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THE INFLUENCE OF HYPERQUENCHING TEMPERATURE ON MICROSTRUCTURE AND MECHANICAL PROPERTIES OF ALLOY CAST STEEL GX2CrNiMoCuN 25-6-3-3

The paper presents the research results concerning the chromium-nickel-molybdenum duplex cast steel GX2CrNiMoCuN 25-6-3-3 grade. The aim of studies was the description of the influence of hyperquenching temperature T_p i.e. 1100, 1125 and 1150°C on microstructure and mainly mechanical properties i.e. tensile strength UTS, yield strength YS, hardness HB, elongation EL and impact energy KV of duplex cast steel GX2CrNiMoCuN 25-6-3-3 grade. The range of studies included ten melts which were conducted in foundry GZUT S.A. Based on the obtained results was confirmed that application of hyperquenching process guarantees the elimination of brittle s phase in the microstructure of studied duplex cast steel. Moreover on the basis of conducted statistical analysis of the researches results is concluded that with the decrease in hyperquenching temperature increases ductility and amount of austenite, while decreases strength and amount of ferrite in studied duplex cast steel GX2CrNiMoCuN 25-6-3-3 grade.

Keywords: Duplex cast steel, Heat treatment, Mechanical properties, Microstructure

1. Introduction

The ferritic-austenitic alloy cast steel also called as duplex cast steel in view of a comparable amount of both phases, according to Standard PN EN 10283 contains C < 0.08% (usually for most grades even C < 0.03%), Cr = 21.0÷27.0%, Ni = 4.5÷8.5%, Mo = 0.1÷5.0%, N = 0.10÷0.25%, Mn < 1.5%, Si < 1.0%, S < 0.025%, P < 0.035% and possibly for some grades Cu = 1.0÷3.5%. In present time these alloys have a very important position in the group of stainless cast steels. In comparison with very popular austenitic cast steels, the duplex cast steels contain a lower amount of scarce and expensive Ni and simultaneously have higher mechanical properties, particularly even two times higher yield strength YS [1] at while maintaining high corrosion resistance, also in environments containing chloride ions [1-4]. The next advantage of duplex cast steels is high crack resistance also in reduced temperatures [4]. Whereas must be noticed that the operating temperature of duplex cast steel does not exceed 300°C as is presented in papers [4,5].

Analysis of the chemical composition of duplex cast steels shows that there are elements which stabilize ferrite (δ) i.e. mainly Cr, Mo and Si or stabilize austenite (γ) i.e. mainly C, Ni, N, Mn and possibly Cu. The amount of δ and γ phases in the microstructure of duplex cast steel with some approximation determines the ratio of equivalent content Ni_{eq} and Cr_{eq} [4,6]:

$$Ni_{eq} = \text{wt. \% Ni} + 30(\text{wt. \% C} + \text{wt. \% N}) + 0.5\text{wt. \% Mn} \quad (1)$$

$$Cr_{eq} = \text{wt. \% Cr} + \text{wt. \% Mo} + 1.5\text{wt \% Si} + 0.5\text{wt. \% Nb} \quad (2)$$

These empirical dependencies Eq. (1) and (2) have a basic character and have many modifications which are presented in detail in papers [1,7]. Unfortunately, besides the presence of the determined amount of ferrite and austenite, the high content of alloy additions favours the precipitation in castings cooled in the mould of many harmful intermetallic phases, carbides and nitrides [1,8-12]. As presented in papers [1,4,13-17] the largest decline in usable properties, mainly toughness and the corrosion resistance of duplex cast steel results from precipitation on grains boundaries the brittle σ phase and carbides $(Cr, Fe)_{23}C_6$ and $(Cr, Fe)_7C_3$. As shown in papers [1,4,18] to reduce the amount of these undesirable phases and to obtain a two-phase ferritic-austenitic microstructure for duplex steel castings, the heat treatment of type hyperquenching is used. Moreover as mentioned in paper [7], by changing the holding temperature in

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hyperquenching process, the δ/γ ratio can be controlled according to Eq. (3), (4) and (5).

