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RESEARCH ON CHANGES IN MICROSTRUCTURES AND MECHANICAL PROPERTIES OF WELDING CAPS AS A RESULT OF THEIR USAGE DURING RESISTANCE SPOT WELDING PROCESS

Mating electrodes made of copper alloys are commonly used for welding galvanized steel sheets used in the production of car bodies. These alloys are characterized by high mechanical properties, a high level of electrical and thermal conductivity as well as the stability of these properties under changing conditions of current, thermal and mechanical load.

Much careful attention was paid to the essence of the ongoing structural changes as well as to the mechanical properties in the welding process (RSW – Resistant Spot Welding) of steel sheets, including high-strength ones. There is a lack of research on structural changes and the related mechanical properties occurring in welding electrodes made of copper alloys caused by the welding process.

This study is devoted to these issues and contains a critical review of the research results enabling a better understanding of the relationships between the structure and properties of welding electrodes caused by the cyclic welding process. In order to illustrate the phenomena occurring during the welding process, both in the material to be welded and in the tip electrodes, hardness and structural tests were carried out on electrode samples before and after their exploitation.

The data collected in the article supplements a certain lack of information in the literature regarding the microstructural aspects of the welding process of galvanized steel sheets for the production of car bodies. The conducted research may be the starting point for the search for more effective materials for the tip electrodes.

Keywords: CuCrZr alloy; Resistance Spot Welding; mechanical properties; microanalysis; tip electrodes

1. Introduction

Car bodies are mostly made of appropriately cut and profiled sets of galvanized steel sheets connected in a permanent manner with the use of resistance spot welding (RSW) process which is carried out in suitably robotic, automated and mechanized technological lines. During a production of a single car body the number of spot welds can reach even several thousands depending on the size of the car and its unique standard.

Highly important elements of the process are welding caps which are used in the process of spot welding of galvanized steel sheets. The welding caps, depending on the complexity of the welded structure, are mainly made from reinforced copper alloys characterized by high and thermally stable mechanical properties and also high electrical conductivity. In addition, above mentioned materials are also highly resistant to variable current, thermal and stress loads.

The most commonly used alloy for production of welding caps dedicated for welding sheets with anti-corrosive zinc coating is chromium-zirconium copper (CuCrZr) which belongs to the A group (chromium copper alloys) and class 2, wherein the specific section constitutes Cu-Cr-Zr alloy, which are materials intended for resistance welding processes. The technological process of welding caps production from this type of alloys contains a series of various operations including: metallurgical synthesis of the alloy, hot and cold forming processes and heat treatment.

In order to better understand the occurring phenomena during the welding process, a detailed microstructure analysis was performed and presented with particular interest in the working area of welding caps made of CuCrZr alloy as well as within the weld itself.

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1.1. Strengthening of copper alloys with chromium and zirconium

One of the classic representative of precipitation hardening copper alloys is chromium copper (CuCr) which due to the addition of appropriate concentration of other alloying elements, i.e. Zr, Ni, Si, Ti, Mg, Al, Ag, and the use of suitable methods of metallurgical synthesis, along with following metal forming processes, creates new, unseen for other alloys commercial possibilities. From this group of materials, the wide industrial application has chromium copper with zirconium addition (CuCrZr). This alloy is widely used for the production of resistance welding electrodes (caps) dedicated for joining of galvanized steel elements, especially in automotive industry [1]. As it turns out, due to the increasing demand for spot connections made with the use of resistance welding process, these alloys, despite achieving a set of high strength properties and electrical conductivity, are no longer sufficient. Therefore, worldwide research works are currently on-going in order to improve exploitational properties of those materials by introducing a small amount of other alloying additives during metallurgical synthesis and by the optimization of the following heat and mechanical treatment [2-6]. As an example of the performed research works it was shown that the use of severe plastic deformation method combined with equal channel angular pressing of the CuCrZr alloy along with hydrostatic extrusion with total value of the real strain at the level of 11.5 made it possible to obtain ultra-fine-grained microstructure of CuCrZr alloy with an average particle diameter of about 200 nm. Obtained structure refinement allowed to increase the mechanical properties of material by about 24% with respect to the commercial CuCrZr alloys [7,8].

The growing interest in CuCrZr alloys results from their deformability in hot and cold metal forming processes along with susceptibility to heat forming by supersaturation and aging processes, precipitation and dispersion hardening and other thermo-plastic treatment combinations [9]. Due to these features, (especially after precipitation hardening), these alloys are characterized by stable properties despite varying thermal, stress and current loads. They are mainly used where there is a need for significant heat input or dissipation as high heat flux materials, for which research on thermal fatigue of these thermal fatigue damage alloys is carried out [10].

A short review of precipitation hardening methods, dispersion strengthening phenomenon and thermal and electrical conductivity research results of selected copper alloys are included in the study [11]. The relationships between the microstructure and the usable properties of multi-component CuNiSiCr alloys are described in [12]. The results of studies on the impact of a small addition of rhenium (Re) on the crystallization process, heat treatment and CuNiSiCr alloy structure are presented in [13].

1.2. Service life of welding caps

Understanding the phenomena occurring in welded elements and in the welding caps should favor the orientation of material tests including: the chemical composition of the electrodes, the ability for alloys to strengthen deformation, dispersion, precipitation hardening, microstructure, mechanical properties, electrical and thermal conductivity, alloy softening temperature, creep resistance, oxidation resistance, stability of properties for changing conditions of thermal, current and stress loads, and thus factors affecting the service life of the welding caps.

Similarly, the chemical composition and mechanical properties of welded steel sheets, their thickness, galvanized surface quality and thickness of the zinc layer are of great importance. If welding parameters such as current density, heat load, dynamics of their changes, cooling conditions of the welding caps and phenomena occurring on the surface and in the volume of both welded sheets as well as on the electrode tip surface are imposed, the complexity of reliability and durability issues of electrodes are more clearly visible.

Having these considerations in mind, the authors of the study [14] made a number of spot welds on uncoated and not galvanized steel sheets. An industrial spot welding machine was used for the tests, using the same welding parameters as in the production conditions. In the conducted experiments, tests were made to capture the relationship between the applied pressure force on the electrode and its service life. Peeling test (peeling) were performed on the welds in order to measure the diameter of the weld and to generate the growth curves of the weld. To simulate the welding process, the SOPRAS commercial FEM (finite element method) program was applied and various welding parameters (current, pressure force, type of electrode, type and thickness of welded sheets, etc.) were used to assess the size of the weld as well as the temperature distribution in the weld area and in the welding caps. Satisfactory compatibility was shown between experimental studies and the results of simulation using the SOPRAS, aiming an attempt to relate the role of the current with the size of the heat affected zone (HAZ) and the possibility of splash occurrence.

The multi-thread problem of welding cap life has been emphasized, especially in car body welding processes for galvanized steel sheets which have a very extensive experimental and research area. One of the examples can be the results of study [15], where special attention was given to changes in the shape of the sheet surface in the vicinity of the weld, the external dimensions of the weld and the dimensions and shape of the nugget depending on the type and shape of the electrodes and welding parameters.

