630\ \mu\text{m}$. The y-coordinate is longitudinal to the conductor axis and thus to the direction of loading. These are two examples selected from the test series of four specimen total.

It can clearly be seen that the surface of the mechanically loaded copper conductor has a greater roughness than the as-new conductor. Drawing grooves in the longitudinal direction (y-axis) can be seen on the as-new specimen. These occur during cold forming in the wire drawing process, are present to the same extent in all test specimens of a batch and therefore do not need to be considered further. The surface roughness of the new copper conductor is $Sq = 0.2267\ \mu\text{m}$. In contrast, the copper conductor mechanically stressed to breakage has a roughness of $Sq = 1.848\ \mu\text{m}$. An increase in surface roughness is observed in the form of a fissuring of the surface. The strong deformation of the surface also ensures that the drawing depths of the manufacturing process are hardly visible anymore. This again shows that the mechanical-dynamic loading of copper conductors leads to a visible and measurable increase in surface roughness.

A more detailed insight into the damage behavior of copper conductors can be obtained with a metallographic microstructure examination. The test specimens shown in Fig. 1 were examined metallographically along their y-axis. The images were taken using the above-mentioned Carl Zeiss microscope. The result is shown in Fig. 2. The black section in the upper part of the two graphs shows the transition of the surface of the copper conductor to the cold mounting resin. The same subjects were used for the metallographic examination as for the optical representation in Fig. 1.

