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Experimental Method for the Controlled Cooling of Steel Sections with Varied Wall Thickness

Abstract: The article presents the results of controlled cooling experiments after austenitising a V36 section made of structural steel S480W. The experiments involved variable cooling intensity affecting the cross-section of the test element. The tests aimed to investigate the possibility of modifying the microstructure and uniformly increasing the mechanical properties of steel sections with varied cross-sectional wall thickness in relation to free-air cooling. The research work involved the determination of section-related cooling characteristics identified using various parameters of compressed air blown from nozzles onto selected surfaces of the section. The accelerated cooling tests led to the formation of a fine ferritic-pearlitic microstructure having ferrite grain size D_α restricted within the range of 6.8 µm to 6.5 µm. In addition, the tests resulted in the obtainment of uniform hardness distribution in cross-section, an increase in yield point R_e and tensile strength R_m (restricted within the range of approximately 40 MPa to 60 MPa) while maintaining similar elongation.

Key words: structural section, structural steel, accelerated cooling, microstructure, mechanical properties

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1. Introduction

The mechanical properties of steel products can be effectively improved using controlled accelerated cooling after plastic working, by controlling changes taking place in the microstructure within the range of austenite stability and as a result of phase transformations. The process requires the use of cooling conditions appropriately designed for a given chemical composition of steel and plastic strain parameters, closely adjusted to the dimensions and geometry of the product. Depending on the type of product, its dimensions and shape complexity as well as intended final properties, cooling after plastic working may require accelerated cooling with an air jet, water spray or by using water mist. Controlled cooling processes performed in integrated rolling lines are widely applied in the production of flat products such as metal sheets or strips [1–3]. Special precision cooling methods are used, among others, in the production of rebars or wire rods [4, 5]. Less popular controlled cooling processes include the cooling of sections, which, after being subjected to hot plastic working, are usually cooled in free air. The fundamental problem, both in technical and technological terms, as regards the design of parameters used in the accelerated cooling of sections is the significantly varied cross-sectional wall thickness. The aforementioned issues were the subject of works [6, 7], in which the Authors addressed the problem of varied cross-sectional temperature distribution in H-shaped sections during accelerated cooling. Related analyses included the use of numerical simulation results as well as the results of experiments involving spray cooling and air-blowing. It was ascertained that the appropriate cooling of the cross-section enabled the obtainment of a relatively uniform temperature field in the cross-section, the reduction of internal stresses triggering the deformation of the section and the improvement of the mechanical properties of the test steel. Similar issues were addressed by the Authors of publication [8], who proposed the use of a cooling system for an isosceles section (L200x200), reducing internal stresses, responsible for the deformation of the section after hot rolling. Publication [9] presents the results of numerical simulations modelling the selective cooling of HP220 *bulb bars,* aimed to increase the homogeneity of mechanical properties across the cross-section of the aforesaid bars. Publication [10] presents a method and the experimental verification of the *accelerated cooling* and *self-tempering* (AC-ST) of the HEA120 H-section.

An example of a section characterised by complex geometry and significantly variable wall thickness in cross-section is the V-section, used in structures safeguarding underground workings [11]. The above-named sections are usually made of carbon-manganese steels containing up to approximately 0.3 % C and, after production, characterised by the presence of ferritic-pearlitic microstructure. Increased requirements formulated by section users in terms of mechanical and functional properties, inspired the development of the aforesaid steel grades and the modification of their chemical composition, by, among other things, adjusting the content of basic chemical elements (C, Mn and Si) and adding alloying microagents (Ti, V and Nb), which, when combined with an appropriate content of nitrogen in the steel during the production process, enable the formation of fine particles of MX-type carbonitrides [12]. The precipitates which are formed during the process restrict the growth of austenite grains during heating (mainly TiN), and rolling; they affect the kinetics of the austenite recrystallisation process and make it possible to adjust the final grain size (NbC). Vanadium precipitates in the form

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of V (N,C) are privileged areas of ferrite nucleation during the transformation, triggering the significant refinement of the microstructure and leading to the obtainment of the uniform volume distribution of grains.

Accelerated cooling directly following the plastic working process makes it possible to effectively affect the parameters of the ferritic-pearlitic microstructure, thus influencing the mechanical properties of steel. An increase in the cooling rate reduces the initial temperature of the austenite-to-ferrite transformation. The significant supercooling of austenite entails a large driving force of the transformation process, increasing the rate of ferrite nucleation. In addition, accelerated cooling restricts grain growth, thus favouring the formation of the fine-grained microstructure. An increase in the cooling rate increases the dispersion of carbonitride particles formed during the transformation. In ferrite, after the transformation, increased cooling intensifies the effect of precipitation hardening. During the pearlitic transformation, higher cooling rates also reduce the interlamellar distance in pearlite.

The tests, the results of which are presented in this article aimed to assess the usability of variable parameters (used when cooling a section with varied wall thickness) for controlling the parameters of the steel microstructure in a manner enabling a uniform increase in mechanical properties in the cross-section. The study discussed in the article concerns the effect of changes in compressed airflow intensity under the conditions of the selective cooling of the section surface on the section cooling rate as well as on the microstructure and mechanical properties of the section. The tests involved the use of the V36 section made of structural steel S480W with microagents.

2. Test materials and methodology

The test materials were fragments of the V36 sections made of S480W steel, the chemical composition of which is presented in Table 1. After the rolling process, the section is characterised by the fine-grained ferritic-pearlitic microstructure, ensuring the obtainment of appropriate mechanical properties required for this type of product (Table 2) [13]. The geometry and nominal dimensions of the section, specified in the PN-H-93441-3:2004 (industry) standard [14], are presented in Figure 1.