As further described, many factors affect the service life of the welding caps. The authors of the study [16] have analyzed the impact of selected factors on the welding process at specific operating parameters. The analysis was also performed with the use of SOPRAS program, designed for calculations related to RSW process. Numerical analyses were made for two pairs of sheet metal with thickness 1 mm + 1 mm and 2 mm + 2 mm made of DX52 steel (C0,12Si0,5Mn0,6P0,1S0,045Ti0,3) and CuCrZr welding caps in A2/ 2 according to ISO 5182 with a flat tip for the outer diameter of 13, 16 and 20 mm and with bevel angles of 60° and 120°, and for electrodes with a spherical tip with a radius of 50mm. Tests also addressed the effect of distance from the working area of the welding cap including the cooling channel distance of 10.5 and 3.0 mm on the temperature distribution in the electrode. Temperature values of electrode were determined at the contact point of the electrode with the welded sheets, at a distance of 0.25, 0.5, 1.0, 2.0, 5.0 and 10.0 mm from the contact point. The calculated temperature values at the electrode contact surface did not exceed 800°C for "soft" welding conditions and 900°C; for "severe" welding conditions. The depth of the softening area (HAZ) was about 1.2 and 1.8 mm, respectively, and the temperature of the electrode softening line was 485°C. The diameter of the 4mm weld for "soft" welding was reached after 500 ms, and for "sharp" welding conditions, a weld diameter of 5 mm was achieved after 220 ms welding. The simulation studies using SOPRAS showed that in the core of the weld, local temperatures are close to 2000°C (the welding parameters used in calculation: hard parameters of welding I = 8 kA, t = 130-240 ms, P = 240 daN and soft parameters of welding I = 5 kA, t = 160-520 ms, P = 80 daN. Cooling water flow: 4 L/min, water temperature: 15°C).

The influence of the zinc layer thickness on resistance-welded steel sheets was also analyzed, and the results of this work were included in the study [17]. The results of RSW parameters for an uncoated mild steel sample and for hot dip galvanized steel samples with different thicknesses of zinc layers were presented. Two welding schemes were considered: a one-stage scheme without preheating phase and a two-stage scheme including a preheating phase followed by the main welding process. The strength and weldability of the joined elements were assessed by peeling tests (breaking, peeling), cross-stress tests and metallographic investigation of the weld with current in the range from 5 to 12 kA and time of welding from 140 to 410 ms. As a result, it was determined that the optimal welding duration is 270 ms. Attention was also paid to the unfavorable phenomenon of metal splash that can occur during welding. It was emphasized that splashing can occur between the electrodes and the sample or between the surfaces of welded sheets. In the first case, the metal splash can be caused by excessive weld thickness. In contrast, the splash spread between the surfaces of the sheets can be caused by an excessive weld diameter. When splash occurs, a defect may be generated inside the weld or it may cause the electrode to stick with the surface of sample. In the above mentioned case, the electrode is subjected to alloying effect which can lead to its accelerated failure.

The cited test results and the literature review regarding the service life of the welding caps used for RSW process of galvanized steel car body sheets includes the most important parameters of the welding process, e.g. pressure force, current intensity, welding duration, cooling intensity, grade and thickness of steel sheets, thickness of the zinc layer, type and kind of the welding caps and their impact on the quality and diameter of welds. However, there is no extensive information about changes in the microstructure occurring in the working areas of both the welding caps and in the welded sheet metal, its surroundings, as well as their dependence with the hardness change in those areas of electrodes. Supplementing of this data is included in this study, both with discussion of selected test results of changes in the microstructure of welds of connected galvanized steel sheets, as well as the microstructure and hardness of the welding caps before and after their exploitation.

2. Material and methods

For testing, two sections of 0.8 mm thick hot galvanized steel sheets (DX54) were selected. Within the first sample 10 welds were made (initial period of operation of caps). In the second case, about 2 000 welds were made, and the sample was cut just before their end of life. A pair of welding caps (with a diameter of 16 mm) from the commonly used CuCr0.65Zr0.05 alloy in the A2 / 2 state were used for the tests. The weld microstructure tests were performed. The cross-section of the welds after the grinding and polishing process was etched with 5% nital etchant. The Vickers microhardness tests were also conducted. Observations of the welding cap microstructure were carried out with the use optical microscope, high-resolution scanning electron microscope (SEM), electron backscatter diffraction (EBSD) and transmission electron microscope (TEM). The cross-section of electrode was etched with the FeCl3 solution. The Vickers hardness of welding cap in various areas was measured.

3. Results

3.1. Test results of weld microstructure and hardness

Comparing the two cross-sections of the welds, significant differences between the shape of the welds and between the slots just behind the welds can be observed. For a more precise determination of differences obtained specimens were chemically etched, and obtained microstructure images along with measurements of characteristic distances, are illustrated in Fig. 1 and Fig. 2.

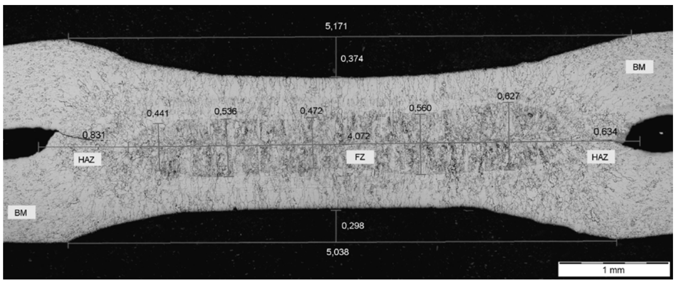


Fig. 1. Microstructure of sample with visible weld nugget (FZ – fusion zone), BM – base metal and HAZ with selected distance measurements in the initial welding phase – about 10

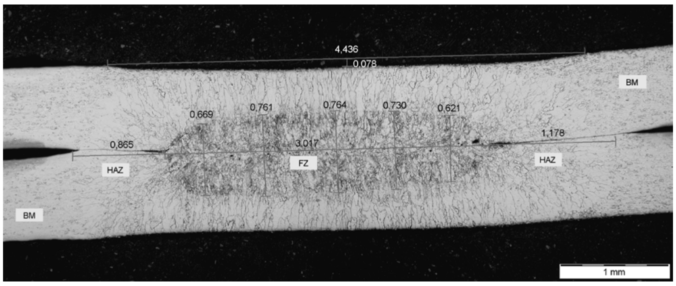


Fig. 2. Microstructure of sample with visible weld nugget (FZ), BM and HAZ with selected distance measurements in the final welding phase – about 2000 welds

As seen in the images of the microstructure in the first case (the initial welding phase – about 10 welds), the average indentation width was about 5.1 mm, and its average depth was about 0,34 mm. The weld nugget diameter (FZ) was 4.00 mm and its thickness ranged from 0.44 mm to 0.63 mm. An average HAZ width after 10 welds was about 0,73 mm. In the second case (after 2000 welds, when the caps were removed), one of the visible indentation width was about 4,4 mm and its depth was 0,08 mm. The weld nugget diameter was about 3.02 mm, and its thickness ranged from 0,62 to 0.76 mm. An average HAZ width after 2000 welds was about 1,02 mm. In both cases, the weld core was located in the middle of the weld. Measurements in the cross-section of the spot weld were made based on the work [18,19].

The welding process causes changes in the microstructure in the core as well as in the area adjacent to the core of the weld. In the nugget, a fine-grained microstructure was observed, and in its close vicinity the grains were elongated in a direction parallel to the direction of heat dissipation. The thin zinc film (with thickness of about 8 μm) due to welding can be eliminated from the outer layers which are in contact with the face surface of the welding cap, like the inner surface in the area of the weld core.

During an extremely short welding cycle (about 200 ms), there is a sufficient temperature level and heat required for the zinc to melt (zinc melting temperature is 419°C), as well as for its evaporation (the boiling point of Zn is 907°C). The pressure generated during welding on the welding caps also promotes changes in the concentration of zinc on the surface and on its close surroundings of internal weld. The short-term presence of liquid zinc and its vapors reacts with the material of the welding cap which are made of copper-based alloys, including those which are reinforced, with precipitation and dispersion.

The microhardness of steel sheet (BM) was about 95HV100, the weld surface about 120HV100 and on the nugget surface in the range 150-200 HV100.

