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Assessment of Electrode Consumption in Resistance Welding

Abstract: The article discusses the assessment of electrode consumption during spot resistance welding processes. The process was performed using a manipulator provided with a welding head. During the process, welding parameters, environmental conditions and the material subjected to welding remained unchanged. The tests involved the performance of five welding cycles including the making of 100, 500, 1 000, 2 000 and 4 000 welds. Afterwards, to compare the consumption of six sets of electrodes, both used and not used in individual cycles, it was necessary to perform metallographic tests and hardness measurements. The tests revealed that the consumption of electrodes, leading to the lack of penetration in the central area of the weld, resulted from progressive recrystallization in the work area and from physical failure manifested by discontinuities having the form of intercrystalline cracks.

Keywords: spot resistance welding, electrode consumption, metallographic tests

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Introduction

Electrodes constitute the most important part of the welding machine secondary circuit. It is estimated that the time necessary to replace or renovate electrodes on a regular basis may amount to 5% of the total welding time. For this reason, it is necessary to maximise the service life of electrodes. The above-named goal can be achieved through the rational and appropriate design of electrodes, the use of appropriate materials as well as by the properly performed cooling of electrodes. The electrode metal utilisation factor K_e (1) should be high, and, in the case of spot resistance welding amount to approximately 20÷30% [1].

$$K_e = \frac{G_1 - G_2}{G_1} \cdot 100\% \quad (1)$$

where G_1 – weight of a new electrode [kG]; G_2 – weight of an entirely used electrode [kG].

For this reason, materials out of which electrodes are made, should, at ambient temperature and at significantly higher temperatures, be characterised by relatively high hardness and strength, appropriate heat and electric conductivity, the lack of tendency to make adhesive or diffusion joints with the metal of elements being welded, good workability and appropriate resistance to the oxidising effect of the atmosphere [1].

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The most popular materials used when making electrodes are copper and its alloys. In spite of the fact that pure electrolytic copper is characterised by a very high electric conductivity of 58 MS/m, i.e. 100% IACS, this metal is not often used because of its low softening point and low hardness. Electrodes made of pure copper are usually used when joining aluminium and its alloys, whereas most electrodes are made of copper alloys [2].

According to the PN-EN ISO 5182:2016-10 standard, materials for electrodes used in resistance welding are divided into three groups including individual types of materials:

a) group A – copper and copper alloys:
- type 1 – alloys not subjected to heat treatment and characterised by high conductivity as well as forged moulds characterised by medium hardness, provided with strength through cold plastic working during fabrication; depending on individual subtypes, these alloys are characterised by the following properties: hardness = min. 40÷100 HV30, specific electric conductivity = min. 50÷57.5 MS/m or 86÷99% IACS, softening point = min. 150°C,
- type 2 – alloys harder than type 1, the mechanical properties of which were obtained through heat treatment during fabrication or through the combination of heat treatment and cold plastic working; depending on individual subtypes, these alloys are characterised by the following properties: hardness = min. 85÷150 HV30; specific electric conductance = min. 43÷47 MS/m or 74÷81% IACS, softening point = min. 475÷500°C,
- type 3 – alloys subjected to heat treatment characterised by more favourable mechanical properties than type 2, yet by less favourable electric conductivity than both type 1 and 2; depending on individual subtypes, these alloys are characterised by the following properties: hardness = min. 160÷270 HV30, specific electric conductance = min. 17÷24 MS/m or 29÷42% IACS; softening point = min. 450÷500°C,
- type 4 – alloys characterised by certain specialist properties, in some cases obtainable through cold plastic working or heat treatment; depending on individual subtypes, these alloys are characterised by the following properties: hardness = min. 110÷350 HV30, specific electric conductance = min. 4÷29 MS/m or 7÷50% IACS, softening point = min. 300÷650°C,