Metallographic tests of the steel were performed using cross-sectional metallographic specimens, an Olympus DSX500 light microscope and an Inspect F scanning electron microscope. The microstructural parameters of the steel were identified using a μGrain software programme

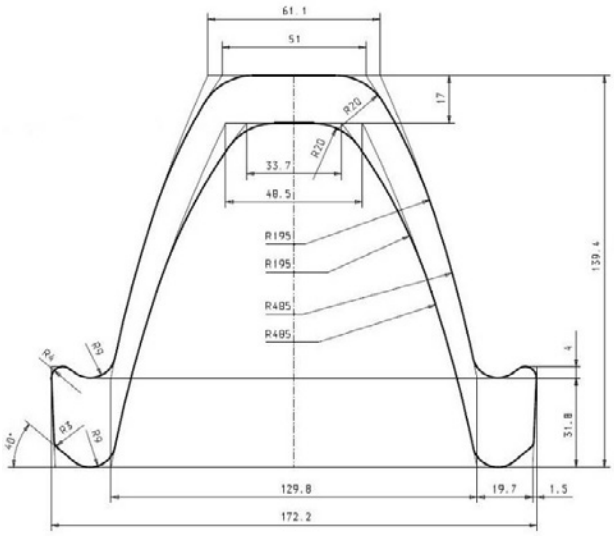

Fig. 1. Nominal dimensions of the V36 section, in accordance with PN-H-93441-3:2004 [14]

for quantitative image analysis [15]. Dilatometric tests were performed using a DIL805A dilatometer and specimens having dimensions ϕ4/ϕ2 mm and a length of 10 mm. The mechanical properties of the sections were determined using a Z250 testing machine (ZwickRoell). The scope of the tests did not include measurements of steel toughness. Hardness measurements were performed using Swiss Max (Brinell) and FM-700 (Future-Tech) hardness testers.

3. Test results

Physical simulations involving the cooling of sections with blown air were performed using a testing station (Fig. 2) and 699 B01A T1SG nozzles (PNR), generating a flat airflow having an apex angle of $\alpha = 60°$ and $\beta = 20°$. The type of nozzles used in the tests enabled the precise concentration of the air flow on selected areas of the section by changing the distance between the nozzle and the surface as well as by adjusting the slot forming the flow. The section was cooled by an air flow striking the external surface of the web perpendicularly (Fig. 3a) or by an air flow affecting the external surface of the flange (Fig. 3b).

The cooling parameters were adjusted by modifying air pressure p_{air} within the range of 0.5 bar to 3.5 bar, which corresponded to air flow rate V_{air} restricted within the range of 3.5 m/s to 16.5 m/s (Fig. 4). Section fragments having a length of 400 mm were subjected to heating in an electric

Table 1. Chemical composition of structural steel S480W; heat analysis [wt %]

Grade	C	Mn	Si	P	S	Cr	Al	Ni	V	Cu	Mo	Ti	N
S480W	0.24	1.23	0.43	0.015	0.012	0.28	0.012	0.07	0.072	0.26	0.013	0.011	0.0096

Table 2. Required mechanical properties of sections made of steel S480W, in accordance with PN-H-84042:2009 [1]

Steel grade	R_e [MPa] (min.)	R_m [MPa] (min.)	A_5 [%] (min.)	$KCU2$ [J/cm^2] (min.)
S480W	480	650	17	30

chamber furnace for 30 minutes up to a temperature of 950 °C, which approximately corresponded to the actual average temperature of sections after the hot rolling process under industrial conditions. During heating and cooling, changes in temperature of selected cross-sectional areas of the test sections were recorded using K-type sheathed thermocouples having a diameter of 2 mm and located at half of the length of the section fragment (Fig. 5). The temperature of the section was measured in the centre of the flange (T1), in the narrowest cross-section of the leg wall (T2) and the axis of symmetry, at half of the web thickness (T3). The sections were cooled continuously from a temperature of approximately 900 °C to ambient temperature, using the constant value of the airflow rate.

The results of preliminary tests were section cooling characteristics in relation to various conditions. Selected results of experimental cooling are presented in Figures 6 and 7. In terms of free cooling, individual cross-sectional areas of the section cooled down to a temperature of 700 °C (i.e. temperature close to that of the transformation of austenite into ferrite) at a mean cooling rate ranging from 1.4 °C/s (web) to 2.0 °C/s (leg). Within the lower temperature range, the rate of cooling evened up, reaching a value of approximately 0.5 °C/s. Under the above-presented conditions, the maximum momentary temperature difference between individual cross-sectional areas amounted to a maximum of 75 °C.

The airflow directed at rate V_{air} = 4.5 m/s onto the surface of the thick-walled areas of the web and flange increased the mean cooling rate (restricted within the range of 900 °C

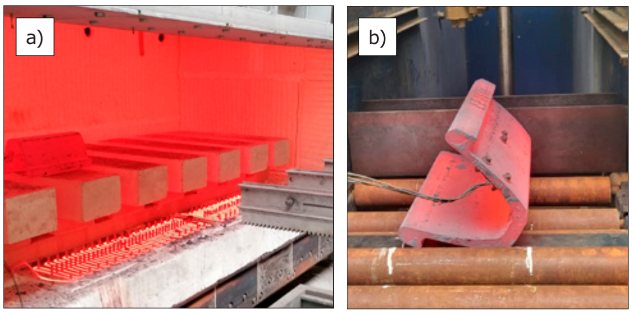

Fig. 2. Station for the experimental accelerated cooling of sections

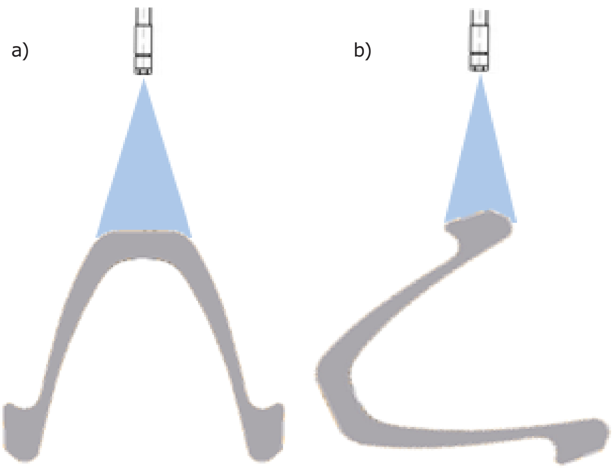

Fig. 3. Schematic diagram presenting the orientation of the nozzles in relation to the shape during experimental accelerated cooling