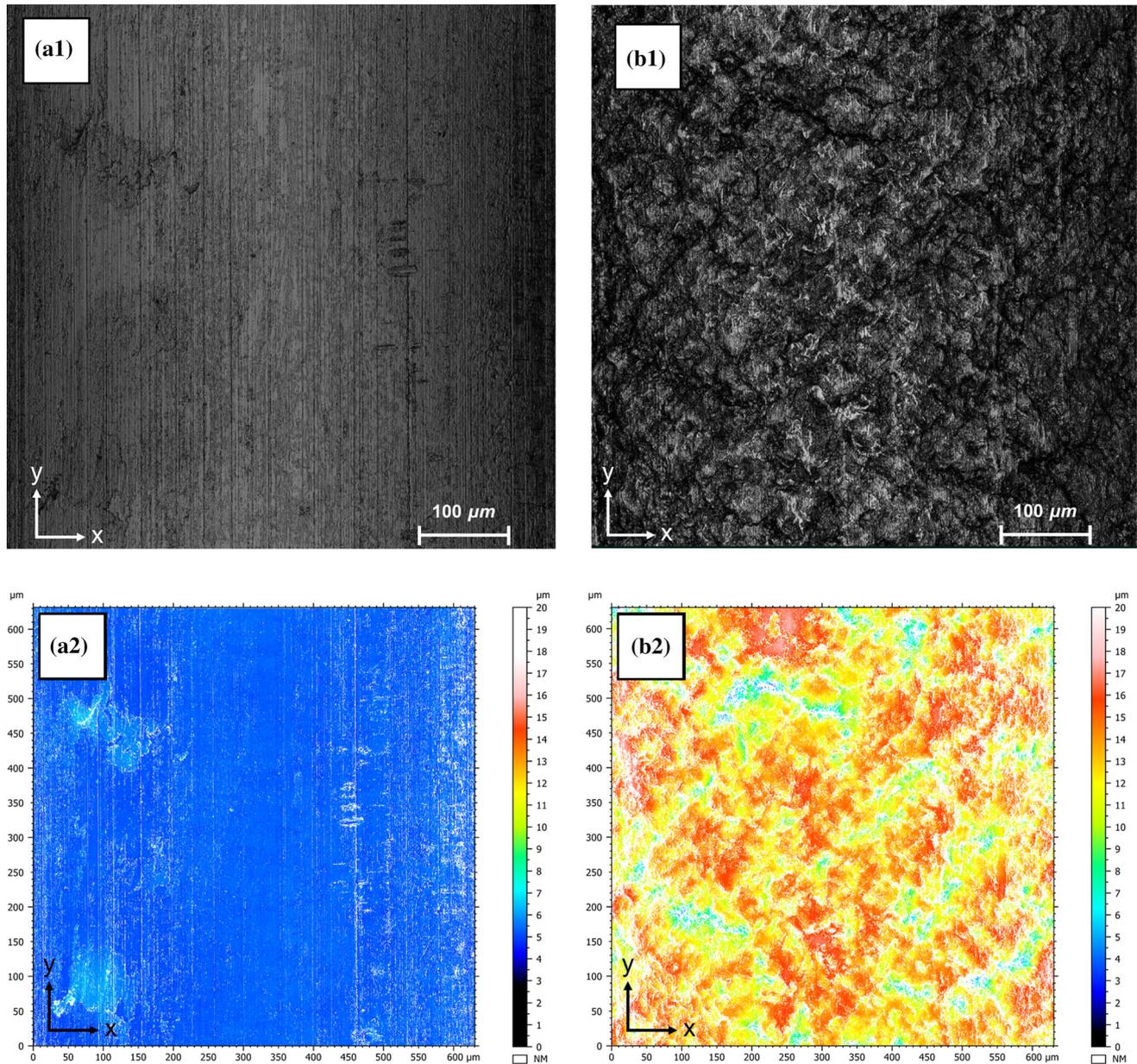


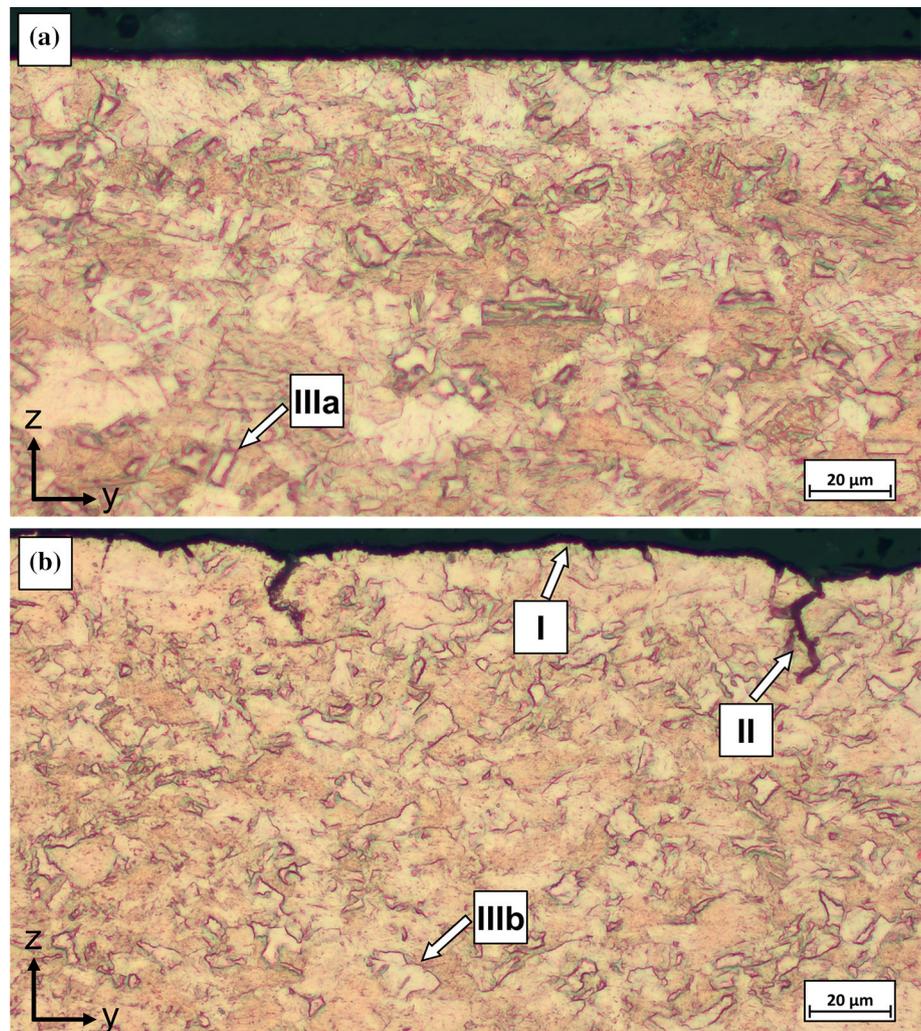
Figure 1 Surface structure obtained by confocal microscopy of copper conductors of type H07V-U 1.5 mm². **a** as new, Sq: 0.2267 μm. **b** 587 cycles according to EN 50,396, loaded until breakage, Sq = 1.848 μm. **a1** and **b1** show the intensity of the

conductor surface in grayscale and **a2** and **b2** the pseudo-color representation of the surface height. For the height visualization, the cylindrical geometry was removed using quartic function in MountainsMap.