b) group B – sintered materials:
- type 10 and 11 – sintered products made of copper and tungsten; depending on individual subtypes, these materials are characterised by the following properties: hardness = min. 220÷240 HV30, specific electric conductance = min. 16÷17 MS/m or 27÷29% IACS, softening point = min. 1000°C,
- type 12 – sintered products made of copper and tungsten carbide; properties: hardness = min. 300 HV30, specific electric conductance = min. 12 MS/m or 20% IACS, softening point = min. 1000°C,
- type 13 – sintered and processed products made of molybdenum; properties: hardness = min. 150 HV30, specific electric conductance = min. 17 MS/m or 29%IACS, softening point = min. 1000°C,
- type 14 – sintered and processed products made of; properties: hardness = min. 420 HV30, specific electric conductance = min. 17 MS/m or 29% IACS, softening point = min. 1000°C,
- type 15 – sintered products made of tungsten and silver; properties: hardness = min. 140 HV 30, specific electric conductance = min. 29 MS/m or 50% IACS, softening point = min. 900°C,

c) group C – dispersion hardened copper alloys:
- C 20/1, C 20/2 and C 20/3 – made through internal oxidation; depending on individual subtypes, these alloys are characterised by the following properties: hardness = min. 120÷150 HV30, specific electric conductance = min. 44÷54 MS/m or 76÷92% IACS, softening point = min. 950÷980°C,
- C 20/4, C 20/5 and C 20/6 – made through

ball grinding or mechanical melting; depending on individual subtypes, are characterised by the following properties: hardness min. 130÷155 HV30, specific conductance = min. 43÷50 MS/m or 74÷86% IACS, softening point = min. 950÷980°C.

The service life of electrodes significantly affects the quality obtained in resistance welding processes. The electrode service life primarily influences the efficiency and course of welding processes, the repeatability and quality of welds and, consequently, the quality of products. Electrodes characterised by appropriate service life enable the automation and mechanisation of welding processes, and, as a result, the application of welding processes in the high-volume production. Factors affecting the service life of electrodes used in resistance welding are the following [3, 4]:

- chemical composition of electrode materials,
- dimensions and the shape of electrode work areas,
- condition of surfaces of elements being joined,
- welding parameters and programme,
- electrode cooling intensity,
- physical properties of semi-finished products used in the production of electrodes and the properties of electrodes.

To ensure the repeatability and continuity of the welding process used in the high-volume fabrication of products characterised by high performance characteristics, it is necessary to integrate high values of heat and electric conductivity with optimum mechanical properties resulting from complex conditions of electrode operation. The first group of activities includes the optimisation of welding process parameters, performed to provide the maximum extension of electrode service life, even if the foregoing entails the deterioration of other features as well as the improvement of cooling systems and electrode design. In turn, the second group of activities includes the modification of electrode material, performed primarily through structural transformations, changes in the chemical composition and the application of various coatings. The structural transformation related to the chemical composition of a given material is obtained through heat treatment or plastic working [5]. As regards copper alloys, heat treatment is used to provide required hardness and determine the limit softening point. In cases of strain-hardened electrodes, the value of softening point equals the value of recrystallisation temperature [3].

Both related research and industrial practice imply that an increase in the hardness of electrodes is also dictated by the partial limitation of the growth of the electrode work area during operation. Popular additions used to increase the hardness of electrodes are primarily zirconium and chromium [3]. In turn, the welding of sheets provided with protective coatings is often connected with dispersion hardening involving the use of aluminium oxide [2]. It should be mentioned that the service life of electrodes is also adversely affected by the condition of surfaces being joined (described using the dependence presented below) [3]:

$$n=a\cdot(H-100)^2 \quad (2),$$

where n – number of welds possible to make in relation to 0.8 mm thick carbon steel sheets using medium parameters, A2/2 class electrodes and a cooling efficiency of 4 l/min, a – sheet surface shape factor (a = 2 in relation to cold rolled and greased sheets, a = 8 in relation to metallically pure sheets), H – electrode hardness of HV30 (important for H = 120÷160 HV30).

Test Materials and Methodology

The tests involved the use of the B0 type tip electrodes having dimensions consistent with the PN-EN ISO 5821:2010 standard. The electrodes were made of the A2/2 type material (according to EN ISO 5182:2016-10) designated as CuCr1Zr (in Poland often designated as MHY). The above-presented material is a low-alloy copper alloy having a single-phase structure composed of solution

Table 1. Chemical composition and properties of alloy CuCr1Zr (according to PN-EN ISO 5182:2016-10)

Chemical composition		R_e [MPa]	R_m [MPa]	Hardness [HV]	Specific conductance		Softening point [°C]
Cr [% by weight]	Zr [% by weight]				MS/m	% IACS	
0.5÷1.4	0.03÷0.3	420	480	100÷140	43	480	500