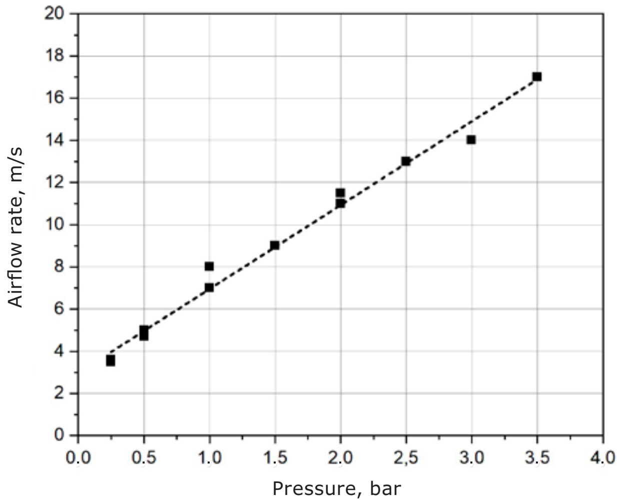

Fig. 4. Measurements concerning the airflow rate in relation to the value of pressure in the cooling system

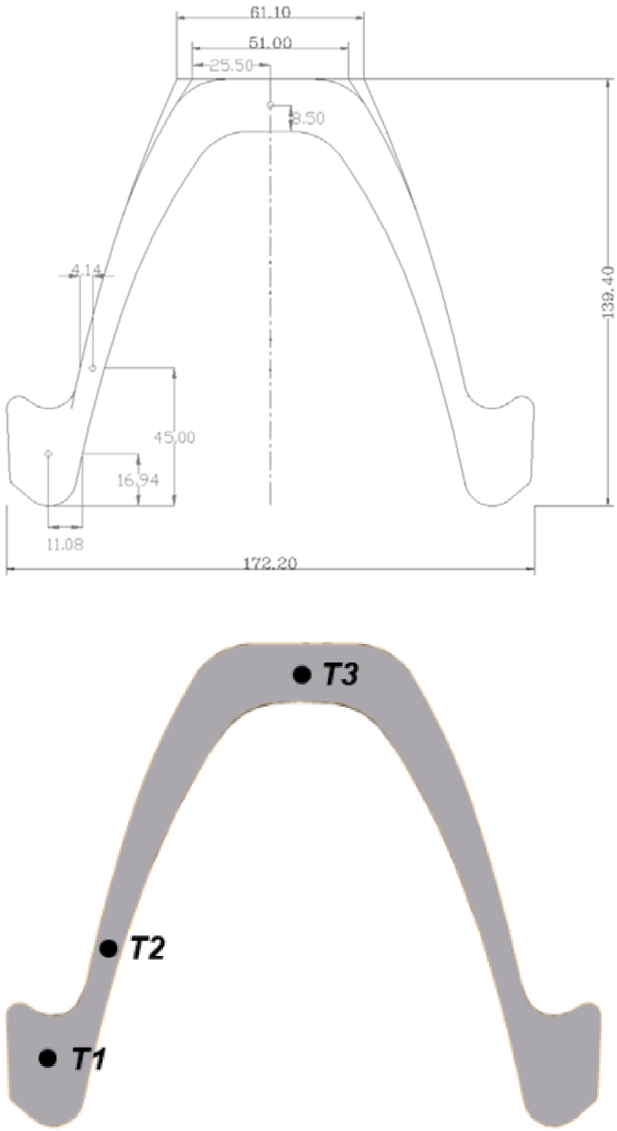

Fig. 5. Arrangement and designation of the sheathed thermocouples used in cross-sectional temperature measurements

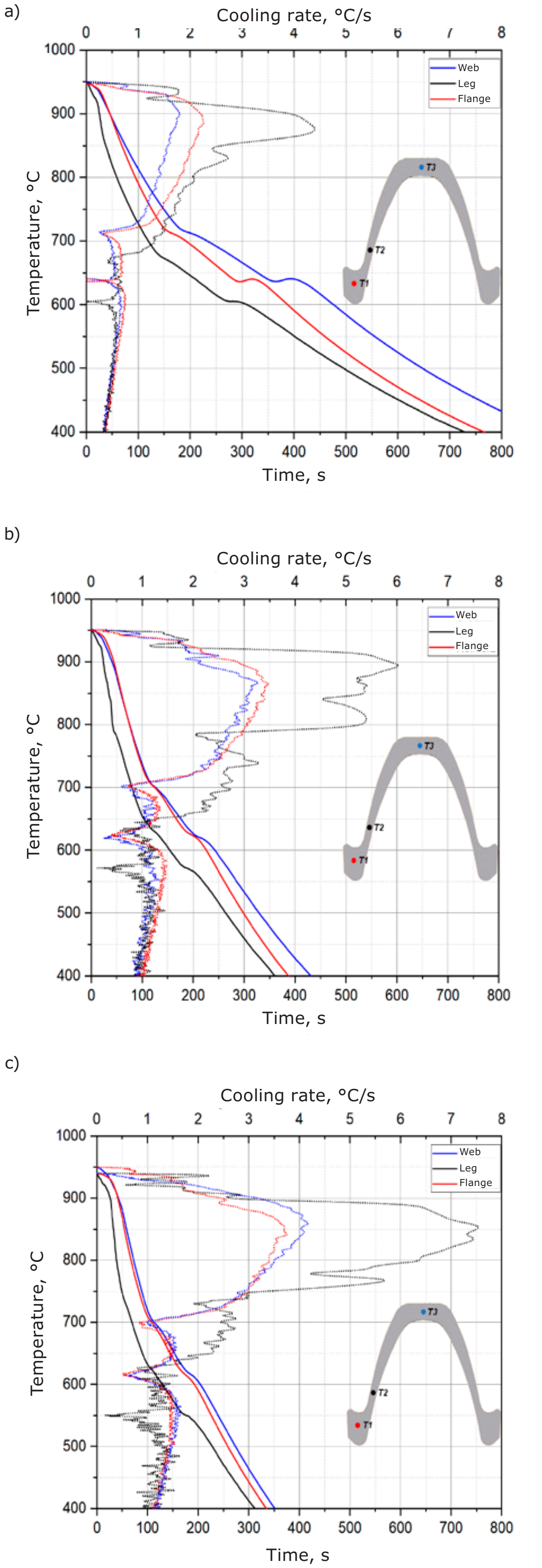

Fig. 6. Changes in temperature and the momentary cooling rate in selected cross-sectional areas of the section during the cooling process: a) free cooling, b) airflow at rate V_{air} = 7.5 m/s / p_{air} = 1 bar and c) airflow at rate V_{air} = 14 m/s / p_{air} = 3 bars

to 700 °C) in all section areas subjected to measurements to approximately 2.5 °C/s. The applied parameters favoured the obtainment of very similar section cooling characteristics in the entire cross-section, slightly increasing the cooling rate in comparison with that of the free cooling of the section.