Tests on the microstructure of welds and the microstructure of the welding caps after their exploitation allow to state that during the welding process of galvanized steel car body sheets, gradual “flattening” of the weld cross-section and change of dimensions of the nugget of welding occurred. For example, after about 10 welds, the diameter of the electrode “imprint” was 5 mm, and the dimensions of the nugget were: diameter about 4 mm, thickness about 0.5 mm. After the end of exploitation, the diameter of the imprint was 4.1 mm, with a nugget diameter of about 3.1 mm, thickness about 0.7 mm.

Hardness values decrease only in the place where zinc diffuses, because it creates brass, and this causes an increase in resistance, which in turn causes excessive heating of these areas. The increase in temperature is a factor that increases the diffusion of chromium from overheated areas towards the welded material, which causes a decrease in hardness, in addition, in these areas overaging of the material is observed, resulting in a decrease in hardness.

3.2. Macrostructure and microstructure of welding caps before and after exploitation

In order to provide a clearer illustration of the phenomena occurring during welding of galvanized steel sheets, macro and microstructure analyses of welding caps were performed before their further inspections. Fig. 3 shows an example image of the macrostructure on the cross-section of the welding caps made of CuCrZr alloy.

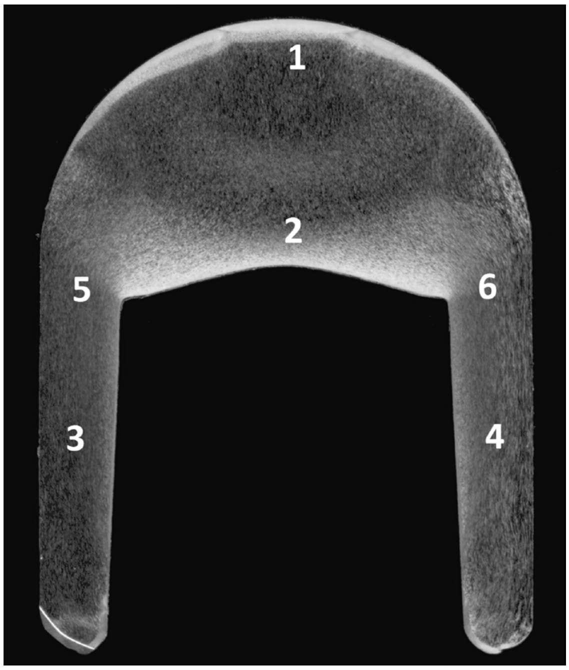


Fig. 3. Cross-sectional macrostructure of the CuCrZr alloy electrode before its exploitation with marked most important areas being a subject for further microstructure analysis

As it can be seen in the macrostructure image of the welding cup cross-section of the welding caps (Fig. 3) several areas can be distinguished that play different roles in the welding process. The area marked with 1 is the “face” of the welding cap, its outer surface is the main working part of the electrode that conducts current and exerts pressure at the welding site of galvanized steel sheets. The pressure is exerted by the cooled cap spindle on which the electrically conductive electrode is mounted. The cap mandrel fills the area between the cap ring marked with 3 and 4 and the “foot” of the cap is marked with 2. The macrostructure of the areas marked with 5 and 6 as well as the entire cap electrode is related to the alloy used and the electrode production technology.

Initial characteristics of the CuCrZr welding cap microstructure are shown in the Fig. 4 for above listed key areas of the samples.

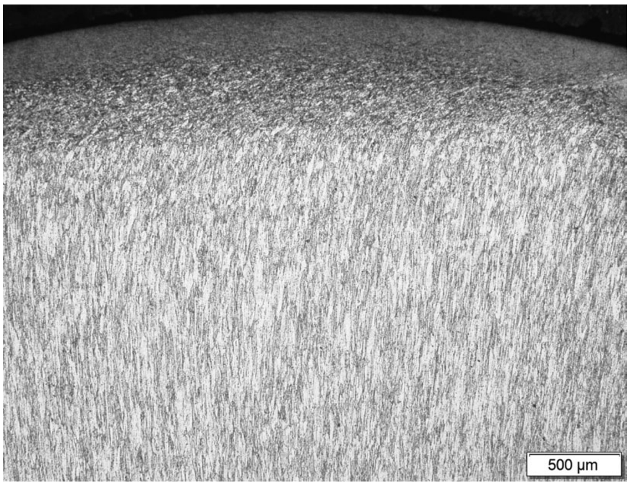


Fig. 4. Microstructure of working part (area 1 from Fig. 3), transverse section

As it can be easily seen, the microstructure of area 1, especially in the surface layer, is very fine-grained (additionally strengthened), while under this layer the fibrous microstructure, with elongated fine grains towards the electrode axis, predominates. A reverse image of the microstructure was observed for area 2 (electrode “foot”). The microstructures of areas 5 and 6 are fibrous (elongated grains) symmetrical to the electrode axis which illustrate the flow lines during deformation. Similarly, the microstructure of areas 3 and 4 is fine-grained, and the grains are strongly elongated in the direction of deformation. This is due to commonly used feed material for the production of electrodes is a fine-grained press. Additional strengthening of the working part by refining the microstructure was probably obtained by additional cold forging operation of the upper part of the electrode and hence the flow lines are visible in the photos. The tested electrode is a commercial product.

A considerable number of the oxide phase occurred on the tip of the welding cap during its exploitation, which was confirmed by the chemical composition analyses of the specified elements in various places on the tip of the electrodes (Fig. 5 and TABLE 1).

For complex analysis of microstructure evolution and chemical composition, studies were carried out on the polished microsections prepared on the tip of the welding caps (Fig. 6).

After the end of exploitation, the welding caps were characterized by a considerable wear and contamination of its tip, as well as the side surfaces. On the tip, the melted zones were observed with oxidized particles of electrode alloy components

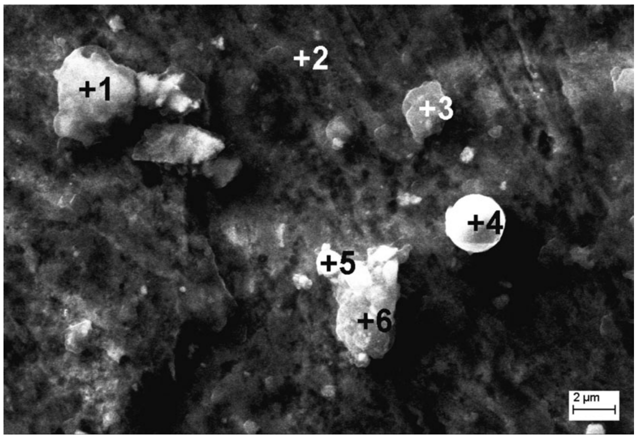


Fig. 5. Microstructure of the electrode tip

TABLE 1

Chemical composition of the tested surface areas (EDS) in %wt. from selected areas in Fig. 5

No.	Cu	Zn	Fe	Cr	O	Zr
1	44.88	30.06	0.52	0.14	16.32	8.07
2	93.99	4.97	0.10	0.36	0.59	—
3	53.25	29.82	1.53	0.31	9.30	5.78
4	4.61	0.80	68.97	—	25.62	—
5	20.33	8.86	48.25	0.10	21.48	0.98
6	43.68	34.01	5.18	0.38	13.66	0.09

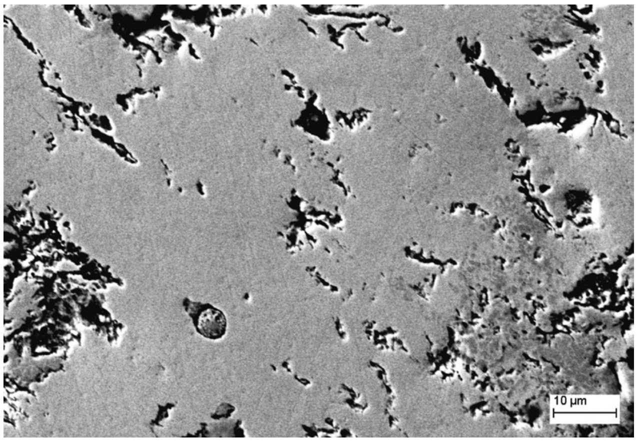


Fig. 6. Microstructure of the electrode tip, polished microsection. The average chemical composition of the tested surface (EDS) in wt.%.: Cu = 66.08; Zn = 3.47; Fe = 28.14; Cr = 0.66; Zr = 0.18; O = 0.64

of both zinc and iron. In microareas of welding cap tip besides the copper, a considerable concentration of zinc, iron, chromium, zirconium and their oxides were observed. This is important as it proves the diffusion of alloying elements (strengthening) from the electrode to the tip and beyond.