α. The additions of chromium and zirconium, the solubility of which in copper at ambient temperature is close to zero, resulted in the precipitation hardening of the alloy along with an increase in its resistance. The chemical composition and selected properties of the alloy are presented in Table 1. It is recommended that the above-named electrodes be used for the spot resistance welding of sheets made of unalloyed and low-alloy copper alloys as well as of steel sheets covered with metallic layers. The tests involved the welding of 1 mm thick sheets made of unalloyed steel DC04. Tables 2 and 3 present the chemical composition and selected mechanical properties of the steel used in the tests. The welding process was performed using an R-2000iA 165F manipulator (FANUC) provided with a V027549000E welding head having a power of 43 kVA (ARO). Parameters used in the technological welding tests could be rated as medium. The above-named parameters were adjusted for new tips and based on a technological peeling test so that welds to be obtained could satisfy related requirements, e.g. the weld diameter equal to or greater than 5 mm. The adjustment of specific parameter values was related to the type of steel subjected to welding as well as to thicknesses of sheets being joined (following information contained in reference publications [3], [6], [7]. The parameters used in the tests are presented in Table 4.

Table 2. Chemical composition of steel DC04 according to PN-EN 10130:2009

C [% by weight] max.	P [% by weight] max.	S [% by weight] max.	Mn [% by weight] max.
0.08	0.03	0.03	0.4

Table 3. Mechanical properties of steel DC04 according to PN-EN 10130:2009

R_e [MPa]	R_m [MPa]	Hardness [HV]	A_{80} [%] min.	r_{90} min.	n_{90} min.
140÷220	270÷350	95	38	1.6	0.180

The technological welding tests involved the use of an AC 50 Hz welding machine and an available option enabling the simultaneous adjustment and control of welding current. This means that the value of welding current was systematically measured during the welding process and that the above-named value was compared with the upper and lower limits of the tolerance field, set separately as a deviation of 3% from a pre-set value. Once the tolerance field limits had been exceeded, the controller generated an error and stopped the process to prevent the formation of a joint characterised by improper technological parameters. The trajectory of the manipulator movements during welding is presented in Figure 1.

To obtain the adopted research objective, individual sets of electrodes were used to make 100, 500, 1000, 2000 and 4000 welds respectively. Afterwards, both the welds and the electrodes used in the tests were subjected to analysis.

Table 4. Parameters applied during welding

Initial force time [s]	Force time [s]	Welding time [s]	Final force time [s]	Welding current [A]	Electrode downward force [N]	Final electrode downward force [N]
0.2	0.3	0.3	0.1	7300	3300	20

The macroscopic tests of the welds were performed using an AZ100 stereoscopic microscope (Nikon) after previously etching the specimens using the Mi1Fe reagent according to PN-H-04503:1961. The electrodes were subjected to macro and microscopic tests using an Eclipse MA200 microscope (Nikon) after previously etching the specimens using the Mi23Cu reagent according to PN-H-04512:1975.

The microstructural tests of the electrodes involved the three zones presented in Figure 2, i.e. zone no. 1 including the work areas of the electrodes, zone no. 2 located at the half of the depth of the longitudinal section of the electrode and zone no. 3 located at the area where the electrode was fixed to the cones of the welding head horns in the direct vicinity of the cooling duct.