The airflow having rate V_{air} = 7.5 m/s led to an increase in the section cooling rate (restricted within the range of 900 °C to 700 °C) to approximately 3 °C/s. The difference in the mean cooling rate of selected section areas amounted to approximately 0.5 °C/s. Within the lower temperature range (of austenite phase transformation), it was possible to observe a decrease in the section cooling rate to approximately 1 °C/s. At the initial cooling stage, the maximum momentary temperature difference between individual cross-sectional areas of the section amounted to approximately 100 °C.

An increase in the airflow rate to V_{air} = 14 m/s led to an increase in the mean cooling rate of the web and flange areas to approximately 3.5 °C/s. It was possible to observe the effect of changes in airflow parameters on the leg area cooling rate. An increase in the intensity of airflow directed onto the flange area was accompanied by an increase in the rate of the airflow washing around the external wall of the leg. The measurement results revealed that, under the above-presented conditions in the leg area, the mean airflow rate amounted to approximately V_{air} = 6 m/s. The mean cooling rate of the thin-walled area within the temperature range of 900 °C to 700 °C amounted to 4.1 °C/s and was twice higher than that during free cooling. At the initial stage, the maximum temperature difference in the cross-section of the section increased to approximately 130 °C. Further cooling within the temperature range of ferritic and pearlitic transformations took place in individual section areas with a similar mean rate of approximately 1.5 °C/s.

The subsequent stage of the tests involved the performance of physical experiments simulating the controlled cooling of sections from the austenitising temperature. The experiments aimed to determine the effect of variable cooling conditions in the cross-section (of the test sections) on the microstructure and mechanical properties of steel S480W.

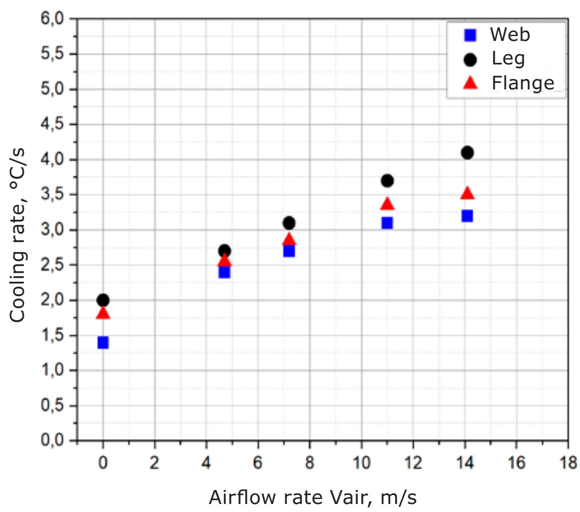

Fig. 7. Effect of the airflow rate on the mean cooling rate in selected cross-sectional areas of the section within the temperature range of 900 °C to 700 °C

The assumption of cooling-related experiments was to obtain higher and uniform mechanical properties in the entire cross-section of the section in comparison with the material cooled conventionally during the production process. An additional criterion was the obtainment of the ferritic-pearlitic microstructure (typical for this type of product) after cooling.

A diagram of phase transformations taking place in steel S480W during continuous cooling at a constant rate, developed on the basis of dilatometric tests in relation to a similar chemical composition, is presented in Figure 8.

Within a wide range of cooling rates, i.e. from 5 °C/s to 200 °C/s, structural steel S480 is characterised by the microstructure being a mixture of ferrite, bainite and martensite in various proportions. Cooling the steel at a rate below 5 °C/s results in the partial transformation of austenite into pearlite and the obtainment of the multi-constituent microstructure. The microstructure of the steel, consisting exclusively of ferrite and pearlite, can be obtained through cooling at a constant rate of <1 °C/s. Within the cooling rate range of 0.5 °C/s to 5 °C/s, the beginning of the austenite-to-ferrite transformation changes within the temperature range of 715 °C to 670 °C, whereas the end of the pearlite transformation takes place at a temperature of approximately 550 °C.

The cooling experiments involving fragments of the test sections were performed using parameters designed on the basis of cooling characteristics and the analysis of the kinetics of phase transformations taking place in structural steel S480W.

Before cooling, the test section fragments were for 30 minutes subjected to austenitisation at a temperature of 950 °C. The average initial austenite grain size of steel S480W heated using the above-presented parameters was $\underline{D}_\gamma$ = 12.4 mm (G = 10.7 in accordance with ASTM) and was comparable with the grain size obtained in the rolling

Table 3. Selected cooling parameters; austenitising temperature T_a = 950 °C; accelerated cooling initial temperature T_s = ~900 °

No.	Variant	Section area cooled with airflow	Time of accelerated cooling [s]	Temperature after the completion of accelerated cooling [°C]		Mean cooling rate to temperature 700 °C [°C/s]	Mean cooling rate within the range of 700 °C to 550 °C [°C/s]
1	V2	flange	120	flange	622	3.5	0.7
2				leg	558	4.1	0.7
3	V3	flange	280	flange	350	3.5	1.7
4				leg	307	4.0	1.7
5	V4	web	190	web	591	2.5	0.8
6				leg	554	3.6	0.8
7	V5 (free cooling)	-	-	flange	-	1.4	0.6
8		-	-	leg	-	2.0	0.6
9		-	-	web	-	1.1	0.5