The welding cap after use (Fig. 3) was cut along the vertical axis in order to examine microstructure changes on the cross section in the area close to the tip. Test results are illustrated in Figs 7 and 8. The depth of zinc diffusion into the electrode core is shown in Fig. 9.

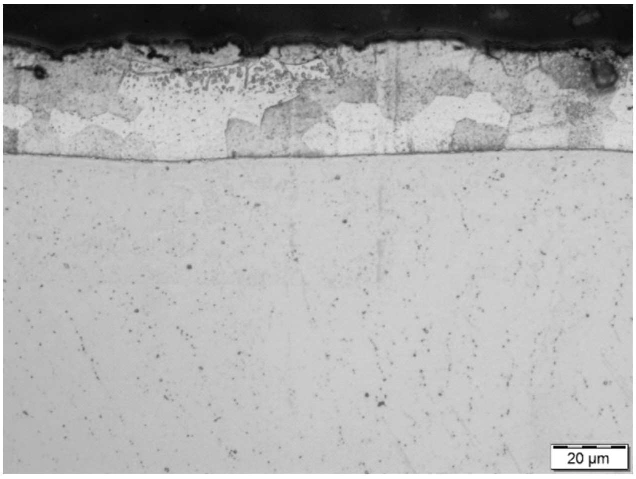


Fig. 7. Cross-section of the microstructure from the tip of the electrode (Fig. 4) with the visible layer enriched with zinc (from the top) and the CuCrZr layer (from the bottom), the microsection etched

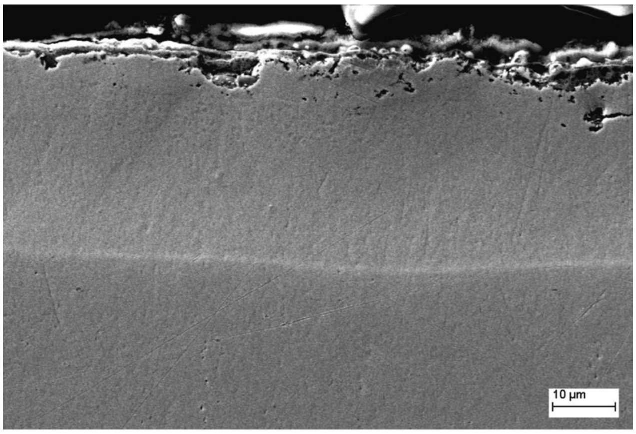


Fig. 8. Cross-section microstructure (SEM) from the working side of the electrode surface (Fig. 7), with the visible layer enriched with zinc (from the top) and the CuCrZr layer (from the bottom), polished microsection

Figs 7-9 show the strong surface development on the electrode tip surface and layers that were rich in zinc create brass. Notches and pits present on the tip are strongly reducing the contact surface of the electrode and thereby change the current density, which can be a direct cause of splashes. In addition, as a result of diffusion from the weld into the cap, zinc diffuses to form a brass layer that is formed during the process, it also has a negative effect on the welding process. This layer has lower mechanical properties and much higher electrical resistance than the CuCrZr base alloy.

To trace structural changes at a distance of about 4 mm from the tip (Fig. 10), i.e. below the layer enriched in zinc, microstructure tests were performed on the surface of metal-

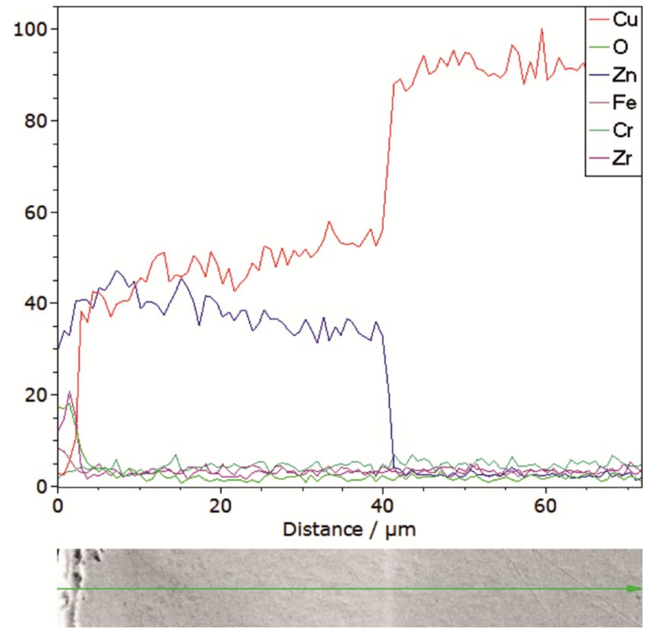


Fig. 9. Changes in the concentration of the tested elements from the tip deep into the electrode, polished microsection (Fig. 8)