$$\%\delta = 4.010Cr_{eq} - 5.600Ni_{eq} + 0.016T_p - 20.93 \quad (3)$$

where: %δ – percentage amount of ferrite in the microstructure of duplex cast steel; T_p – hyperquenching temperature in °C; Cr_{eq} – equivalent content of chromium equaling:

$$Cr_{eq} = \text{wt. \% Cr} + 1.73\text{wt. \% Si} + 0.88\text{wt. \% Mo} \quad (4)$$

Nir_{eq} – equivalent content of nickel equaling:

$$Ni_{eq} = \text{wt. \% Ni} + 24.55\text{wt. \% C} + \\ + 21.75\text{wt. \% N} + 0.40\text{wt. \% Cu} \quad (5)$$

The holding temperature in process of hyperquenching of duplex cast steel, for example, GX2CrNiMoCu25-6-3-3 grade according to the Polish / European Standard PN EN 10283 is from 1100 to 1150°C. It should be noted that in foundry practice in point of view of economic of the manufacturing process, in the stage of heat treatment is searching the holding temperature as lowest as possible but simultaneously sufficient to dissolve any precipitated phases in the solution. This economic aspect of production is also important for GZUT S.A. which manufactures castings being elements of marine pumps, parts of valves, mining pumps, parts of machines for the chemical industry and building industry. Often these parts work in aggressive environments, where both high mechanical properties and excellent resistance to localized and stress corrosion are required by customers.

Therefore the paper presents the possibilities of optimization of the heat treatment of type hyperquenching in range of the holding temperature value in the case of duplex steel castings GX2CrNiMoCu25-6-3-3 grade manufactured in GZUT S.A. conditions.

2. Materials and methods

The material for examinations has been the duplex cast steel GX2CrNiMoN25-6-3-3 grade. The samples of this cast steel in form of test castings with a standard shape of four-leaf clover were made during ten industrial melts conducted with the regenerative method in the medium frequency induction furnace Elzamet 750 of about 700 kg capacity. Therefore, for each of ten melts was obtained in the sand mould (silica sand with a binder in form of CO_2 hardened resin) one test casting of four-leaf clover shape consisting of four bars, each with dimensions 30 mm in diameter and 300 mm length. In the result of this finally, after machining for each melt was obtained three samples to tensile test and three to impact test.

The chemical composition of samples measured by the optical emission spectrometer Foundry Master Xpert is presented in Table 1. The nitrogen content was not determined.

For the purposes of the elaborated experiment, the samples from every melt were used to the heat treatment of type hyperquenching in three holding temperature T_p variants i.e. 1100, 1125 and 1150°C. The heat treatment was carried out in electric resistance furnace Linn High Term VMK-1600-G. After the hyperquenching mechanical properties have been tested. Tensile strength UTS, yield strength YS, elongation EL were measured by WPM Measure Machine, applying samples with a diameter 14 mm and a gauge length 70 mm, hardness was measured by the Brinell method, impact energy KV was measured with Charpy's method, applying V-notched standard samples (10×10×55 mm) at ambient temperature and energy 300 J of hammer Losenhausenwerk.

The metallographic researches were made with use of an optical microscope (OM) Nikon Eclipse LV150N and scanning electron microscope (SEM) Phenom ProX with an energy X-ray dispersive spectrometer. Metallographic samples were electrolytically etched using LectroPol-5 Struers. In presented researches were applied two etching reagents, first Mi19Fe (etching voltage 15 V at time 30 s) to microscopic observations and second A2 (etching voltage 20 V at time 15 s) to obtain proper contrast for evaluation the amount of ferrite and austenite in the microstructure of studied duplex cast steel using NIS-Elements image analysis program. The reagent Mi19Fe contained 3 g of ferric chloride, 10 cm^3 hydrochloric acid and 90 cm^3 ethanol, whereas the reagent A2 contained 78 ml perchloric acid, 100 ml butoxyethanol, 730 ml ethanol and 90 ml distilled water. Example microstructures of studied duplex cast steel developed after etching with the use of both reagents are presented in Fig. 1.