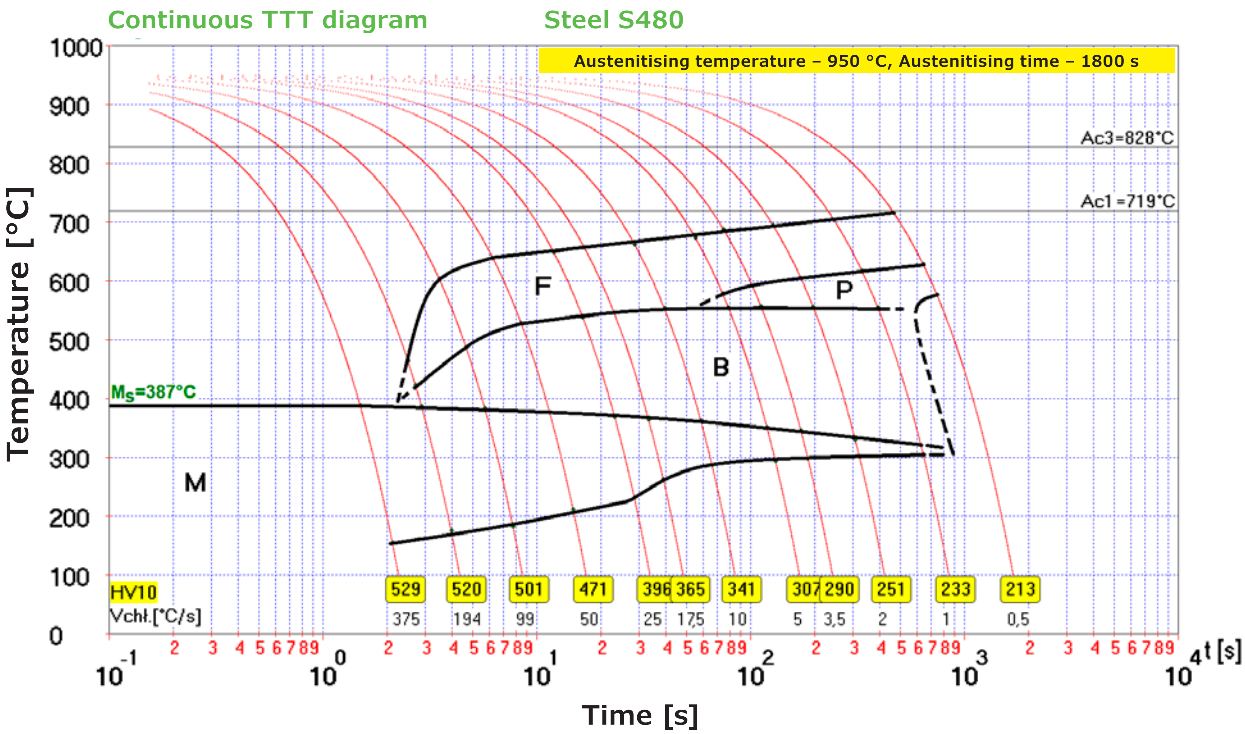

Fig. 8. Diagram of phase transformations taking place in steel S480W during constant cooling in relation to an austenitising temperature of 950 °C; austenite grain diameter D_γ = 11 mm (developed for a similar chemical composition: C = 0.25 %, Mn = 1.35 %, Si = 0.35 %, Cr = 0.26 %, Cu = 0.26 %, Ni = 0.136 % and V = 0.1 %)

process. The forced cooling of the thick-walled areas of the sections was performed from a temperature of approximately 900 °C by blowing compressed air at a flow rate of V_{air} = 14 m/s (pressure p_{air} = 3 bar). The airflow time for each variant was varied so that forced cooling could finish following the obtainment of a previously assumed temperature in the cross-section of the test section. The cooling process was accompanied by the controlling of the temperature of selected cross-sectional areas.

The most important parameters of the experiments are presented in Table 3. Variants V-2 and V-4 consisted in the accelerated cooling of the flange or web until the obtainment (in the fastest cooling area of the leg) of temperature close to that of the beginning of the austenite-to-bainite transformation (i.e. approximately 550 °C). Variant V-3 was characterised by a longer airflow time and involved the accelerated cooling of the flange to a temperature of 350 °C. The further cooling of the material was slower and took place in air. For comparative purposes, a free cooling test of the section was performed from a temperature of 950 °C, simulating the cooling of the material after rolling on a cooling bed.

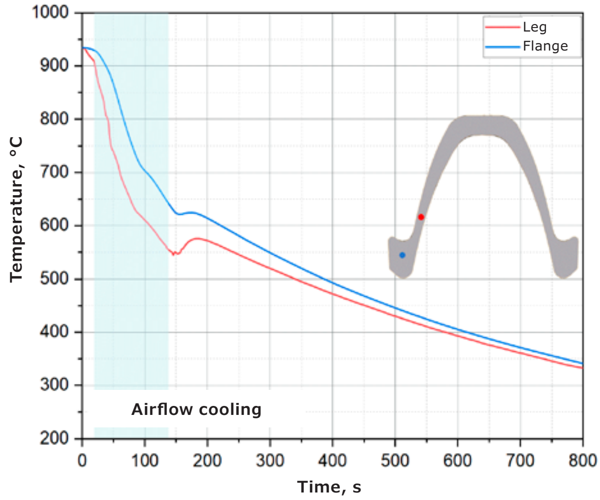

Fig. 9. Changes in the temperature of selected areas in the cross-section of the V36 section during the accelerated cooling of the flange, in accordance with variant V-2

The exemplary cooling of selected areas in the cross-section of the test section in relation to variant V-2 is presented in Figure 9. Microstructural photographs of steel S480W revealed on the specimens sampled from the fragments of the test sections after cooling tests are presented in Figures 10–12. The results of hardness distribution measurements in the cross-section of selected areas are presented in Figure 13. Table 4 presents the averaged results of the mechanical properties of the sections and selected parameters characteristic of the microstructure of the steel obtained through cooling.

Under free cooling conditions, the steel in the cross-section of the test section was characterised by the fine-grained ferritic-pearlitic microstructure with a ferrite content of approximately V_α = 60 %. A slight differentiation of ferrite grain size D_α could be seen in individual areas of the section, within the range of 8.6 mm to 7.5 mm.

The use of airflow led to an approximately twofold increase in the cooling rate of the individual areas of the section within the temperature range of austenite stability in relation to free cooling. Cooling to a temperature of 700 °C in accordance with variant V-2 in the area of the flange and that of the leg took place at a rate restricted within the range of 3.5 °C/s to 4.0 °C/s. After the completion of the accelerated cooling process, it was possible to observe an increase in temperature, connected with the emission of heat during the pearlitic transformation and the compensation of temperature in the cross-section of the test section (Fig. 9). The mean cooling rate within the range of austenite diffusion transformations (700 °C to 550 °C) amounted 0.7 °C/s The use of variant V-2 led to the obtainment of the fine-grained ferritic-pearlitic microstructure in the entire cross-section of the test section (Fig. 10 and 11), characterised by the presence of equiaxial ferrite grains, characterised by similar diameters, i.e. in relation to the flange D_α = 6.8 mm and in relation to the leg D_α = 6.5 mm. An increase in the degree of the supercooling of austenite before the start of transformation favoured the refinement of the microstructure in relation to the uninterruptedly cooled material, whereas the mean volume fraction of the components was very similar.