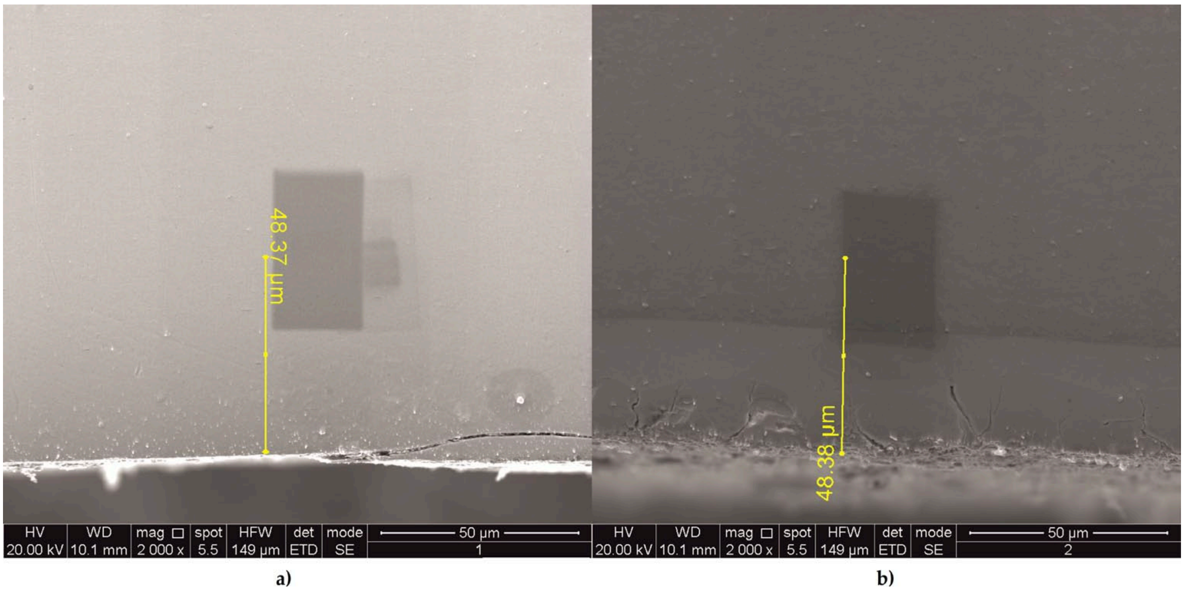


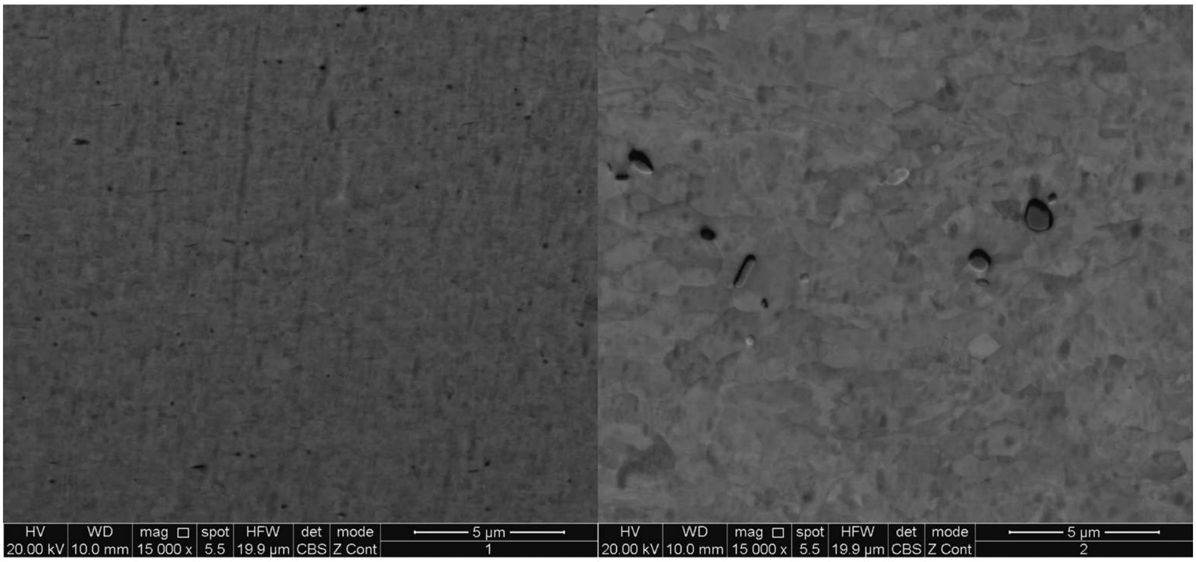
Fig. 10. Microstructure examination areas and sampling areas for transmission electron microscopy analysis (dark spots) before exploitation (a) and after exploitation (b)

lographic microsections obtained from the welding caps before and after their exploitation (Fig. 11). From the electrode core (just behind the brass layer), samples were cut out before and after their operation (Fig. 10), and then thin foils were made of them for analysis by transmission electron microscopy.

Size and orientation of grains on a cross section of the electrodes before and after their exploitation are illustrated in Fig. 12, while changes of grain texture in Fig. 13.

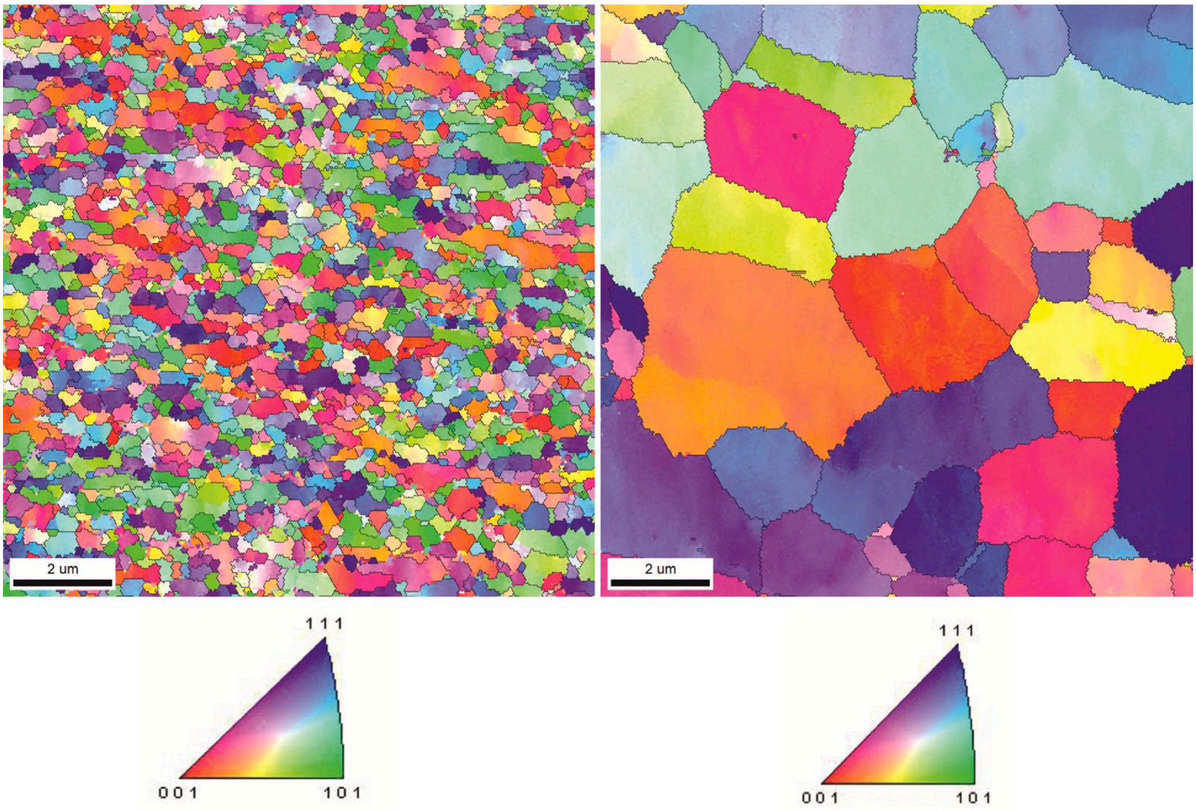
Fig. 14 shows characteristic changes in the microstructure of the electrodes before and after their exploitation. The average grain size increased from 0.3 μm to 3.1 μm.

The grain growth (Fig. 13), changes in orientation (Fig. 14) and the texture image (Fig. 15) are visible clearly and indicate the recrystallized nature of the structure after exploitation. All these phenomena proceeded simultaneously with the number of welds made, constantly deteriorating their quality.



a) b)

Fig. 11. Microstructure (SEM) of the cross-section of the electrodes before exploitation (a) and after exploitation (b)



a) b)

Fig. 12. EBSD illustrations showing size and direction of grains on a cross section of the electrodes before exploitation (a) and after exploitation (b)

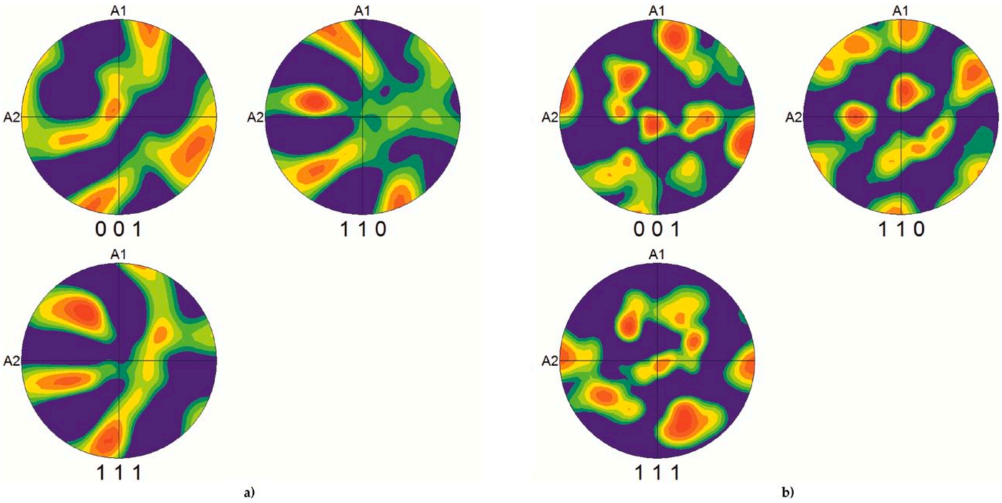


Fig. 13. Changes of grain texture before exploitation (a) and after exploitation (b)