The metallographic examination of the as-new copper conductor (a) shows a clear demarcation between the conductor surface and the cold embedding medium. This means that there are hardly any cracks or deformation or extrusion of material on the surface. This is confirmed by the optical observation shown in Fig. 1a. Drawing grooves cannot be seen in Fig. 2a as these lie alongside the image plane.

Compared to the as-new conductor, a clear fissuring of the surface can be observed on the mechanically stressed copper conductor (b). Deformation or extrusion of the microstructure at the surface (mark I.) is evident. The reason for the extrusion of material (mark I.) is a local alternating plastic deformation, and the associated strain hardening [17, p. 280]. The stresses on the surface of the conductor are the greatest due to the maximum distance from the

Figure 2 Conductor surface longitudinally to loading direction for copper conductor type H07V-U 1.5 mm². Metallographic etching with ammonium persulfate (magnification 500 ×). **a** as new. **b** 587 cycles loaded according to EN 50,396 until breakage. Mark I. shows material extrusion on the surface of the mechanically loaded conductor. Mark II. shows cracks propagating starting from the surface of the conductor. Due to the selected image plane, cracks always appear perpendicular to the direction of loading. Mark IIIa shows an example of the angular grains of the as-new conductor, which round off due to plastic deformation, as shown in mark IIIb.



neutral axis. Thus, signs of fatigue fracture occur first at the surface. Bending stresses cause defects in the microstructure or dislocations and thus hinder slip in the surface region. The result is strain hardening [17, p. 194], which leads to local stress peaks. At these, the stress is many times higher than the nominal value. As a result of this brittleness, material is extruded under varying loads, which leads to surface roughness. [17, p. 280f].

Another sign of wear is the formation of fatigue cracks (mark II.). These are caused by the aforementioned stress peaks due to hardening processes. The cracking process starts by slip-bands, which form at 45° to the loading direction [18]. Due to the high ductility of the material, brittle fractures do not occur directly and slip-bands can form. This issue will be addressed in the later section “Orientation of structures in the surface roughness over service life.” If the

notch stress at the crack tip increases due to strain hardening, multiple deflections occur, leading to sub-macroscopic crack propagation [18]. Since large stress amplitudes act on the copper conductor during dynamic bending loading according to EN 50,396, cracks preferentially occur at grain boundaries, which can be seen at the marked location (II.) [18].

Figure 2 also shows that the microstructure of the mechanically stressed conductor is finer-grained than that of the unloaded one. This conclusion can be supported by a grain size measurement. For this purpose, the microstructural images shown in Fig. 2 were analyzed with the μ Grain software already presented in chapter methods. To generate a precise result, 9 parallel lines with an angle of 45° were superimposed on the images. Using the watershed (image processing) algorithm, the grain boundaries were automatically detected. The calculation of the

grain size number G for the as-new copper conductor resulted in a value of 9.6. The mechanically loaded conductor has a grain size number of 11.0. This means that the stressed conductor has a larger number of grains per area and therefore a finer microstructure. This results from the plastic deformation of the specimen, which is also responsible for the rounding of the grains in the microstructure. This becomes clear when comparing the grains, which are marked with (IIIa) and (IIIb). A larger number of grain boundaries also ensures work hardening, since slip processes are hindered [17, p. 163]. The observed rounding can be explained by the plastic deformation of the individual grains which, due to the cyclical rolling motion resulting from the test according to EN 50,396, grind against each other.

Intensity of surface roughness over service life

Ehlenz was the first to show that the roughness on the surface of mechanically loaded copper conductors varies as a function of the load until breakage [1, p. 82]. For this purpose, he plotted the arithmetical mean height R_a against the number of loading cycles on the two-pulley apparatus according to EN 50,396. This surface roughness parameter has the disadvantage that the result is largely dependent on the choice of orientation of the underlying 1D surface profile. Moreover, an alignment according to the standard, transverse to recognizable structures, cannot be guaranteed with increasing roughness. For this

reason, the surface roughness S_q was chosen instead and is shown below. The left ordinate in Fig. 3 shows the surface roughness S_q [μm] of a copper conductor loaded on the two-pulley apparatus. The test subjects were loaded at intervals of 100 cycles each and subsequently measured. The reference point is marked by the roughness of the copper conductors already shown in Fig. 1. As mentioned before, cable breakage for this specimen occurred at 587 cycles. Of course, not all of the four samples broke at exactly 587 cycles, so the range is denoted by a horizontal error bar in Fig. 3. Since the metallography samples are only available for the new conductor and the conductor loaded to 587 cycles, all broken samples are grouped under this value. The roughness values S_q are average values from eight measurements. Four different samples from one production batch were examined. The first sample was measured five times at different points on the circumference, while the others were measured once. In this way, it became clear that the inter-sample variations in the measured values were lower than those between the different measurement points on a sample. This was to be expected since the conductor develops surface roughness preferentially at the apex as well as the bottom of the circumference, where the compressive and tensile forces are greatest. Therefore, the other three conductors were measured at this exact location.