Table 4. Test results concerning the mechanical and microstructural parameters of steel S480W determined in the specimens sampled from selected areas of sections after cooling

No.	Variant	Test area	$Rp_{0,2}$ [MPa]	Rm [MPa]	A5 [%]	Z [%]	Mean hardness HBW	Microstructural parameters		
								Ferrite grain diameter D_α [mm]	Ferrite content V_α [%]	Pearlite content V_P [%]
1	V-2	flange	533	698	28	65	206	6.8	61	39
2		leg	-	-	-	-	206	6.5	59	41
3	V-3	flange	528	718	27	64	208	6.8	60	40 (bainite <3 %)
4		leg	-	-	-	-	207	6.6	58	42 (bainite <3 %)
5	V-4	web	527	680	25	62	206	6.9	59	41
6		leg	-	-	-	-	206	6.5	61	39
7	free cooling V-5	flange z	491	659	29	65	198	7.7	59	41
8		leg	-	-	-	-	196	7.4	58	42
9		web	473	654	28	68	192	8.6	61	39

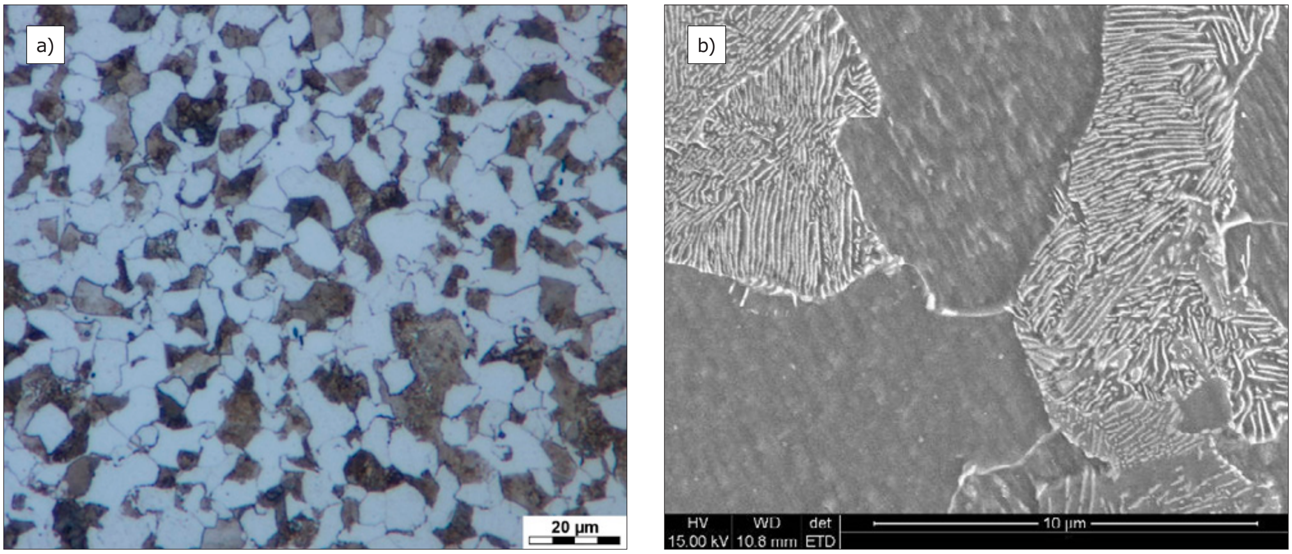

Fig. 10. Microstructure of steel S480W in the cross-section of the test section in the flange area after airflow cooling (V-2): a) light microscope and b) SEM

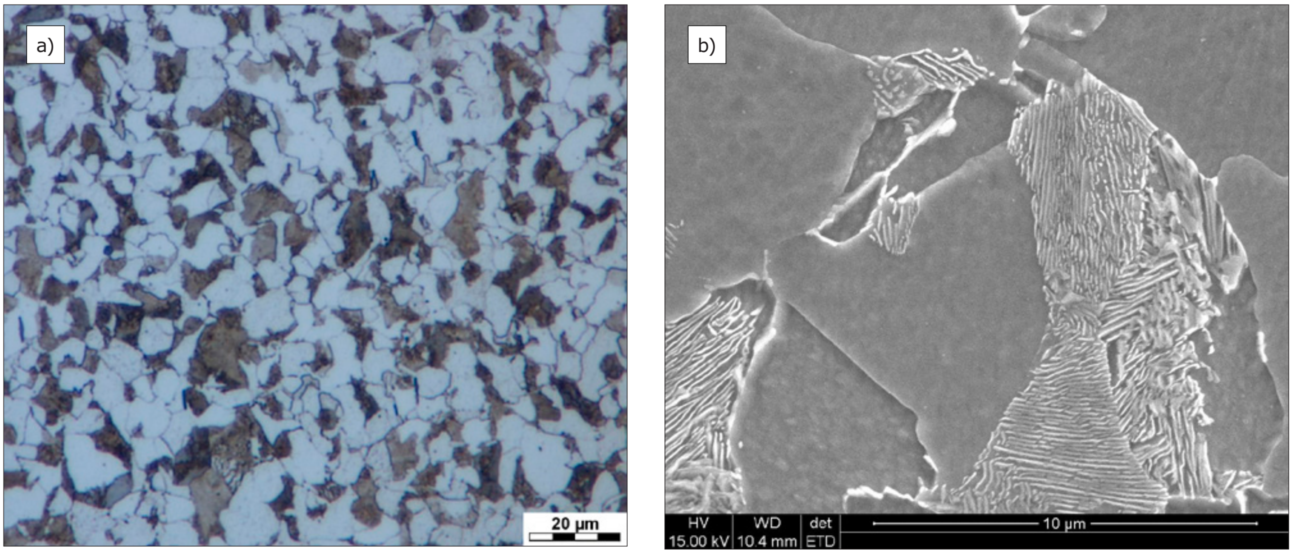

Fig. 11. Microstructure of steel S480W in the cross-section of the test section in the leg area after airflow cooling (V-2): a) light microscope and b) SEM