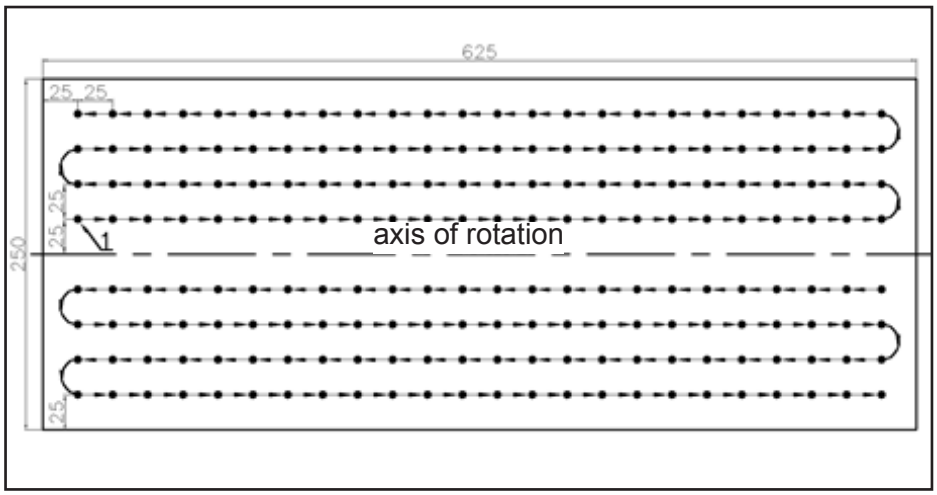

Fig. 1. Trajectory of manipulator movements during welding

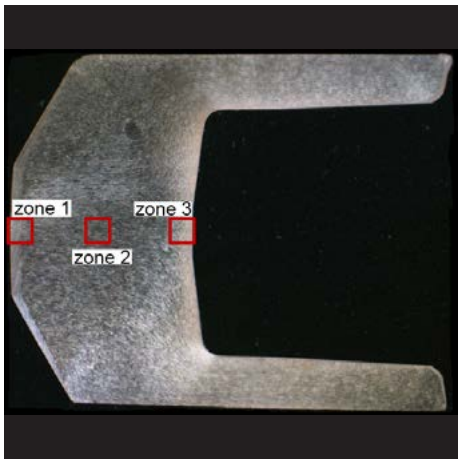

Fig. 2. Zones subjected to the microstructural tests; stereoscopic microscopy; etchant: Mi23Cu

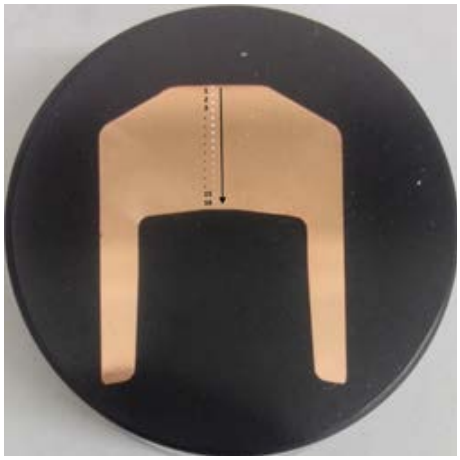

Fig. 3. Arrangement of the measurement points (1 through 16) and the direction of testing

The macro and microscopic tests were supplemented by hardness measurements of electrodes. The measurements were performed using the Vickers hardness tests in accordance with PN-EN ISO 6507-1:2007 and applying the nominal value of a load force of 9.807 N with a scale of 1.0 mm. The hardness measurements were performed using an MMT-X7B hardness tester (Matzuzawa). The arrangement of the measurement points is presented in Figure 3.

Test Results

The continuity of the welded joints was assessed on the basis of the macroscopic metallographic tests (Fig. 4) involving each last weld of a given series. The assessment revealed that only the 100th and 500th weld could be evaluated as proper ones, whereas the 1000th and 2000th weld revealed the lack of penetration in the central part of the joint. The 4000th weld in a related series fell apart during cutting.

The macrostructural test results concerning the electrodes are presented in Figure 5. It is possible to notice easily visible traces of plastic working the electrodes were subjected to during fabrication. The macrostructural tests were followed by microstructural examinations.

Figure 6 presents the microstructure of the electrode work area (on the right side), i.e. the area most exposed to consumption during welding. It can be seen that, in terms of the above-named zone, the structure of the electrode not subjected to operation (Fig. 6a) contained intensely crushed grains of solution α, characterised by clearly visible banding consistent with the direction of plastic working. The