The graph also shows the intensity of selected texture directions of the surface structure of the copper conductor over the lifetime, which will be

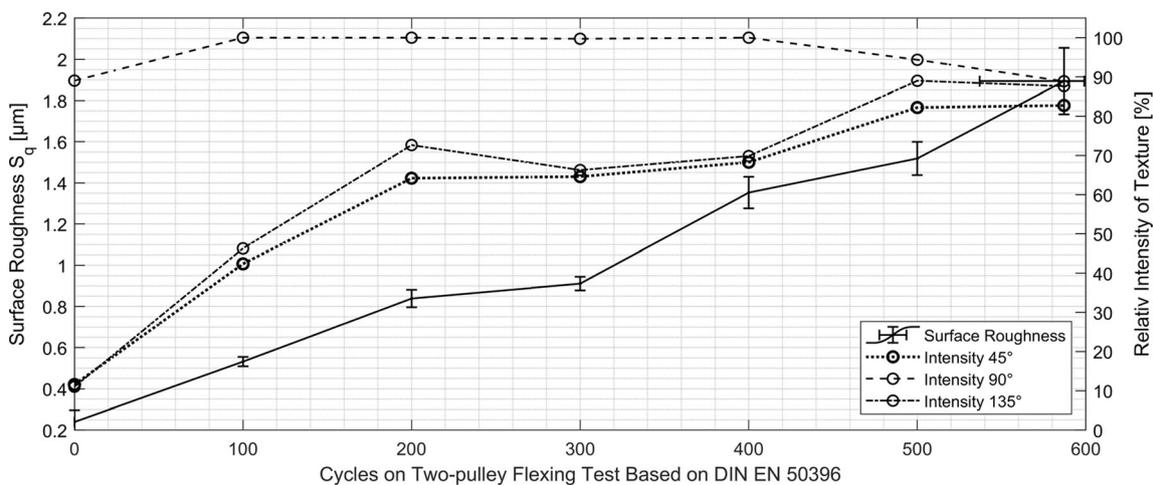


Figure 3 Surface roughness and texture formation of a copper conductor of type H07V-U 1.5 mm² mechanically loaded on two-pulley apparatus according to EN 50,396. Error bars denote the standard deviation from 8 measurements.

discussed in the next section. Corresponding raw data can be found in Online Resource 1.

It can be seen that the roughness increases monotonically, but not linearly, over the service life of the loaded copper conductor. This can also be determined by the parameter R_q , as already shown in [19]. The roughness development can be divided into three sections. The first section ranges from 0 to 200 cycles where a linear increase in surface roughness can be observed. This increase is due to the dislocation formation on the surface as a result of the plastic deformation of the specimen. In the second section between 200 and 300 cycles, roughness formation progresses only at a reduced rate under constant mechanical load. One possible explanation is an increasing number of dislocation blockages in the microstructure, which are a consequence of the plastic deformation. These blockages impede further sliding of dislocations [17, p. 194]. The third section ranging from 300 to 587 cycles is characterized by a steeper increase in roughness until the conductor breaks. Due to the mechanical stress, strain hardening occurs and material is extruded from the surface, which leads to a more significant optical visibility of the roughness. The conductor surface becomes visibly dull [2]. The steep increase in roughness is additionally reinforced by the formation of cracks in the surface, which finally leads to conductor rupture.

Ehlenz, who presents the center roughness value R_a over the service life [1, p. 82], was not able to determine any significant increase of this roughness parameter over the service life in his investigations, since the observed increase is in the same order of magnitude as the variance of the measured values. Thanks to improved measurement technology, it can now be proven unambiguously for the first time in this paper that the surface roughness increases monotonically, but not linearly, as a function of the mechanical load. The reason for the nonlinear course of the roughness S_q is microstructural processes such as dislocation blockages and strain hardening. Despite the nonlinear course, the roughness can be used to derive a statement about the current service life condition of the copper conductor. Thus, it can be shown that the surface roughness, which has been mentioned several times as a service life indicator [1, p. 83, 2, 10, 20], arises due to material extrusion and cracks in the surface. It is worth mentioning that cracks, which are responsible for cable breakage, cannot be quantified by pure surface observation.

