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ON THE EVOLUTION OF STEEL STUB THERMO-PHYSICAL AND THERMO-MECHANICAL PROPERTIES DURING OPERATIONAL STAGE OF ANODIC ASSEMBLIES

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Abstract

The properties of steel stubs change with each operational cycle of the Hall-Héroult process at high temperatures due to a carburization that occurs in carbon containing environments. The operability of carburized steels and its impact on the performance of the anodic assembly can be determined by evaluating the properties of new and recycled stubs. The chemical composition, mechanical, creep and thermo-physical properties were investigated to evaluate their changes regarding operational cycle and take into account in a numerical model for the assessment of their impact on the thermo-mechanical behavior of the anode, evolution of air gap between the anode and the cast iron connector, and voltage drop.

The first results show that the initial carbon content of the new stub 0.2% increases up to 1.1% after 2-3 years of operational cycles and accompanied by cardinal microstructure changes that contributes to change of thermal expansion, tensile and creep strength, elongation and specific heat.

Introduction

During the operational cycles of the Hall-Héroult process, the properties of the industrial steel stub change with operational time and have to be defined for the analysis of the thermo-mechanical behavior of anodic assemblies. The relevance of this problem is noted in the literature [1] and proved by some experiments with new and recycled steel stubs. These experiments show that in the real long-term conditions at high temperatures the carbon steel does not keep a stable chemical composition including the content of carbon, microstructure, thermo-physical and thermo-mechanical properties. Depending on time and temperature, the affected area can vary in carbon content. Longer carburizing times and higher temperatures (especially above temperature of Ac3) increase the depth of carbon diffusion, lead to change of microstructure of the initial carbon steel, mechanical and physical properties at room and high temperatures.

Evolution of steel microstructure with each operational cycle due to the carburization significantly depends on the distance from the contact zone with cast iron connector and has the essential influence on the thermal expansion of steel stub and its displacement. Some of the mechanical properties of the carburized layer vary from the typical unaffected metal. For example, ductility and toughness decrease, hardness increases significantly. The evolution of the properties is more important if the carburized layer is stressed in tension, because cracking is quite likely to occur. Minor amounts of carburization do not affect the creep and rupture strengths significantly, but the amounts, which can change the microstructure of the steel in cross-section, have a noticeable impact on the creep properties [2].

Thus, the work is directly related to the definition and analysis of the new and recycled steel stub properties for evaluation of their influence on the thermo-mechanical behavior of anodic assemblies.

Materials and experimental procedures

The properties of the new steel stub (steel 1020 AISI, hot rolled) were partially found in literature [2,3,7,13], however, some distinction of the properties was noted at the use of the different literature sources. In practice, the distinction in the chemical compositions and properties of steels depends on steelmaking: the process of refining pig iron or ferrous scrap by removing the undesirable elements from the melt, adding the desired elements in predetermined amounts. In this connection, such properties of the new steel as thermal expansion, thermo-physical properties, etc. were determined by our own experiments using samples extracted from the new hot rolled steel stub.

Three recycled industrial steel stubs after 2-3 years operational cycles were cut at different heights (see Figure 1a); the obtained cross-sections were used to extract samples with the different content of the carbon and microstructures depending on the height of the stub and distance from the contact zone with the cast iron connector. All recycled steel samples were chosen with the condition of the microstructure uniformity through out the cross-section and length.