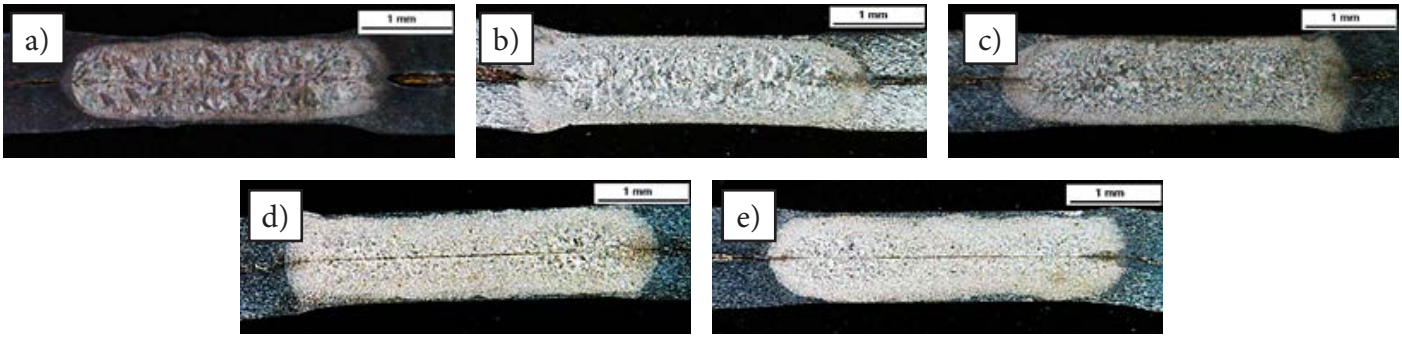

Fig. 4. Macrostructure of the a) 1st, b) 100th, c) 500th, d) 1000th and e) 2000th weld; stereoscopic microscopy; etchant Mi1Fe

work zone of the electrode used to make 100 welds (Fig. 6b) continued to be characterised by the intense strain of the grains of solution α directed in consistence with the direction of manufacture, yet the width of the work zone decreased significantly. The foregoing could be ascribed to the fact that the work surface being in direct contact with elements subjected to welding could wear off during operation. In turn, the work zone of the electrode used to make 500 joints (Fig. 6c) revealed the occurrence of recrystallization resulting from intense periodical heating. It can be stated that the process of recrystallisation did not take place in the electrode used to make 100 welds as the time of heating was overly short. In such situations, the only process which might take place in the material is that of recovery, related to the relaxation of stresses. In the work zone of the electrodes used to make 1000, 2000 and 4000 welds (Fig. 6d-6f) the process of recrystallization occurred and also affected grains located further from the work area. In addition, the process of electrode consumption was manifested not only by the recrystallisation in the work area but also by the physical damage to the material (particularly visible as regards the electrode used to make the greatest number of welds; see Fig. 6f). The above-named work area underwent significant degradation, revealed material discontinues as well as a significant number of intercrystalline cracks. The changes in the microstructure were accompanied by an increase in the electrode work area (initially amounting to 5.0 mm²) and in terms of the electrode used to make 100, 500, 1000, 2000 and 4000 welds amounted to 5.1 mm², 5.3 mm², 5.8 mm², 6.0 mm², 6.2 mm² and 6.3 mm² respectively.