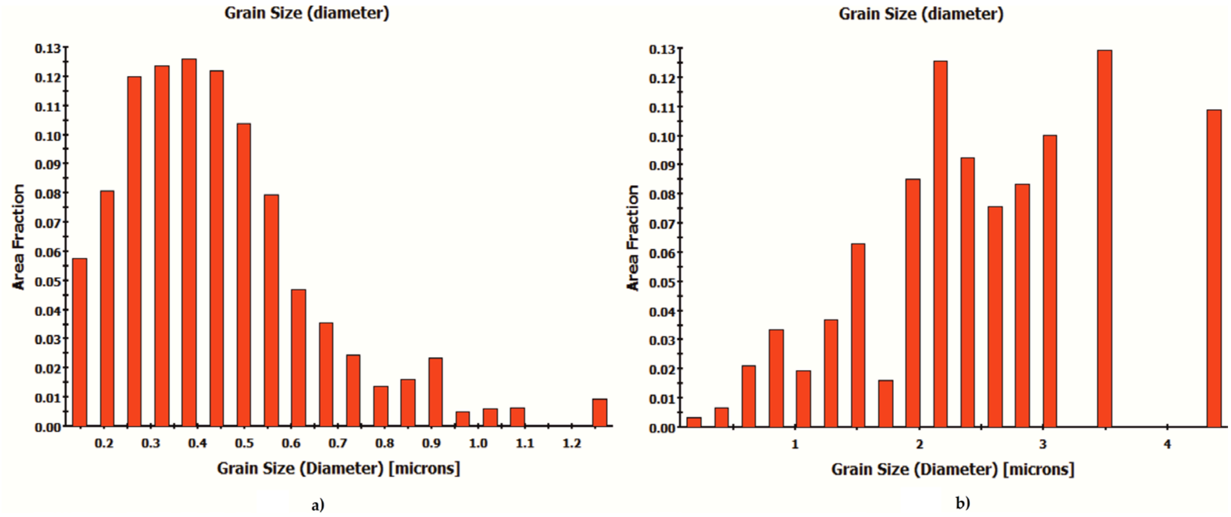


Fig. 14. Grain size distribution on the cross-section of the electrode before exploitation (a) and after exploitation (b)

Results of microstructure observations of welding cap before and after exploitation carried out with the use of transmission electron microscope (TEM) are shown in Figs 15-19. Example of microstructure image of welding cap made of CuCrZr alloy before its exploitation is shown in Fig. 15, in which a high dislocation density can be observed (about 1×1015 mm^{-2}).

Before exploitation, the electrodes had a fine microstructure, which during operation changed to coarser grained and textured with the predominant direction 111. The average grain diameter increased during operation from 0.3 to 3.1 μm. At the same time, a decrease in the dislocation density and the thinning of the deformation bands were observed, although in their region of the deformation bands the dislocation density remained high.

Inside large grains predominated wide deformation bands and cells were observed that shows high dislocation density. The degree of disorientation in the areas of deformation bands was small (Fig. 16).

In some areas, on the borders and inside the grains on the thin foil the chromium was visible. Cr excretions occurring at grain boundaries had the shape of elongated “rods” (Fig. 17a),

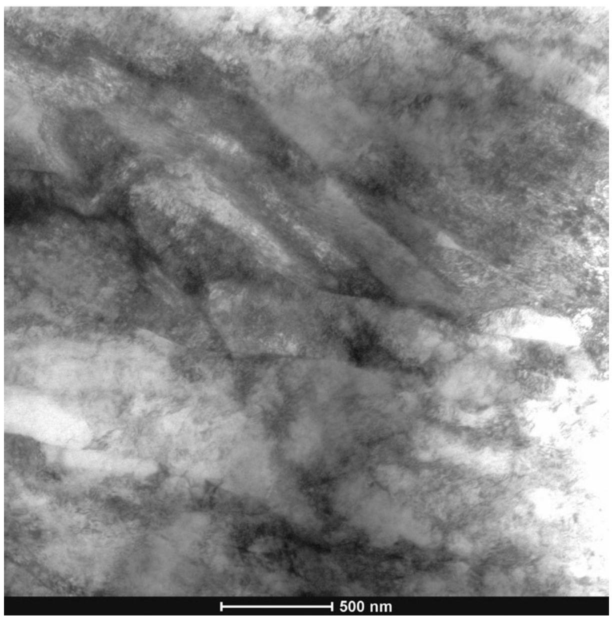


Fig. 15. Example of electrode microstructure (TEM) images before exploitation

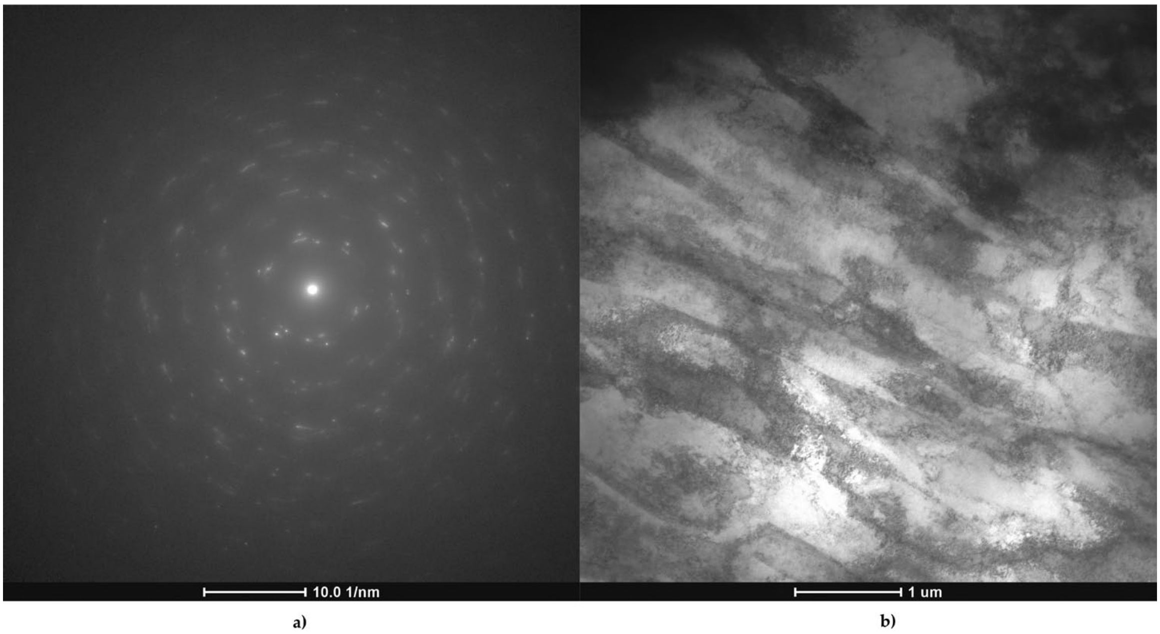


Fig. 16. Point diffraction a) made from the microstructure area with a diameter of 3 μm, b) indicating a slight difference in direction between the deformation bands inside the grain