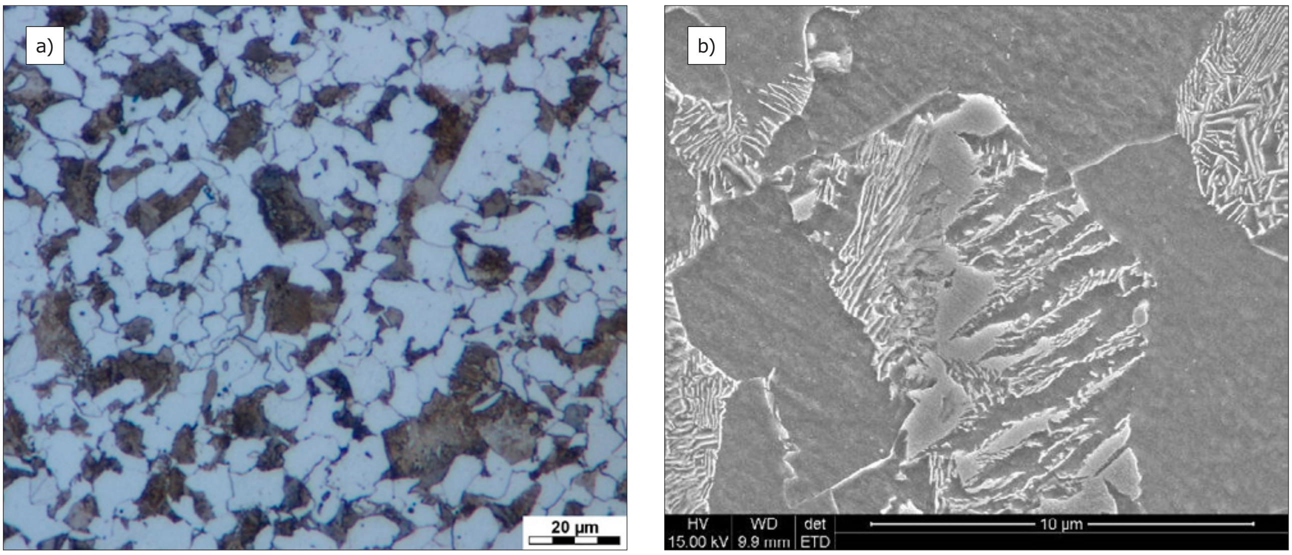

Fig. 12. Microstructure of steel S480W in the cross-section of the test section in the flange area after airflow cooling (V-3): a) light microscope and b) SEM

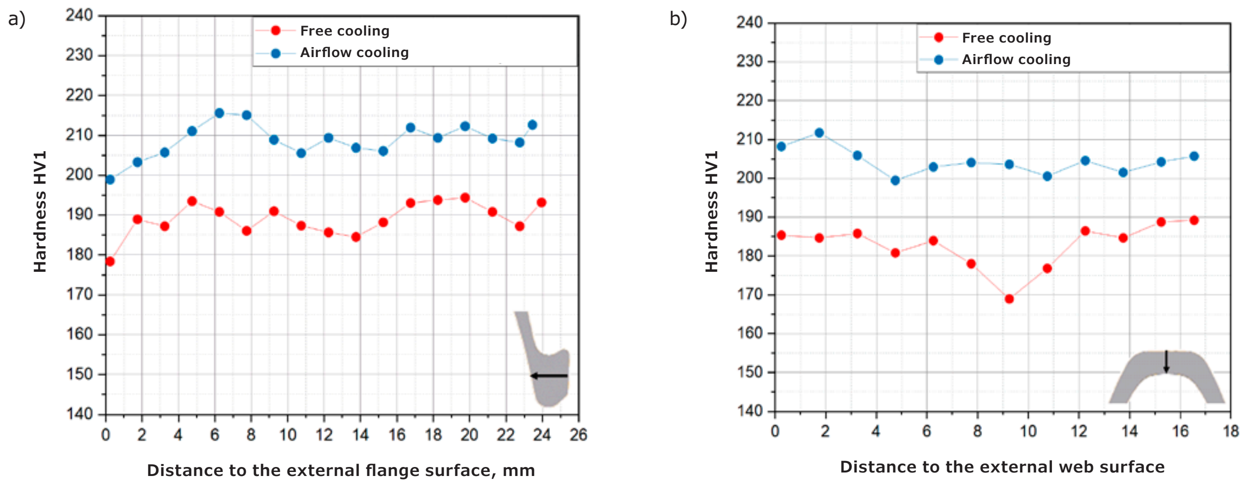

Fig. 13. Distribution of hardness HV1 in the cross-section of the test section after free cooling and airflow cooling in the area of a) flange (V-3) and b) web (V-4)

The microstructure was characterised by the large content of pearlite grains composed of colonies, characterised by the small interlamellar distance. The cooling conditions applied in the tests increased the mechanical properties in the cross-section of the test section in relation to the reference material. The value of hardness in the flange and leg areas was the same and amounted to 206 HBW. The measurement results also indicated the uniform distribution of hardness HV1 in the cross-section of the flange cooled with the airflow (Fig. 13a). The cooling parameters used in the tests were also reflected in the results of the static tensile test. In cases of the specimens sampled from the flange area, the mean values of the yield point and tensile strength were by approximately 40 MPa higher (R_e = 533 MPa, R_m = 698 MPa) than those of the section cooled uninterruptedly. The above-named increase was not accompanied by the deterioration of plastic properties (A_5 = 27 %, Z = 65 %).

Longer airflow-based cooling, performed in accordance with variant V-3, increased the mean cooling rate of the flange and leg areas (within the temperature range of 700 °C to 550 °C) to 1.7 °C/s. The final temperature of the accelerated cooling of the section was restricted within the range of approximately 300 °C to 350 °C. The microscopic observations of the entire cross-section revealed the presence of the homogeneous and fine-grained microstructure consisting of ferrite and pearlite as well as a few (volume fraction <3 %) small areas, being primarily the mixture of bainite structures characterised by varied morphology (Fig. 12). As a result of cooling, the steel was characterized by a very similar grain diameter (restricted within the range of 6.8 mm to 6.6 mm) and a similar ferrite volume fraction as was the case with variant V-2. In the flange and leg areas, the section was characterised by mean hardness restricted within the range of 207 HBW to 208 HBW. The results of the static tensile test indicated similar mechanical properties as those observed in variant V-2. Cooling the section in accordance with variant V-3 enabled the obtainment of tensile strength in the flange area higher by approximately 60 MPa (R_m = 718 MPa) and the similar value of elongation A_5 in relation to free cooling.