TABLE 1

Chemical composition of all ten melts of studied duplex cast steel GX2CrNiMoCuN 25-6-3-3 grade

No. of melt	Chemical composition wt. %									
	C	Si	Mn	Cr	Mo	Ni	Al	Cu	P	S
1	0.035	0.70	0.61	24.77	3.36	5.91	0.05	2.10	0.02	0.010
2	0.039	0.78	0.68	24.71	3.28	6.04	0.06	2.13	0.02	0.010
3	0.033	0.73	0.68	24.81	3.37	5.94	0.05	2.12	0.02	0.010
4	0.030	0.67	0.59	25.05	3.37	5.84	0.03	2.08	0.02	0.010
5	0.033	0.72	0.68	24.98	3.38	5.94	0.05	2.07	0.02	0.010
6	0.035	0.72	0.67	24.79	3.34	5.88	0.05	2.11	0.02	0.010
7	0.025	0.77	0.49	24.48	3.03	5.78	0.28	2.09	0.02	0.009
8	0.026	0.73	0.52	24.63	3.01	5.82	0.02	2.14	0.02	0.010
9	0.029	0.84	0.67	23.30	3.03	5.43	0.22	2.08	0.02	0.010
10	0.028	0.77	0.56	24.44	2.89	5.55	0.02	2.21	0.02	0.009

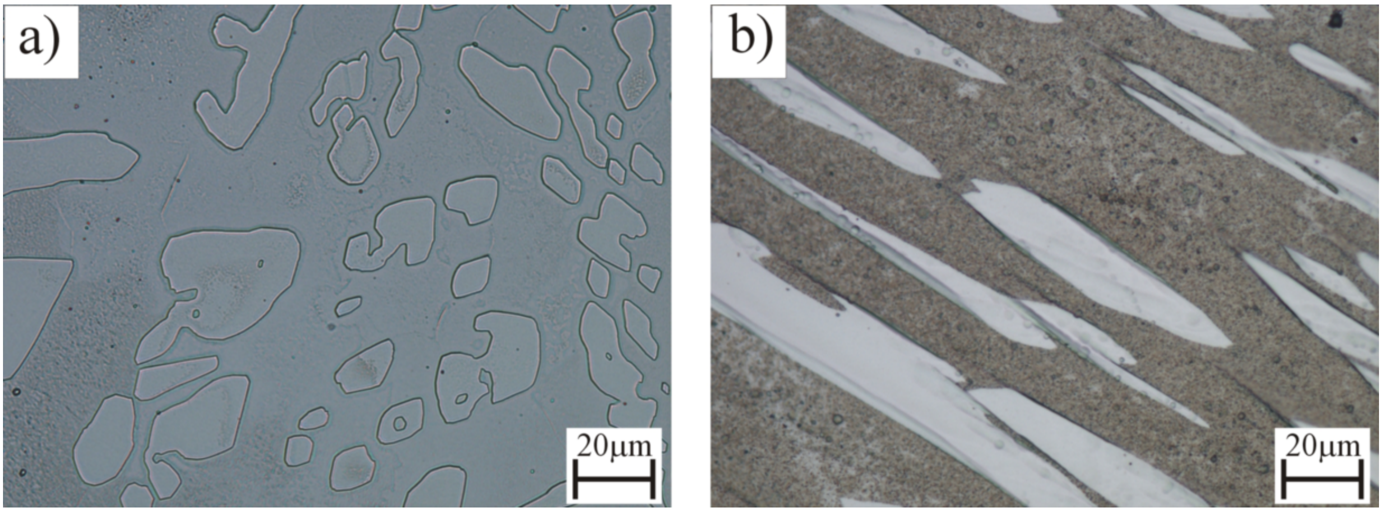

Fig. 1. Example microstructures of duplex cast steel GX2CrNiMoCu25-6-3-3 grade after etching in: a) Mi19Fe; OM, mag. 500× and b) A2; OM, mag. 500×

Additionally, the results of studies were statistically elaborated using stepwise regression in Statistica v.13.3 software. The verification of statistical signification of elaborated empirical dependencies was made based on the Fisher test.

3. Results and discussion

The results of the mechanical properties researches of duplex cast steel GX2CrNiMoN25-6-3-3 grade after hyperquenching in adopted holding temperatures are presented in Table 2.