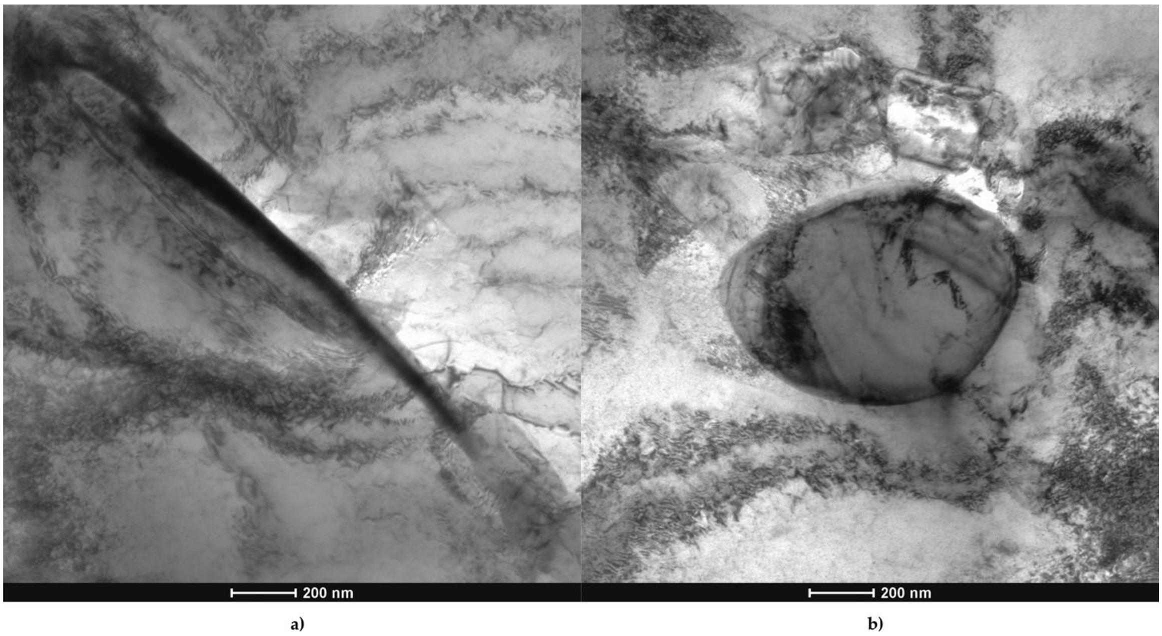


Fig. 17. Primary Cr precipitates in microstructure (TEM) of welding cap before exploitation: a) at the grain boundary, b) inside the grains

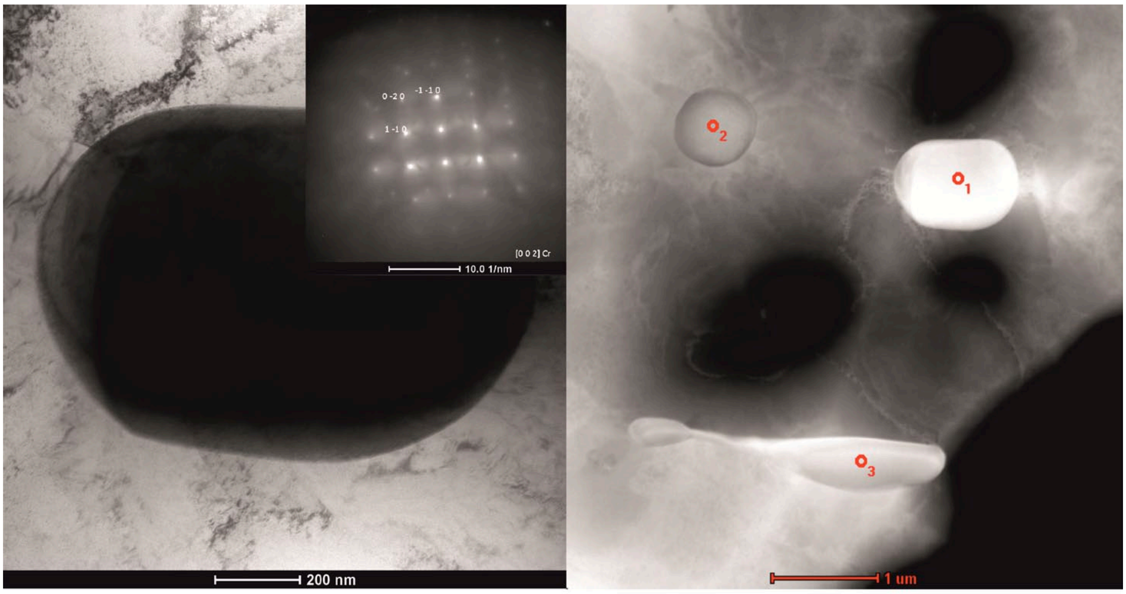
while those inside the grain were oval (Fig. 17b). From point diffraction and chemical analysis appears that these were only primary Cr precipitates (Fig. 18). Secondary precipitates were not revealed during the SEM investigations or were probably dissolved in the matrix during operation of the electrodes.

In the sample taken from the electrode after its exploitation, a much lower dislocation density and narrower shear bands were observed, compared to the sample before exploitation (Fig. 19a and 19b).

Higher dislocation density was found inside narrow deformation bands and on their borders. The boundaries of intersecting deformation bands were bent into slight arches, which may indicate the occurrence of initial dynamic recovery processes (Fig. 19b). Compared to the microstructure of the sample before use, in the dislocation cells the grain boundary outlines were visible (Fig. 20). Cr precipitates were characterized by similar morphology in the Cu matrix as in the unused sample (Fig. 18).

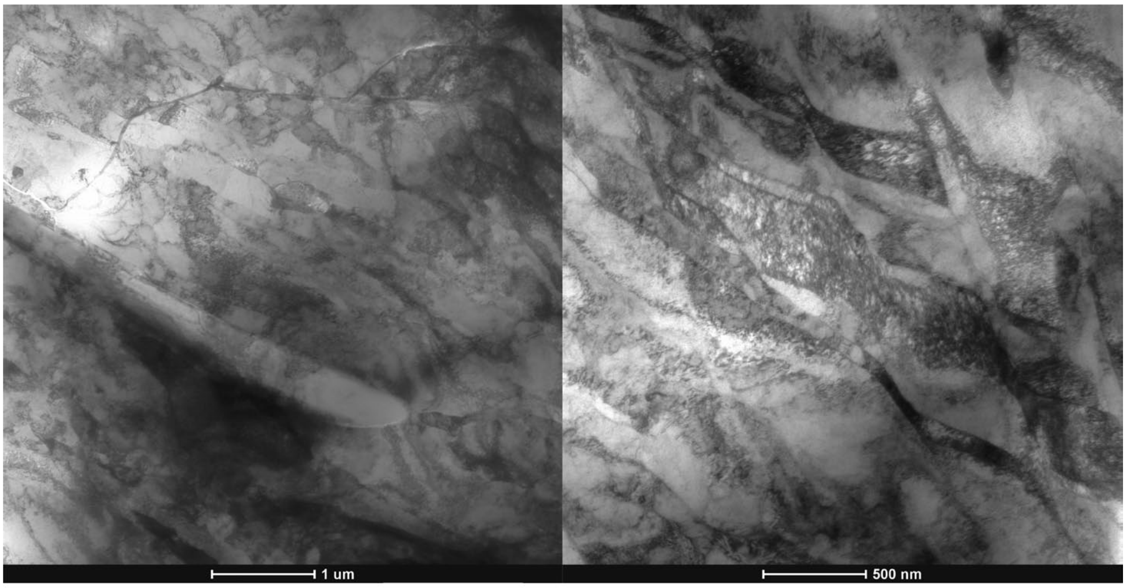
3.3. Testing of welding caps hardness in various stages of use

As part of the research on the phenomena occurring in the structure of the welding caps during exploitation, their hardness



a) b)

Fig. 18. Point diffraction (a) and chemical analysis in microareas (b) confirming the presence of primary Cr precipitates in the Cu matrix [wt.%]: 1 – Cr = 96.88; Cu = 3.11; 2 – Cr = 98.38; Cu = 1.61; 3 – Cr = 97.67; Cu = 2.32



a) b)

Fig. 19. Microstructure (TEM) of welding cap after exploitation with visible grain boundaries (a) and interior of grains with intersecting families of shear bands (b)

was measured at various stages of wear, namely after 0, 500 and 2000 welds. Hardness tests were conducted on cross-sections of electrodes to verify the occurring changes in the structure of the material during the exposure of temperature resulting from spot resistance welding process. In total 12 areas were selected for the tests, in which the Vickers's hardness measurements were performed (Fig. 21). Results of hardness measurements are shown in TABLE 2.