The vertical dilatometer "Anter Uniterm 1101" was used to obtain the family of the dilatometric curves and microstructure evolution (phase transitions) of the steels during the heating/operational stage. The dilatometer has digital displacement transducers with an accuracy of 0,001 mm; the inert gas was used to protect the samples from the oxidation. Based on data about the thermal expansion, the density of each sample was calculated and used to determine the thermal properties. The flash diffusivity system "Anter Flashline 5000" was used to determine the specific heat capacity and thermal diffusivity by the flash method [4]. It allowed us to calculate the thermal conductivity of the samples (12.5mm diameter thin disks) with using the obtained density. The thermo-mechanical tests were performed according to specific ASTM standards to determine elastic (Young's modulus and Poisson ratio) and mechanical properties (tensile strength, yield strength, elongation) at the elevated temperatures 25-900^{0}C using the testing system "Gleeble 3800" with a high speed heating method and the tensile testing machine "Instron" with the furnace. In both cases, the extensometers were used to measure the axial and lateral strains, and three thermocouples to measure the temperature distribution. The temperature difference between middle thermocouple and the side thermocouples (where the tips of the extensometer were installed) was about 10-20^{0}C. The creep properties of different carbon steels were taken from literature [5, 6].

The obtained experimental results and literature review about the steel stub properties are used to feed the numerical model of the thermo-mechanical behavior of anodic assemblies that can allow us to evaluate their influence on evolution of the contact zone between cast iron and the anode during the operational stage.

Evolution of steel stub microstructure during operational stage of anodic assemblies

The industrial recycled steel stubs of similar geometric shape and operational time were investigated (see Figure 1a). Figure 1b demonstrates the typical change of the carbon content and microstructure in the steel after ≈ 2 to 3 years of the use. Depending on the height of the stub and distance from the contact zone with the cast iron connector, the carbon content is varied. The carbon content of the initial steel 1020 is 0.17-0.24% [7].

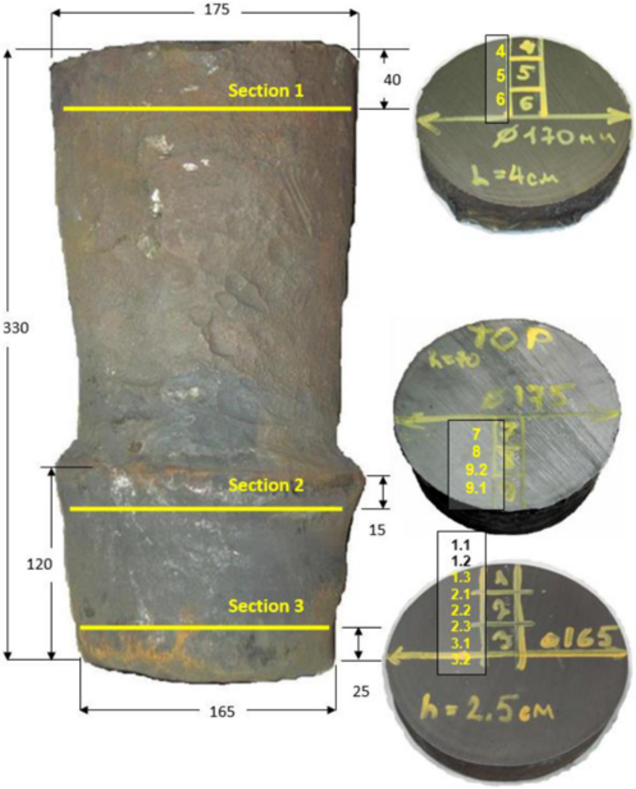


Figure 1a. The sections of the industrial recycled steel stub.

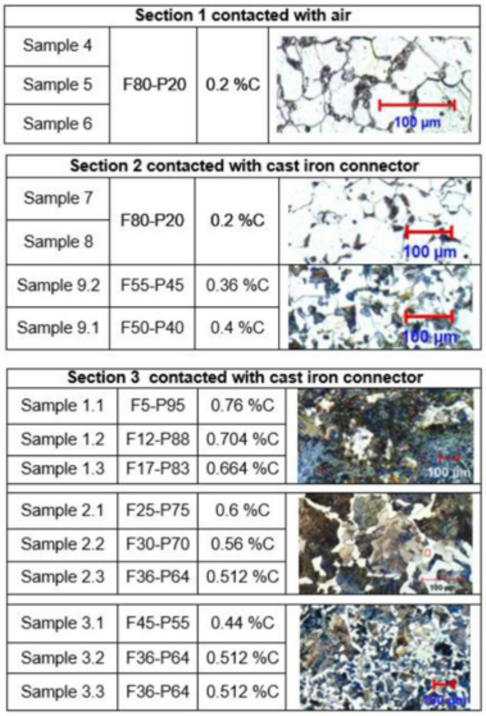
The top part of the steel stub (see Figure 1a,b, section 1) during the operational stage contacts with air and has the typical ferritic-pearlitic microstructure F80/P20 of the carbon steel 1020 with the carbon content of about 0.2%.