Table 3 presents the average values of the studied mechanical properties of duplex cast steel together with values of the correlation coefficient, standard deviation and the Fisher test for Eq. (6-10) which were elaborated on the basis of statistical analysis.

$$\overline{UTS} = 0.58T_p + 198.15 \tag{6}$$

$$\overline{YS} = 0.55T_p + 78.26 \tag{7}$$

$$\overline{HB} = 0.28T_p - 63.53 \tag{8}$$

$$\overline{EL} = -0.03T_p + 58.09 \tag{9}$$

$$\overline{KV} = -0.10T_p + 263.49 \tag{10}$$

As show the results of conducted verification made with use of the Fisher test (Tab. 3) the statistical signification of Eq. (6-10) is confirmed. Therefore on the basis of obtained results and its analysis unequivocally was concluded that with the decrease in the holding temperature in the hyperquenching process increases the ductility and decreases the strength of studied duplex cast steel GX2CrNiMoCuN 25-6-3-3 grade (Fig. 2 and 3).

It was concluded that among the strength properties, the value of tensile and yield strength strongly depend on the holding temperature, while its influence on obtained hardness is low. Whereas in the case of ductility properties, the value of impact energy depends more on the holding temperature than the value of obtained elongation. In generally the obtained results comply with the requirements of the Polish / European Standard PN EN

TABLE 2

Mechanical properties of all ten melts of studied duplex cast steel GX2CrNiMoCuN 25-6-3-3 grade after hyperquenching

No. of melt	T_p, °C	UTS, MPa	YS, MPa	Hardness HB	EL, %	KV, J
1	1100	835.3	708.9	241	23.2	153.9
	1125	870.0	737.2	255	24.1	158.8
	1150	832.0	680.6	255	22.8	129.4
2	1100	839.7	676.9	255	23.4	156.9
	1125	855.4	731.6	255	24.0	150.2
	1150	873.6	721.7	255	26.2	149.0
3	1100	806.2	671.5	229	23.0	176.5
	1125	870.7	682.9	229	25.3	162.9
	1150	881.7	702.8	229	22.6	161.8
4	1100	828.0	679.2	241	22.2	177.5
	1125	860.3	695.7	255	23.4	162.2
	1150	872.0	721.6	269	20.6	150.0
5	1100	852.6	705.5	241	27.7	149.0
	1125	859.5	693.7	255	24.5	146.3
	1150	865.9	693.6	255	21.3	152.9
6	1100	838.5	676.5	241	22.9	145.1
	1125	856.6	726.6	255	22.1	137.3
	1150	880.4	720.5	255	21.9	152.9
7	1100	851.4	677.6	241	19.4	157.9
	1125	862.8	734.1	241	21.6	155.9
	1150	888.3	734.6	269	10.7	146.0
8	1100	846.5	669.4	255	22.1	137.3
	1125	855.1	681.6	269	23.4	145.1
	1150	855.0	682.5	269	21.7	166.7
9	1100	817.3	660.0	241	22.6	161.7
	1125	841.2	704.6	255	20.8	151.9
	1150	862.8	708.4	269	20.1	149.0
10	1100	861.1	702.2	255	28.4	140.2
	1125	864.4	704.9	255	24.0	159.8
	1150	856.7	738.1	255	20.3	146.1

TABLE 3

Average values of the studied mechanical properties of duplex cast steel GX2CrNiMoCuN 25-6-3-3 grade after hyperquenching and values of correlation coefficient R^2, standard deviation S, Fisher test F and critical value of Fisher test $F_{0.05}$ for Eq. (6-10)

Mechanical properties	T_p, °C			No. of Eq.	R^2	S	F	$F_{0.05}$
	1100	1125	1150					
UTS, MPa	837.7	859.6	866.8	(6)	0.92	18.8	11.82	4.17
YS, MPa	682.8	709.3	710.4	(7)	0.78	22.9	9.37	
HB	244.0	252.4	258.0	(8)	0.98	11.7	75.00	
EL, %	23.5	22.2	21.9	(9)	0.89	3.0	8.47	
KV, J	155.3	153.0	150.4	(10)	0.98	10.7	464.48	