The hardness tests performed on the welding caps showed that the new type of welding cap has a cross-sectional hardness in the range from 167 to 193 HV. The differentiation of the welding cap hardness results from the technology of its production, namely the die forging process, in which the material deforms in a specific (heterogeneous) way, which was mentioned in the earlier part of the paper. The welding cap after 500 welds shows changes in hardness, especially in the working part of the bowl, where the contact with the welded sheets occurs. The hardness in this area, which is about 1 mm (5) away from the working bowl decreases to 89 HV. Observations of the area above in the direct part of electrode contact during resistance welding (10), also indicate a decrease in hardness. In this area, the hardness drops to 149 HV. Other measuring points do not show significant decreases in hardness, which means that the cooling process during welding took place intensively and prevented the welding

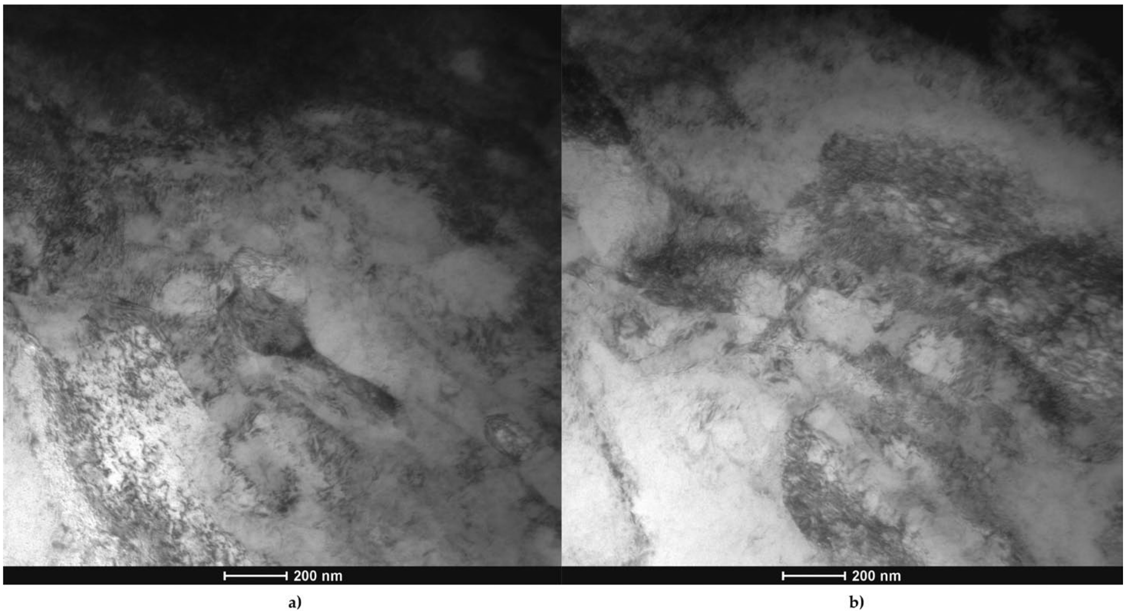


Fig. 20. Two images of the same microstructure differing in the angle of inclination (approx. 10°) of the holder to sample

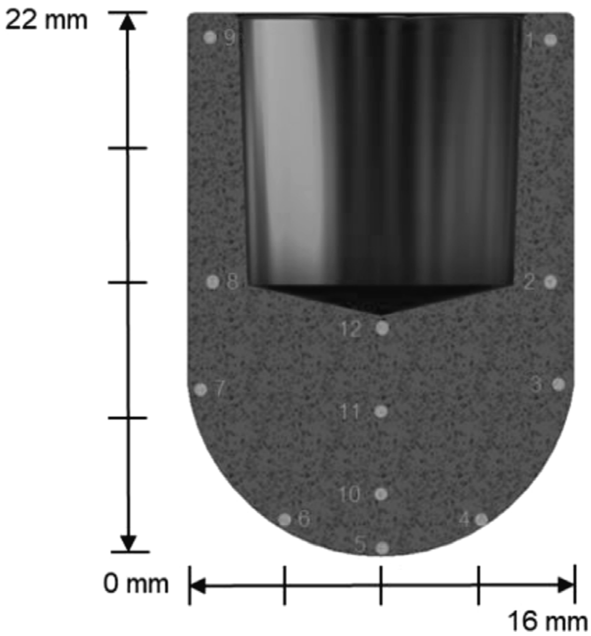


Fig. 21. View of analysed areas of sample

TABLE 2

Results of hardness measurements performed on the welding caps at various stages of its wear

Location of measurment	Hardness, HV10		
	After 0 welds	After 500 welds	After 2 000 welds
1	178	178	173
2	192	180	180
3	177	171	173
4	182	152	149
5	179	89	92
6	176	158	148
7	185	168	168
8	193	176	186
9	179	179	178
10	180	149	145
11	178	173	170
12	167	172	171

cap from overheating. The results of hardness analysis of the welding cap after 2000 welds also show a significant decrease in hardness in the location (5) to 92 HV (about 1 mm from the working bowl). The areas around the part directly adjacent to the welded elements, which are 4, 6 and 10, also show a decrease in hardness. In the area 4, hardness drops to 149 HV, in the area 6 to 148 HV, and in the area 10 to 149 HV.

The hardness tests of the welding caps at various stages of their wear show that along with the increase of welds made during operation in the conditions of RSW process, hardness degradation occurs, mainly in the working part of the electrode in the area directly exposed to high temperature (about 1 mm from the tip). The decrease in hardness to a level of about 90 HV from the initial level of 170 to 190 HV results during the applied load in welding process, that the material is being deformed to the sides of the bowl, which results in the increase of the welds diameter. Hardness degradation in the remaining area is not significant and does not affect the exploitation of the welding caps during resistance welding process.

4. Conclusions

Zinc used for the coating of steel body car sheet during welding diffuses into the electrode tip and promotes the formation of deposits on and around the electrode tip. Emerging surface contamination, of both the electrode and the welded sheets, leads to the increase in contact resistivity [16] and consequently, to the heterogeneous temperature between the electrode and the welded sheets. This results in deterioration of the weld quality and the possibility of liquid metal "splashing" causing partial melting and craters on the electrode tip surface, which results in its low service life.

Similarly, with the increase welds, the alloy components also diffuse into the tip at the contact point of the welded material, thus weakening the electrode's exploitational properties (grains grew from 0.3 to 3.1 μm on average and softened the electrode core). This tendency is also confirmed by the research results presented in the work [20].

As a result of this research, it was found that the quality of the obtained welds deteriorated during resistance welding, which was the result of grain growth in the electrode. However, the hardness in the area of the joint increases even twice as compared to the welded sheets. At the same time, the tip of the resistance welding electrodes erodes during operation. The presence of steel particles on its surface and a brass layer in the vicinity of the surface, resulting from the diffusion of zinc from the sheet coating, was observed. These effects reduce the functional properties and quality of the welds performed along with the increase in the number of joints. It was found that the way to extend the life of the electrode can be seen in the introduction of low concentrations of alloying additives limiting or slowing down the diffusion of zinc into the copper matrix of the electrode.

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