The upper part of the steel stub, which contacts with the cast iron connector (see Figure 1a,b, section 2) has the carburized layer of about 40-45mm (at the stub radius of 87mm) with the maximal carbon content of about 0.4%. With the moving away from the contact zone to the centre of the stub, the carbon content decreases, and samples 7 and 8 in the central unaffected area have the carbon content of 0.16-0.24% that corresponds to the initial carbon content of the steel 1020.

The carburization is increased especially in the lowest stub part (see Figure 1a,b, section 3), which has a bottom and a side contact with the cast iron connector. With the lapse of time, after each operational stage, the carburization depth increases as well as the carbon content. The chemical analysis of two steel samples with the pearlitic microstructure and cementite in the grain boundary, which were located at the side interface border, showed the average composition: 1.05%C, 0.14%Si, 0.5%Mn, 0.006%P, 0.018%S.

The bottom part of the steel stub has a maximal level of carburization with varied content of carbon. Near the side contact zone with the cast iron connector the carbon content reaches up to 0.7-1.0%, the microstructure becomes almost pearlitic with the cementite. The side and bottom contact with cast iron connector has a decisive influence on the carburizing level. In the lower central part of the steel stub (see Figure 1a,b, section 3), where there is only bottom contact, the carbon content reaches only 0.5-0.6%, the content of pearlite is 50-70%.

In case of contact with cast irons, the carburization of carbon steels increases at the temperatures above 625÷650°C when the cementite in the cast irons disintegrates with the precipitation of free carbon.



Section 1 contacted with air		
Sample 4	F80-P20	0.2 %C
Sample 5		
Sample 6		

Section 2 contacted with cast iron connector		
Sample 7	F80-P20	0.2 %C
Sample 8		
Sample 9.2	F55-P45	0.36 %C
Sample 9.1	F50-P40	0.4 %C

Section 3 contacted with cast iron connector		
Sample 1.1	F5-P95	0.76 %C
Sample 1.2	F12-P88	0.704 %C
Sample 1.3	F17-P83	0.664 %C
Sample 2.1	F25-P75	0.6 %C
Sample 2.2	F30-P70	0.56 %C
Sample 2.3	F36-P64	0.512 %C
Sample 3.1	F45-P55	0.44 %C
Sample 3.2	F36-P64	0.512 %C
Sample 3.3	F36-P64	0.512 %C

Figure 1b. Evolution of the microstructure and carbon content in the steel stub after 2-3 years of use.

The figure 2 [1] shows the carburized layer with the thickness of 150÷200µm on the steel surface with a significant modification in the grain structure on the steel side after multiple heating / cooling cycles, increasing the electrical and thermal contact resistivity.

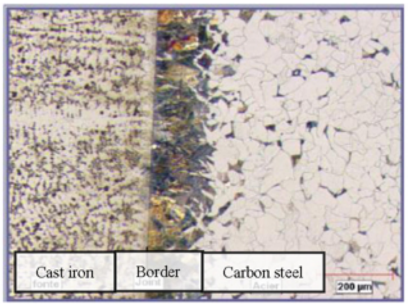


Figure 2. The steel / cast iron interface after one test of heating / cooling cycle (9 hours) [1].