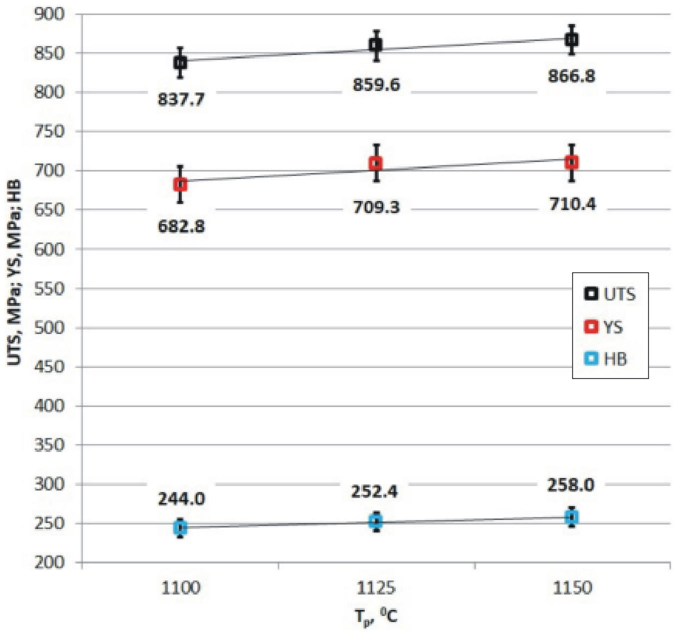

Fig. 2. Influence of hyperquenching temperature T_p on average tensile strength UTS, yield strength YS and hardness HB of duplex cast steel GX2CrNiMoCuN 25-6-3-3 grade

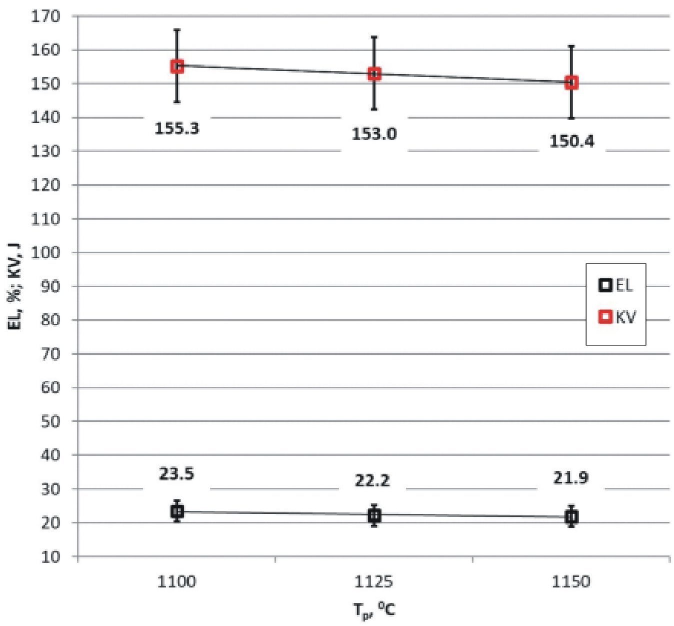

Fig. 3. Influence of hyperquenching temperature T_p on average elongation EL and impact energy KV of duplex cast steel GX2CrNiMoCuN 25-6-3-3 grade

10283 for GX2CrNiMoCuN 25-6-3-3 grade i.e. UTS ≥ 650 MPa, YS ≥ 480 MPa, KV ≥ 50 J, EL ≥ 22%. Moreover, it was concluded that described above the impact of holding temperature in hyperquenching process in point of view of its tendency is conforming with the results obtained in paper [18] which concerning the related problem. However in the reason of applied slightly different range of the main variable value in presented studies were obtained the typical linear course of mechanical properties changes in the function of the holding temperature, while in paper [18] shown nonlinear course with clear maximum of a function, particularly in the case of the influence of hyperquenching temperature on impact energy.

Whereas in Figs. 4-7, example microstructures of duplex cast steel GX2CrNiMoCu25-6-3-3 in as-cast state and after hyperquenching from the holding temperature 1100, 1125 and 1150°C are presented. In the as-cast state, the microstructure of studied cast steel contains δ ferrite, γ austenite and intermetallic phase FeCr marked as σ phase which is placed on δ/γ interfaces (Fig. 4, 5 and Tab. 4).