Thus, the optically measured roughness S_q cannot provide any information about the crack propagation below the materials surface. In impedance-controlled radio-frequency lines however, the cracks can be associated with origins of discontinuities in wave propagation. Measurements with high-frequency alternating current are therefore further examined for in situ measurements. For more details, see [21].

Orientation of structures in the surface roughness over service life

A close look at the rough surfaces of the mechanically stressed copper conductors reveals structures whose orientations are reminiscent of the familiar slip-bands [8–10]. This effect, first described by Ehlenz [1, p. 77], will be qualitatively elaborated in the following. For this purpose, the angular power spectrum of the test subjects already presented in Fig. 1 was examined. The spectrum is calculated by the Fourier transformation of the surface [22, p. 37] with an angular resolution of 0.25 degrees. The software performs a relative evaluation of roughness by assigning 100% to the most intense structure and ranking all other intensities relative to it.

Figure 4 shows the angular power spectrum of the (a) unloaded and (b) the copper conductor loaded 587 cycles on the two-pulley apparatus. The orientation of the conductors is identical to Fig. 1 with the y-coordinate longitudinal to the conductor axis and thus to the direction of loading.

The angular power spectrum of the unloaded conductor (a) clearly shows that the most significant texture direction of the surface is at about 90° . This is due to the drawing grooves, which can be seen in Fig. 1. The reason why these are not exactly at 90° is a possible torsion of the conductor in the drawing process. This causes the drawing grooves to rotate around the conductor axis. In addition, the manual positioning of the conductor under the confocal microscope is subject to a finite accuracy. The mechanically loaded test specimen (b) shows a significantly wider angular power spectrum.

A peak at 90° can still be observed, since the structures of the drawing grooves can still be spotted in isolated cases. In addition, clear peaks can be seen at $90^\circ \pm 45^\circ$, which results in 45° and 135° here due to the orientation of the conductor under the microscope. These are to be treated the same, since both lie in the 45° direction to the tensile load. This

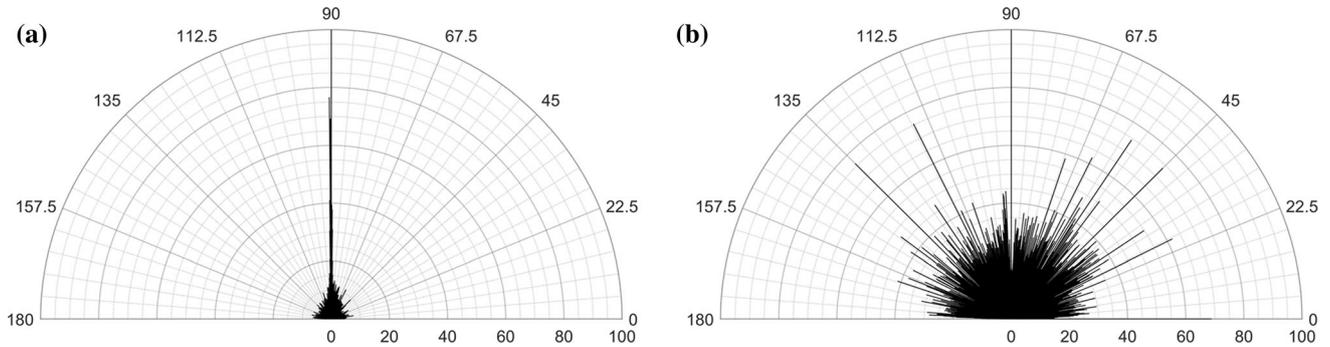


Figure 4 Angular power spectrum of the copper conductor as new (a) and mechanically stressed to 587 cycles with two-pulley flexing test (b).

observation is in accordance with Schmid's shear stress law. Plastic deformation in metallic materials is always linked to the movement of dislocations. It is not the applied shear stress but the resulting shear stress that is responsible for this dislocation motion. This shear stress can be calculated with the help of the tensile stress σ and the slip plane position [12, p. 29]:

$$\tau_{\text{krit}} = \sigma \cdot \cos(\lambda) \cdot \cos(\theta)$$

Here λ is the angle formed between the tensile direction and the plane normal vector of the slip plane, while θ describes the angle between the tensile direction and the slip direction of the plane. If both angles are 45° , the Schmid factor reaches its maximum. For this reason, planes orientated 45° to the direction of tension are the first to exceed the critical shear stress τ_{krit} and begin to flow. Due to the high plastic deformation, the activation energy is locally sufficient to enable sliding of other planes that are not below $+ / - 45^\circ$ to the tensile direction, which explains the other angles that occur in Fig. 4.