The properties of the initial steel 1020 gradually change after each operational stage. The working part of the steel stub (height 120mm), affected by carburization, has the intermediate properties between the properties of the low carbon ferritic-pearlitic steel 1020 and the properties of the high carbon pearlitic steel 1090, which is very strong with a high hardness, ultimate and yield strengths, low elongation, and can be used for springs and high-strength wires (see Figure 3).

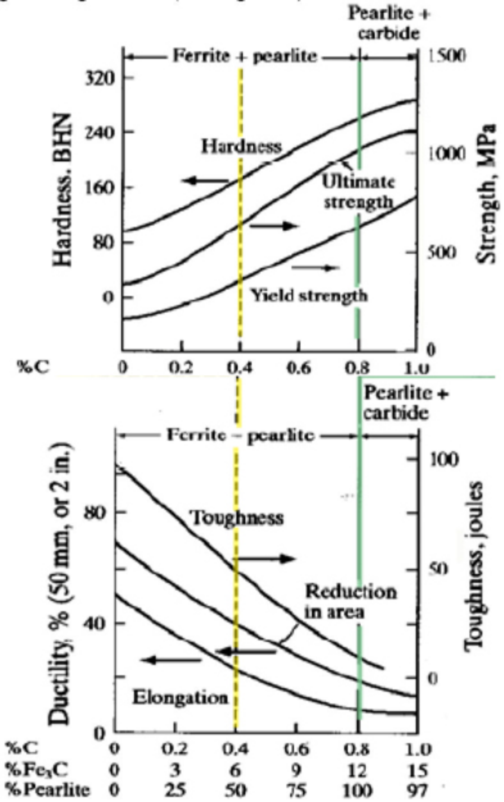


Figure 3. The mechanical properties of the carbon steels with different content of carbon [8].

The thermal expansion of the steel stubs

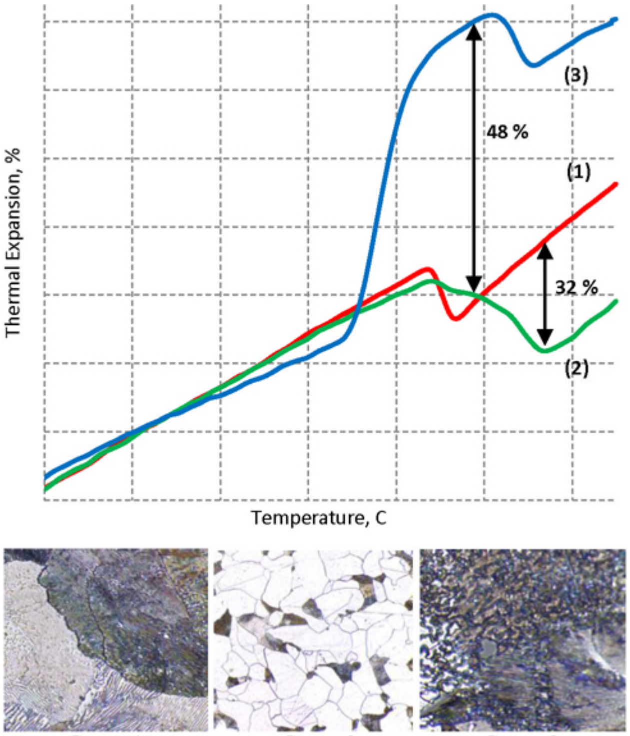
The difference in the phase transformation of the ferrite and pearlite is defined by transformation rates of the microstructures, diffusion processes, redistribution of silicon, etc. The typical high carbon pearlitic steel has the short temperature range 30÷70^{0}C between Ac1 (start temperature of pearlite to austenite transformation) and Ac3 (austenite formation finish temperature) that is accompanied by comparatively not large specific effect of volume contraction.