TABLE 4

The results of EDS analysis in points 1, 2 and 3 from Fig. 4b

No. of point from Fig. 4b	Element	Atomic concentration at. %	Weight concentration wt. %
1	Fe	65.7	66.2
	Cr	26.8	25.1
	Mo	3.2	5.5
	Ni	1.7	1.8
	Si	2.6	1.4
2	Fe	70.1	71.1
	Cr	22.9	21.7
	Ni	3.7	3.9
	Mo	1.3	2.3
	Si	2.0	1.0
3	Fe	50.8	50.9
	Cr	43.8	41.0
	Mo	4.4	7.6
	Si	1.0	0.5

This brittle s phase in the microstructure of studied duplex cast steel was eliminated in the result of hyperquenching regardless of the used holding temperature in this heat treatment process (Fig. 6).

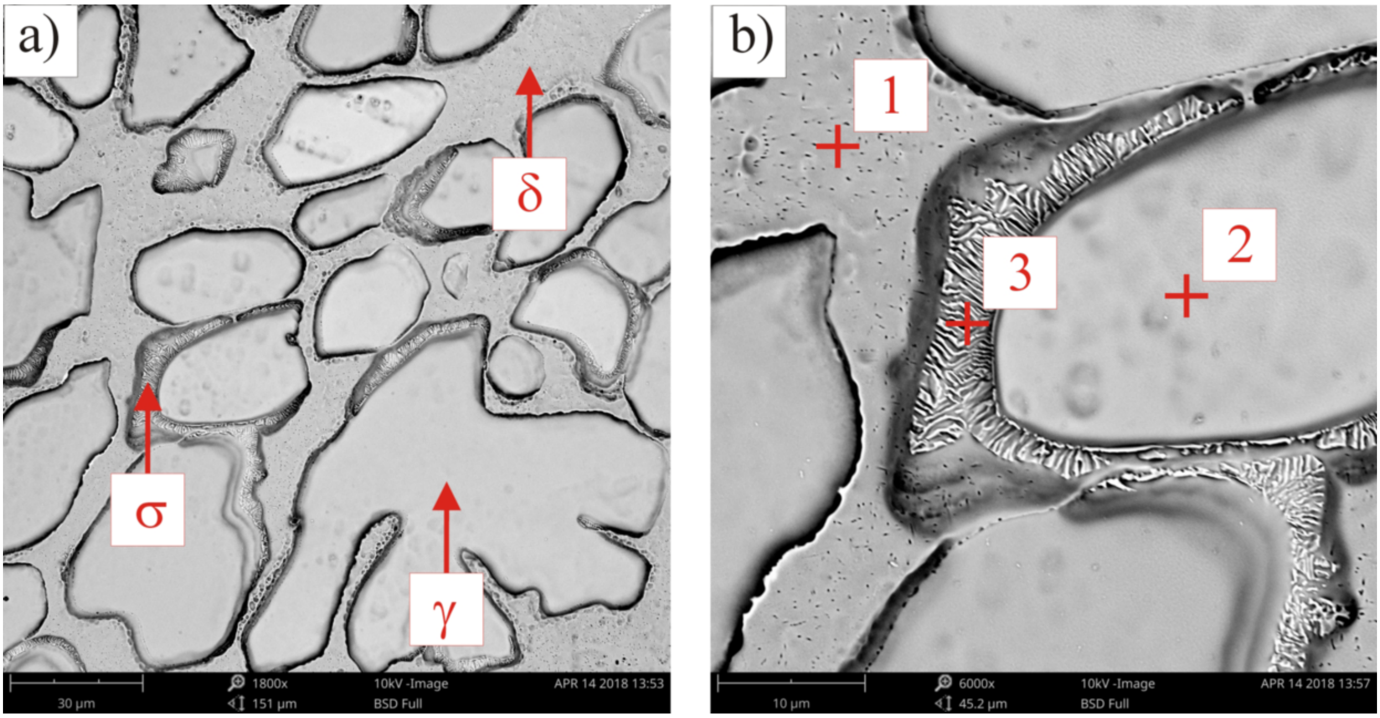

Fig. 4. Example microstructures of duplex cast steel GX2CrNiMoCu25-6-3-3 grade (melt no. 1) in as-cast state – δ ferrite, γ austenite and intermetallic σ phase: a) SEM, mag. 800×, b) SEM, mag. 6000×; 1,2 and 3 points of EDS analysis