In the following, the formation of the directional texture over the lifetime of a copper conductor will be investigated qualitatively. In addition to the surface roughness over cycles on the two-pulley apparatus, Fig. 3 also shows the relative intensity of the texture at 45° , 90° and 135° on the conductor surface. This figure describes the relative proportion of texture direction in the total angular power spectrum of the surface, with 100% always assigned to the most intense texture. The formation of the directional texture can also be divided into sections similar to the surface roughness. The first section is defined between 0 and 200 cycles where the relative proportion of 45° and 135° structures increases almost

linearly. This behavior is explained by the fact that slip planes of this orientation are in their energetically most favorable configuration due to Schmid's shear stress and thus slip first. The second section lies between 200 and 400 cycles. In this range, there is no further increase in the 45° and 135° structures because strain hardening processes lead to dislocation blockages in the microstructure.

The third section extends from 400 to 587 cycles. First, a renewed increase in 45° and 135° structures can be observed because the energetically favorable structures can slide again, as the cross section of the copper conductor is gradually reduced (12% reduction in cross section compared to the new conductor). As a result, the effective stress increases and the critical shear stress can be exceeded again.

The results of this analysis are to be interpreted qualitatively overall, and a quantitative verification is still to be provided. It can be noted that the intensity of the 45° structures behaves similarly to that of the surface roughness over the service life. The formation of the three temporal phases is particularly significant in all observed values. This correlation can be logically justified, since the measured structures are based on roughness and without a change in the surface, the structure orientation does not change either. Another aspect is the relationship between macroscopic and microscopic structure formation on the surface. In this paper, it is shown that the macroscopic surface roughness on a copper conductor is formed in a similar structure to the already known slip-bands, which are formed due to Schmid's shear stress at 45° to the loading direction. Their size is known to be in the nanometer range [9, 23, 24], and they can already occur at low plastic deformation rates. Possible reasons for the strong correlation are

dislocations at 45° to the loading direction in the microstructure, which block slip processes and thus ensure material extrusion along this line. A correlation in the structural formation of micro- and macroscopic structures would thus also speak for a self-affinity of the surface. This self-affinity has already been discovered in a simulative formation of surface roughness under dynamic loading with molecular dynamics simulations [24].

Conclusion

The aim of this work was to further investigate the mechanical damage behavior of copper conductors. In the first part, it was confirmed that mechanically stressed copper conductors develop surface roughness compared to new conductors. To further investigate this material behavior, the microstructures of the test specimens in the surface area were examined metallographically and compared with each other. It was shown that the surface roughness is not only formed by dislocations as assumed before, but that the extrusion of material and cracks because of these dislocations are decisive. This is due to strain hardening caused by plastic deformation, which becomes visible through a change in the grain boundary structure. Changes in grain size were verified using the line intersection method, which showed that mechanical stresses on copper conductors lead to a smaller grain structure.

In addition, it was possible for the first time to show a significant formation of the roughness S_q on the surface over the service life of a mechanically loaded copper conductor. It was found that the roughness increases monotonically but not linearly and can thus be divided into three temporal phases. Possible reasons for this behavior include structural changes such as dislocation blockages and strain hardening. In the future, these effects need to be further investigated with transmission electron microscopy (TEM) or scanning electron microscopy (SEM).

In the last part of this paper, the structural orientation of the surface roughness was examined. Here, the focus was on structures that lie at $\pm 45^\circ$ to the loading direction. It was shown that there is a correlation between the intensity of the 45° structures and the surface roughness over service life. Thus, it is shown that the macroscopic surface roughness has a

similar structural orientation as the microscopic flow figures. Possible reasons are dislocation blockages at 45° to the loading direction, which center the material extrusion around this region. The structural orientation of the dislocations must be investigated in more detail. Special attention should be given to the microscopic dislocations. This correlation between microscopic and macroscopic structures possibly indicates a self-affinity of the rough surface.

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Declarations

Conflicts of interest The authors declare no conflicts of interest.

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