The difference in thermal expansions of the low and high carbon steels can be observed on Figure 4, which shows the thermal expansion of the new (curve 2) and recycled (curve 1) steel stubs as a function of temperature. The scale was removed for reasons of confidentiality.

Below the phase transition temperature range (see Figure 4), the dilatometric curves of the new and recycled steel are practically identical; whereas the transformation period between Ac1 and Ac3 is significantly shorter for the recycled steel with the pearlitic microstructure. The phase transition temperature range of the new steel is about 750÷870^{0}C and about 735-770^{0}C for the recycled steel with the pearlitic microstructure.

The different behavior of the steel stubs can be observed at the temperatures 760-770^{0}C when the new steel stub continues to contract whereas the recycled steel stub starts to expand. The maximal difference between them reaches up to 32% at the temperatures 850-870^{0}C. It is maximal value, but really, the 100% pearlitic microstructure is located generally close to the contact zone with the cast iron connector. In other places, there is the ferritic-pearlitic microstructure (F10-80/P20-90) with the intermediate properties. However, each recycling of the steel stub decreases the temperature Ac3; in this connection, the time of carburization period increases [9, 12], and the dilatometric curve of the recycled steel stub moves away from the dilatometric curve of the new steel 1020.

It was established by own experiments that the thermal expansion of the cast iron connector with the typical ferritic-pearlitic microstructure (see Figure 4, curve 3) upper 650^{0}C is considerable more (max. 48% at 780-810^{0}C) than thermal expansion of the steel stubs.



Curve 1 Curve 2 Curve 3

Figure 4. The thermal expansion curves of the recycled and new steel stubs, and the cast iron connector:

(1) – Recycled steel stub with the pearlitic microstructure and cementite (1%C, 0.14%Si, 0.5Mn, 0.006%P, 0.018%S);

(2) – Initial steel 1020 with ferritic-pearlitic microstructure F80/P20, (0.2%C, 0.25%Si, 0.5%Mn, 0.04%P, 0.04%S);

(3) – Cast iron connector with the ferritic-pearlitic microstructure P90/F10.

The thermo-physical properties of the steel stubs

The thermo-physical properties of the standard carbon steels were taken in literature [2,3,7,14]; the properties of steel stubs with the typical microstructures were determined by our own experiments. The comparison of the literature and experimental data allowed us to confront our results with data of the standard carbon steels and choose the correct database for feeding the numerical model.

The microstructure of the recycled steel stubs is not constant and changes with the depth and height of the stub. Taking into account the real microstructure distribution in the recycled steel stub and the results of the thermo-physical tests, the intermediate properties of the recycled stub are similar to the properties of the carbon steels 1040-1050 (see Figure 5). The thermal conductivity of the recycled steel stub corresponds to the carbon steel 1050, the specific heat corresponds to the carbon steel 1040.

It is necessary to emphasize the role of the specific heat during the microstructure changes and include it into the numerical model because the specific heat is very sensitive to them [10,11]. If there is a shift of the phase equilibrium during the heating process, it gives an additional contribution to the specific heat. In this connection, the specific heat of the heterogeneous system is not equal to the sum of the specific heats of the constituent phases, and exceeds it. Thus, in many alloys with the mix of microstructures, during the phase transitions, a strong leap of specific heat is observed that is shown, for example, for the carbon steel 1040.