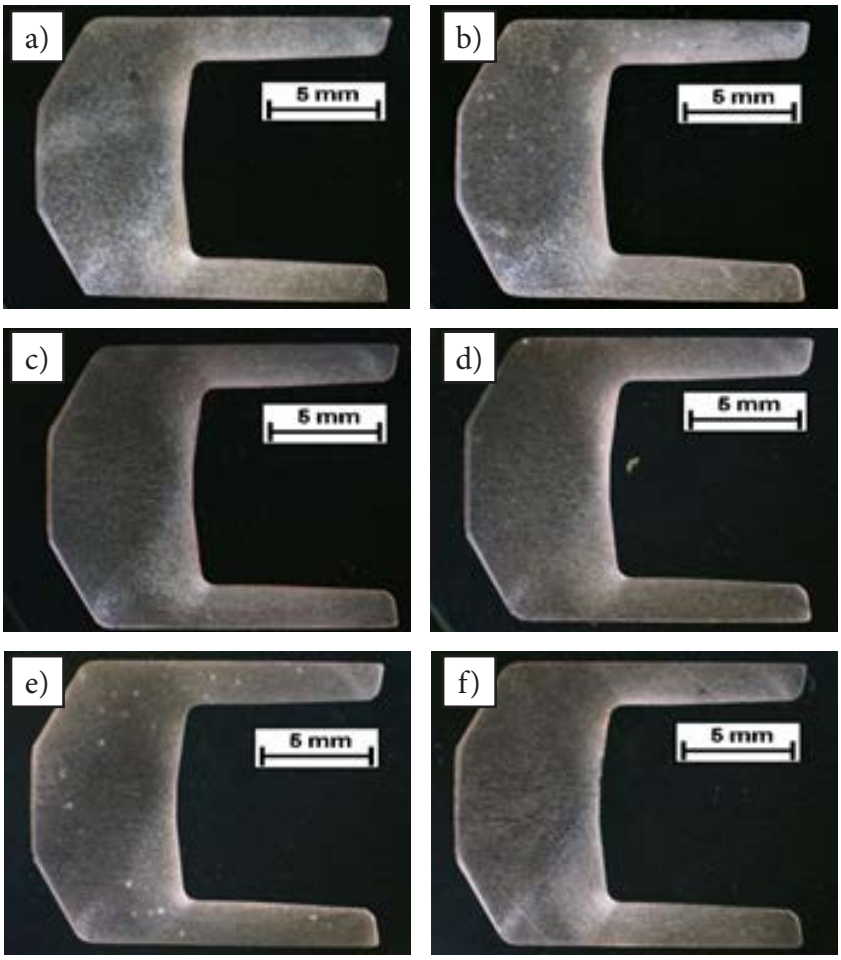

Fig. 5. Macrostructure of the electrodes after the making of: a) 0 (new tip), b) 100, c) 500, d) 1000, e) 2000 and f) 4000 welds; stereoscopic microscopy; etchant: Mi23Cu

Figure 7 presents the microstructure of electrode zone no. 2. The zone revealed the presence of intensely crushed grains of solution α and slip bands. The zone did not reveal any significant

quality changes in relation to the new electrode (Fig. 7a) and the electrode used to make 4000 welds (Fig. 7b). For this reason, the comparison involved the presentation of zone no. 2 of the new electrode tips and the tips of the electrode after making 4000 welds.

The furthest zone from the work surface is presented in Figure 8. The zone was characterised by a change in the direction of banding (connected with the manner in which the electrodes were manufactured). Because of the fact that the electrodes were made of drawn bars, in the intermediate zone the grains were elongated and located along the axes of the electrodes (in consistence with the direction in which the bars were subjected to plastic working). In turn, at the fixing area the grains were arranged perpendicularly, where the change in the direction resulted directly from the punch action. Similar to zone no. 2, the electrodes subjected to analysis did not reveal any clearly visible structural differences. As a result, for comparison, Figure 8a presents the above-named zone in the new electrode, whereas Figure 8b presents the zone in the electrode used to make 4000 welds.

The microstructural tests were supplemented by hardness measurements. The hardness measurement results are presented in Figure 9. The analysis of the results revealed a significant decrease in hardness at the first measurement point located on the surface of the electrodes subjected to operation (apart from the electrode used to make 100 welds) in comparison with the hardness values related to the electrode not