In terms of variant V-4, the cooling rate of the web and leg areas within the temperature range of 700 °C to 550 °C was restricted within the range of 2.5 °C/s to 3.6 °C/s, whereas the further free cooling of the section, until the end of the austenite phase transformation, took place at an average rate of 0.8 °C/s. Similar to the other cooling variants, the cross-section of the steel was characterised by the homogeneous fine-grained ferritic-pearlitic microstructure and the same volume fraction of ferrite. The performance of the above-named cooling variant led to an increase in the mean hardness of the cross-section (of the test section) to 206 HBW, in comparison with that of the material cooled uninterruptedly. The distribution of hardness HV1 in the cross-section of the web wall after cooling was uniform (Fig. 13b). In relation to the web material subjected to free cooling, it was possible to observe significantly higher mechanical properties (R_e = 527 MPa, R_m = 680 MPa) and a slightly lower value of uniform elongation A_5.

4. Conclusions

The above-presented results of physical experiments, tests and analyses justified the formulation of the conclusions presented below:

1. The cooling method involving compressed air blown onto thick-walled areas of the section led to the obtainment of similar mean cooling rate values across the entire cross-section. The foregoing implies that accelerated cooling took place under conditions of the relatively uniform discharge of heat from the material. The airflow performed at rate V_{air} = 14 m/s made it possible to approximately double the mean cooling rate of the section across its cross-section in comparison with free cooling conditions, restricted within the range of approximately 3.5 °C/s to 4.0 °C/s, within the temperature range of 900 °C to 700 °C.
2. The applied parameters of accelerated intermittent cooling led to the obtainment of the fine-grained ferritic-pearlitic microstructure of the steel with a ferrite content of approximately 60 %. Depending on the area in the cross-section of the test section subjected to analysis, the steel was characterized by the ferrite grain size approximately 10 % to 20 % smaller than that of the material subjected to free cooling. The equiaxial ferrite grains present in the microstructure were characterised by mean diameter D_α restricted within the range of 6.8 mm to 6.5mm. In the thin-walled leg of the section, the microstructure did not differ qualitatively from that of the areas subjected to airflow cooling.

3. The results of the static tensile tests and those of hardness measurements indicated that, during accelerated cooling, the appropriate adjustment of the airflow intensity affecting individual areas of the section enabled the obtainment of higher and more uniform mechanical properties in the cross-section. The cooling parameters applied in the tests led to the obtainment of the uniform cross-sectional hardness distribution and, depending on the time of accelerated cooling, enabled the obtainment of an increase in yield point R_e and tensile strength R_m the restricted within the range of approximately 40 MPa to 60 MPa, while maintaining the similar value of uniform elongation A_5 in relation to that of the material subjected to free cooling.
4. The test results indicate the possibility of obtaining a greater or similar effect of section hardening after a shorter cooling time by increasing the section cooling rate using a medium characterised by a higher heat discharge intensity. The cooling method proposed by the Authors is characterised by significant developmental potential and will be the subject of further research.

REFERENCES

[1] Dilg Ch., Kirsch H. J., Streisselberger A.: Accelerated cooling during plate production. Steel Technol. Int., 1992, pp. 211–217.
[2] Dilg Ch., Kirsch H. J., Schutz W. et al.: TMCP process including two accelerated cooling stages. Rev. Metall. CIT, 1995, no. 7/8, pp. 883–892.
[3] Grajcar A.: Technologie wytwarzania blach cienkich ze stali wielofazowych AHSS dla motoryzacji. Stal Metale & Nowe Technologie, 2014, no. 5–6, pp. 97–102.
[4] Grosman F., Woźniak D.: Technologiczne aspekty walcowania walcówki z nowoczesnych stali. Hutnik, Wiadomości Hutnicze, 2002, vol. 69, no. 11, pp. 408–414.
[5] Grajcar A., Morawiec M., Kozłowska A.: Obróbka cieplna prętów zbrojeniowych z samoodpuszczaniem martenzytu, Stal Metale & Nowe Technologie, 7–8/2018, pp. 22–25.
[6] Guo Fei, Zhao Xian-ming, Wang Li-na et al.: Effect of Controlled Cooling on Microstructure and Mechanical Properties of H-Beam. Journal of iron and steel research, international, 2013, 20(8), pp. 60–65.
[7] Yu-Feng Gan, Jiin-Yuh Jang: Optimal Heat Transfer Coefficient Distributions during the Controlled Cooling Process of an H-Shape Steel Beam. Advances in Materials Science and Engineering, T. 2017, Article ID 9873283, pp. 1–15.
[8] Garstka T., Dobrakowski R., Koczurkiewicz B., Dyja H.: The system of automation for controlled cooling of the shapes. Journal of Materials Processing Technology, 20 December 2004, vol. 157–158, pp.159–164.
[9] Mróz S., Szota P., Koczurkiewicz B.: Modelling Of Rolling And Cooling Processes Of The Bulb Bars HP220. Numiform 07. Materials Processing and design: Modelling, Simulation and Applications, 2007, pp. 1243–1248.
[10] Işıkgül A., Ahlatci H., Esen İ., Türen Y., Yağız O.: Investigation of Mechanical Properties of Accelerated Cooled and Self-Tempered H-Type Structural Sections. Arch. Metall. Mater., 2023, vol. 68, no. 3, pp. 1191–1204.
[11] Caban P., Stoiński K., Rotkegel M., Rajwa S., Pacześniowski K.: Rozwój konstrukcji stalowych odrzwi do rozcinek ścianowych. Mining – Informatics, Automation and Electrical Engineering, 2020, vol. 542, no. 2, pp. 41–58.
[12] Kuziak R., Żak A., Woźniak D., Rotkegel M. et al.: Odrzwia obudowy chodnikowej ze stali II generacji. Prace IMŻ 2012, vol. 64, no. 4, pp. 4–17.
[13] PN-H-84042:2009. Stale mikrostopowe na kształtowniki i akcesoria górnicze.
[14] Norma PN-H-93441-3:2004. Kształtowniki stalowe walcowane na gorąco dla górnictwa – Część 3: Kształtowniki typu V – Wymiary.
[15] Program μGrain – Micrograph Processing and Analysis Tool, https://www.mark-henning.de/mhm_about_eng.php