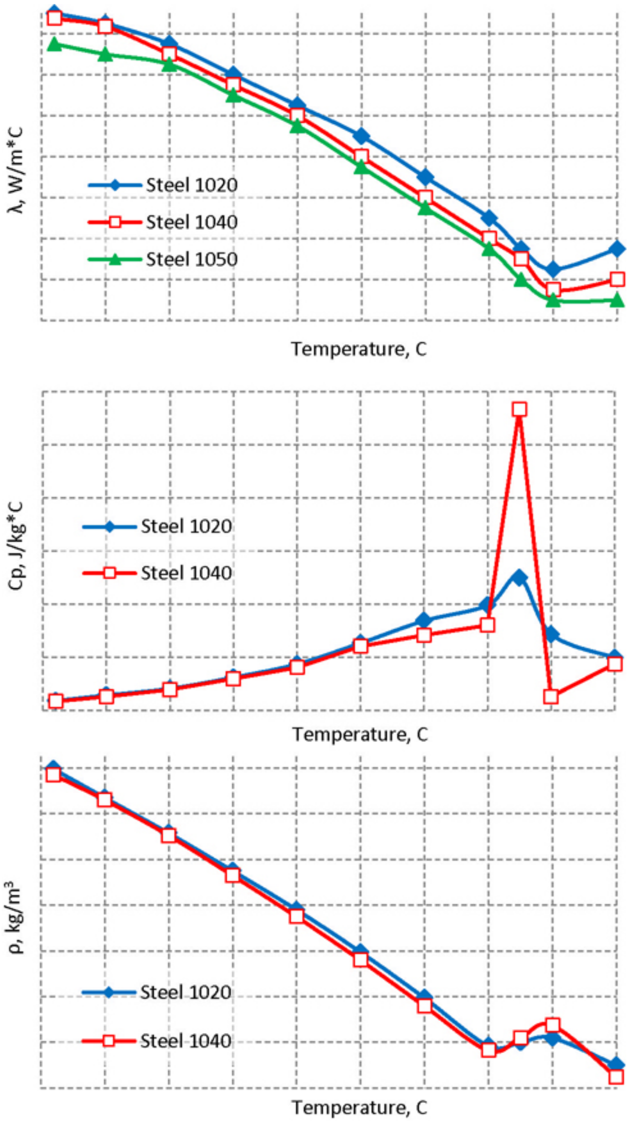


Figure 5. The average thermo-physical properties of the new and recycled steel stubs that correspond to the carbon steels 1020, 1040 and 1050.

The thermo-mechanical properties of the steel stubs

The samples for the determination of the thermo-mechanical properties were extracted from the new and recycled steel stubs with the typical microstructures; the results were compared with some known properties of the standard steels: 1020, 1040, 1045 and 1065.

The first results of the tests confirm that the Young's modulus of the different carbon steels practically depends weakly on their microstructure and decreases with increasing the temperature (see Figure 6). It is known that shear modulus decreases slightly more than the Young's modulus; the Poisson's ratio slightly increases with the temperature. The small difference in the elastic properties of the new and recycled stub between experimental data and literature can be explained by various steelmaking, grain size of the steels, experimental conditions and measurement errors.

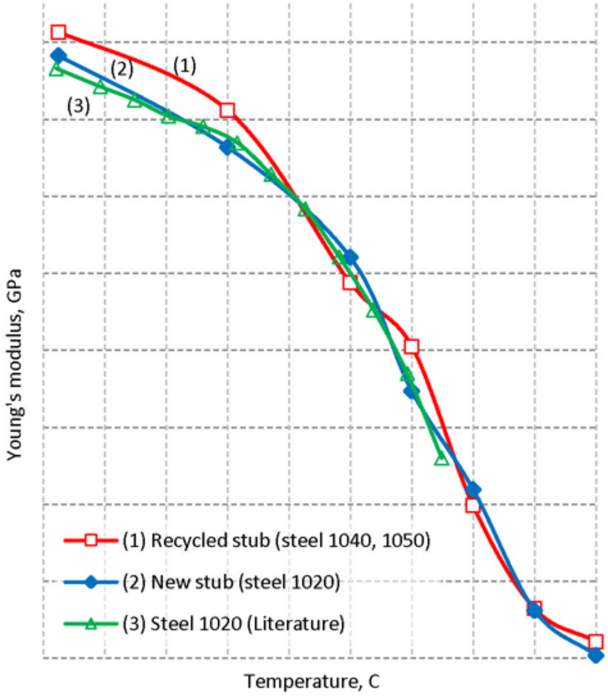


Figure 6. Young modulus of the steel stubs.