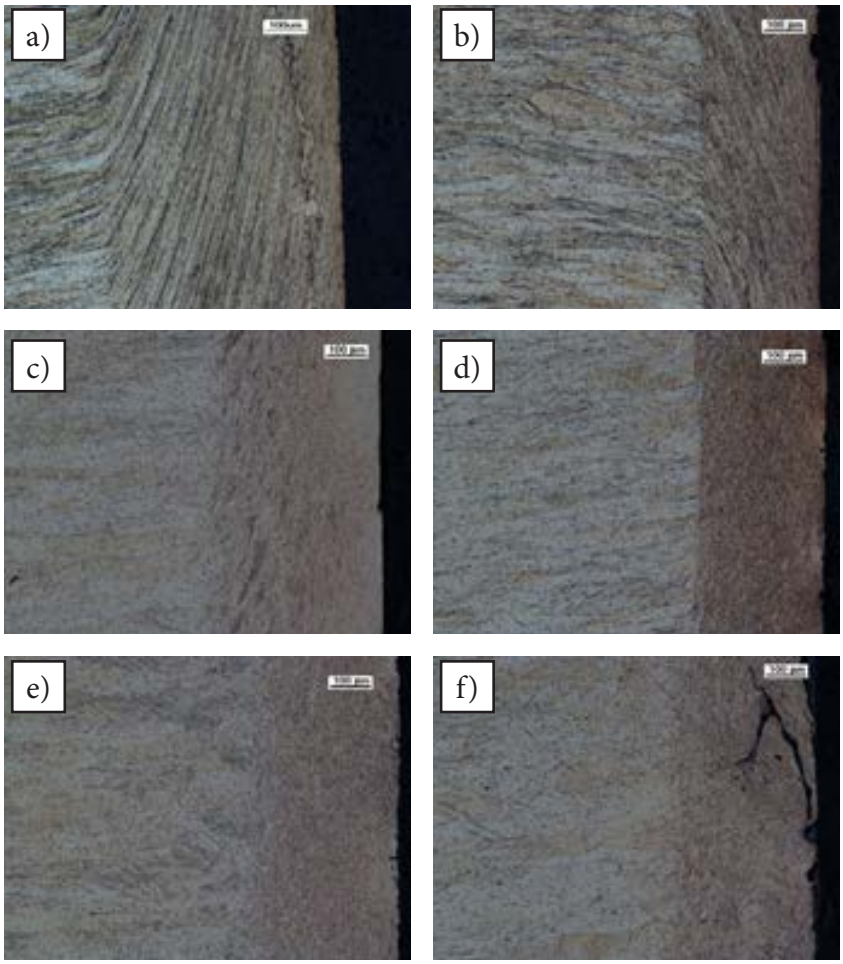

Fig. 6. Microstructure of the work zone in the electrodes after the making of: a) 0 (new tip), b) 100, c) 500, d) 1 000, e) 2000, f) 4000 welds; light microscopy; etchant: Mi23Cu

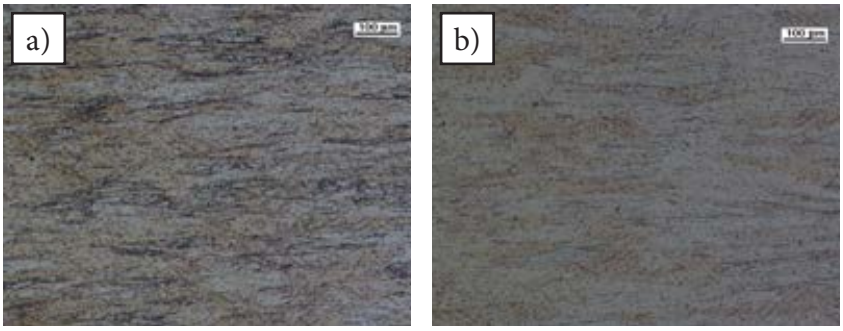

Fig. 7. Microstructure of the second zone in the electrodes after the making of: a) 0 (new electrode) and b) 4000 welds respectively; light microscopy; etchant: Mi23Cu

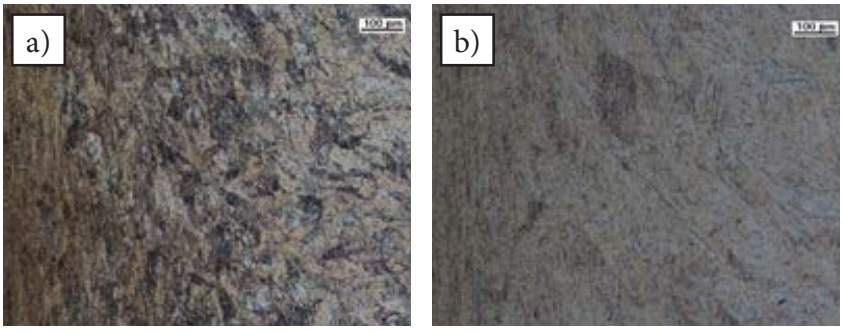

Fig. 8. Microstructure of the third zone in the electrodes after the making of: a) 0 (new electrode) and b) 4000 welds respectively; light microscopy; etchant: Mi23Cu

subjected to operation. As regards the new electrode, the hardness at the above-named point amounted to more than 180 HV1, whereas in terms of the electrode used to make 4000 welds, the value of hardness fell by nearly a half, i.e. to approximately 95 HV1. As can be seen, the decrease in hardness accompanied the consumption of electrodes and resulted from the recrystallisation of the electrodes, entailing the fast and significant loss of mechanical properties. The process of recrystallization was the fastest in the work zone, i.e. the area most exposed to the effect of high temperature during welding. The above-presented phenomena were consistent with numerical calculations extensively described in study [4]. As regards the third measurement point (and further ones), nearly all hardness values of electrodes used in the welding process were higher than the hardness values related to the new, i.e. unused electrode. The above-named increase could be ascribed to the process of precipitation hardening progressing in the material. The process was triggered by the intentional addition of chromium and zirconium to the electrode material. The subsequent increase in hardness could be noticed at the last two measurement points in relation to all of the specimens subjected to analysis. The increase resulted from the location of the above-named points in the last zone, where the material was additionally hardened by strain resulting from the direct action of a punch during the manufacturing of the electrodes.