The obtained results of the mechanical tests (see Figure 7) indicate that properties of the extracted samples correspond to the steel 1020 (the unaffected, no carburized zone), to the steel 1045 (the affected, carburized zone with the main typical ferritic-pearlitic microstructure: F30-70 / P70-30), and to the steels 1065-1080 (the affected, carburized external layer of the stubs).

The low carbon steels with 0.2%C and medium-high carbon steels with 0.4-0.8%C have the essential difference in tensile/yield strength and elongation at the same elastic limit. With increasing the carbon content, the elongation decreases, the tensile/yield strength and creep properties [5,14] increase significantly at the low temperatures, but all values become similar at the high temperatures >700^{0}C. The strength of the carbon steels decreases about 4-5 times with increasing the temperature from 25^{0}C up to 600-700^{0}C; during the heating at the 200-400^{0}C it is also noted the embrittling effect of the steel surface that increases with each operational cycle and contributes to creation of additional electrical/thermal resistance of the contact zone with the cast iron connector.

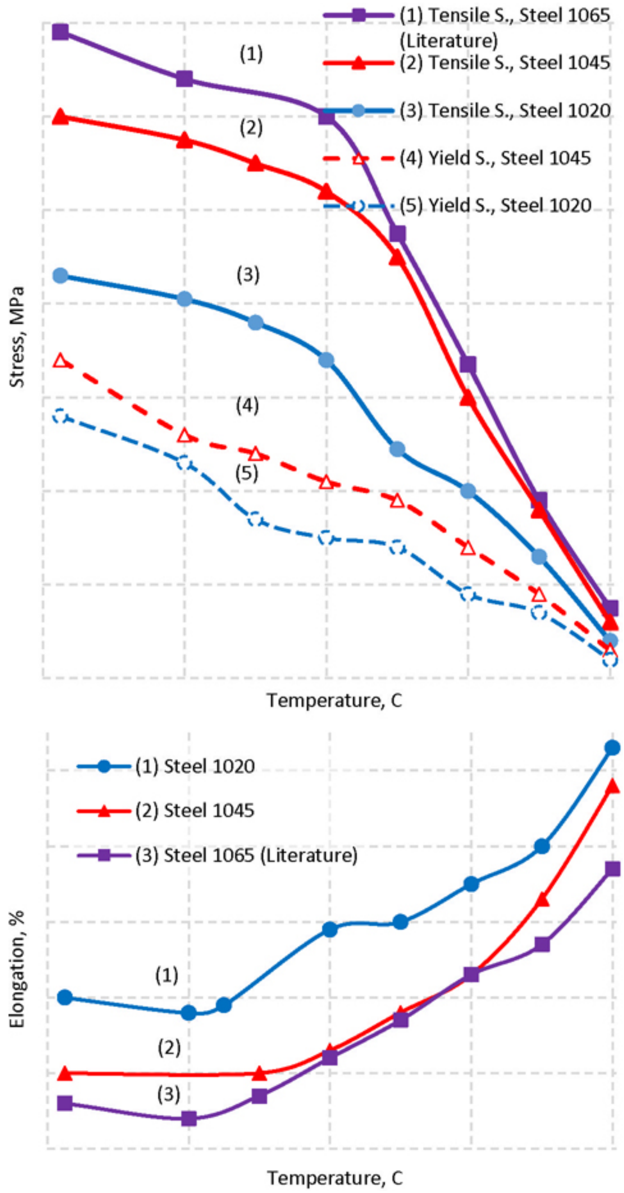


Figure 7. The tensile/yield strength and elongation of the new and recycled steel stubs.

Literature sources [2,3,5,13] were investigated additionally to compare the creep curves of the carbon steels 1020 and 1045. The found results are related to the creep tests at the different temperatures and stress level, and confirm the low level of the creep properties at elevated temperatures (see Figure 8). At the high temperatures 700-900^{0}C the creep strength values of the carbon and some stainless steels decrease significantly and become similar.