Conclusions

The subject of the research work presented in this article included electrodes (tips) and welds made using the electrodes. The welds were subjected to tests in order to verify whether joints obtained in a given cycle (as last ones) were acceptable in terms of quality. The macroscopic examinations revealed easily visible traces of plastic working the joints were subjected to during fabrication. The microscopic tests revealed the structure of intensely crushed grains of solution α and the visible consumption of electrode work surface. In cases of electrodes used to make a minimum of 500 welds, the above-named area revealed recrystallization related to the intense heating of the material. The foregoing was connected with the fast and significant hardness decrease in this areas triggered by the decay of hardening and the releasing of the material from internal stresses. In addition, it was possible to observe the significant deterioration of the work surface, particularly in cases of electrodes used to make 4000 welds. The damage to the work zone involved material discontinuities, primarily in the form of intercrystalline cracks. In the area located behind the work zone, the material structure contained considerably deformed grains of solution *α* along with slip bands. In turn, in the last zone, i.e. in the area where the electrode was fixed to the cones of welding head horns it was possible to observe a change in the direction of banding related to the manner of electrode manufacture.

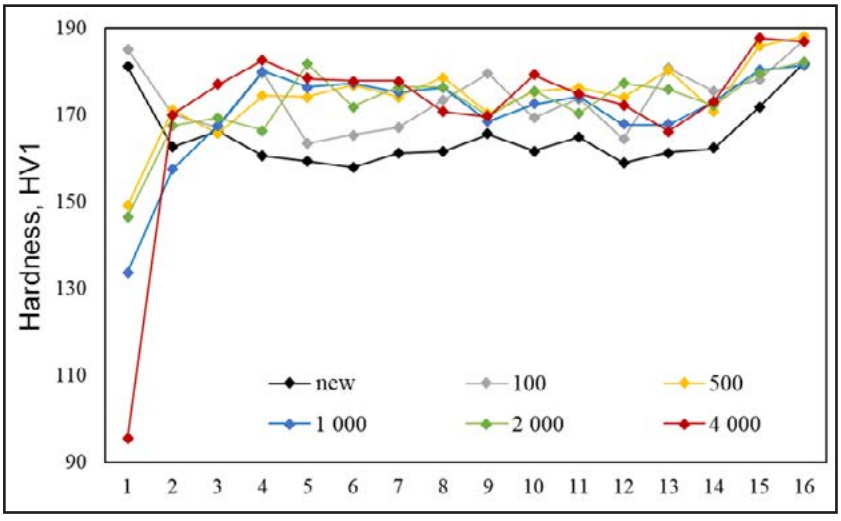

Fig. 9. Hardness distribution along the centre line of the cross-section of electrodes

Taking into consideration all of the tests performed within the above-presented research work it can be stated that the highest number of proper welds obtainable using the above-presented electrodes,

materials and programmed welding parameters amounted to 500. This number resulted from recrystallization progressing in the work zone and from its deteriorating surface, entailing decreasing hardness in this area and preventing the further making of joints satisfying all necessary requirements. The softening of the electrode material triggered by temperature and plastic deformation resulting from the specific nature of electrode operation increased the working area diameter. In terms of new electrodes, the above-named diameter amounted to 5.0 mm, whereas as regards electrodes used to make 4000 welds, the diameter was 6.3 mm in length. The aforesaid phenomenon translated directly into the density of current flowing through the weld. As regards extremely consumed electrodes, the current density was by approximately 55% lower than that related to new electrodes. The depth of microstructural changes resulting from the obtainment of the softening point was limited exclusively to the zone near the electrode work surface, which was confirmed by data found in reference publications. Approximately 3-4 mm away from the electrode surface, hardness measurement values were restricted within the range of 170 to 180 HV1.

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