The figure 9 demonstrates the creep deformation of the steel 1045, which is smaller than the creep deformation of the steel 1020 by 2.5-3 times after 100 hours of operation at 140MPa and 475^{0}C. At 500^{0}C the difference between the creep deformations reaches 6-7 times after 120 hours. The creep strength strongly depends on temperature, decreasing by 2-3 times at each 100^{0}C that is more than the decrease of the yield strength [3]. The longer the steel is exposed to high temperatures, the smaller is the stress, causing its destruction after a period of work.

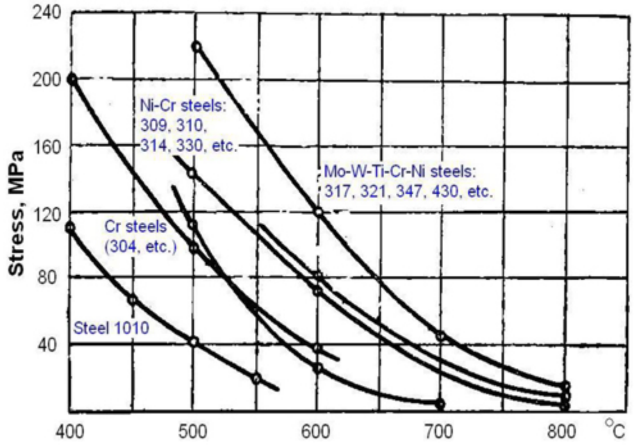


Figure 8. The creep rate curves of several steels, 1% creep in 100 000 hours, [2].

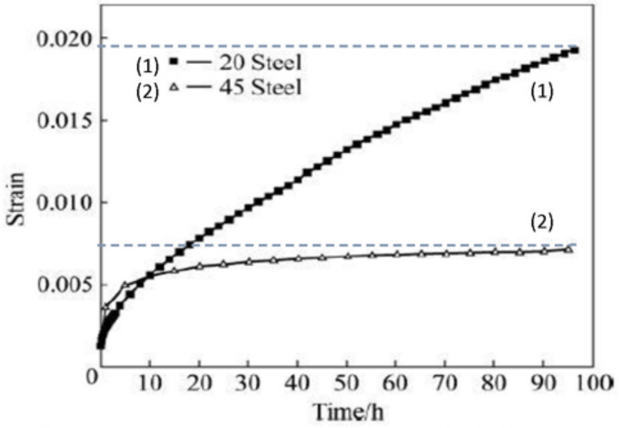


Figure 9. The creep deformation of the steels 1020 and 1045 at 475^{0}C and 140MPa, [5].

Conclusions

1. The chemical composition, microstructure and properties of the steel stub change after each operational stage depending on its height and distance from the contact zone with the cast iron connector. The carburization increases especially in the lowest stub part which has a bottom and side contact with the cast iron. The carbon content in this part of the steel stub reaches up to 1.0-1.1%, the microstructure becomes pearlitic with the cementite in the grain boundaries; in the center of the section the carbon content reaches up to 0.5-0.6%. After 2-3 years of use, the carbon content reaches up to 0.3-0.4% in the highest stub part close to the contact zone with the cast iron.
2. A higher content of pearlite and cementite in the recycled carbon steels increases the brittleness that limits their application. The voltage drop at the contact zone with the cast iron connector increases with each operational stage due to an embrittling effect and brittleness of the carbonized steel surface, and difference in the thermal expansion of the carbon steel and cast irons.
3. The properties of the recycled steel stub, which are changed considerably during the operational stage (thermal expansion, specific heat, elongation, tensile/yield and creep strength), should be included to the numerical model for the assessment of their impact on the thermo-mechanical behavior of the anode and evolution of the voltage drop.

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