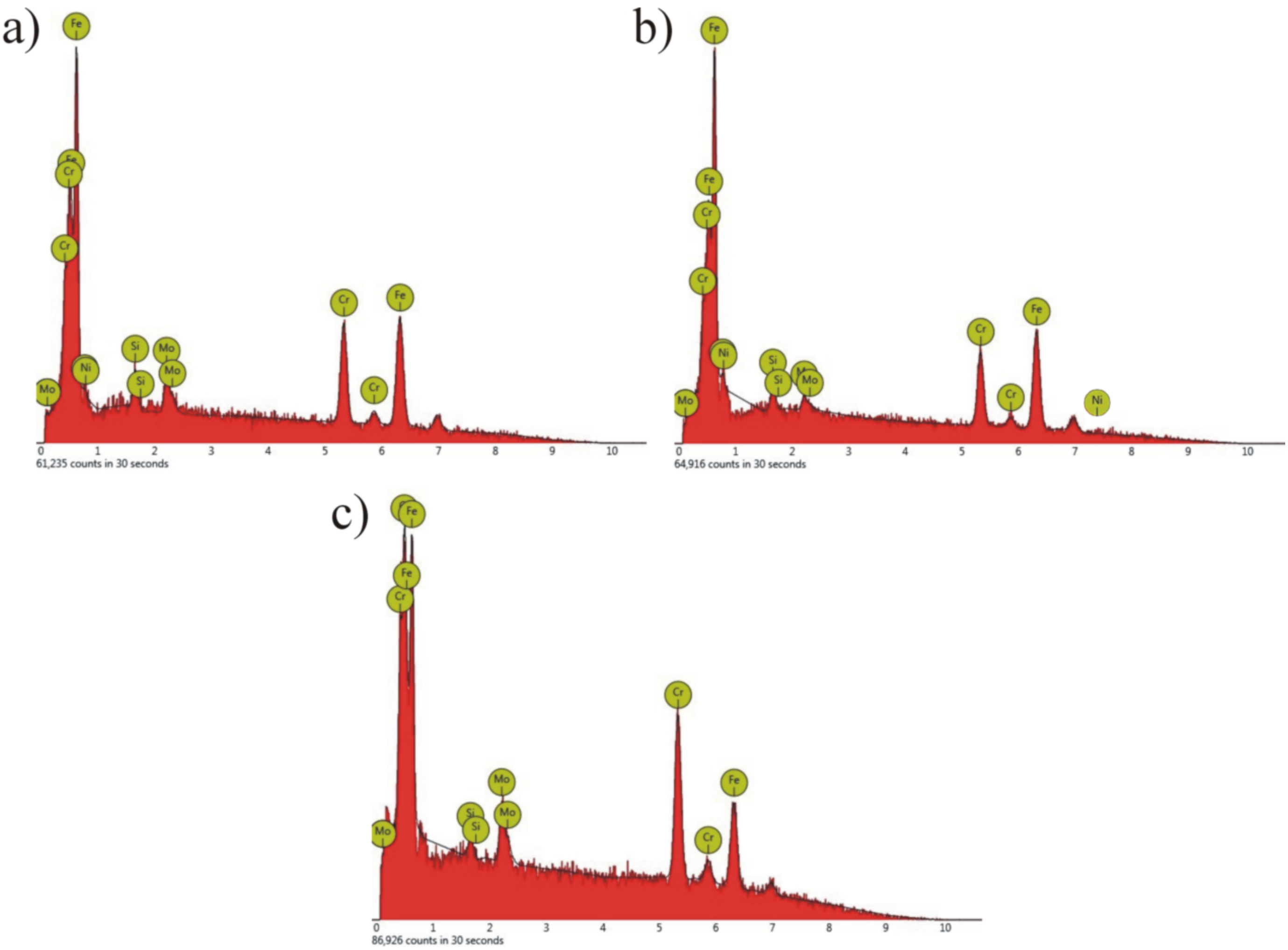

Fig. 5. The result of EDS analysis in: a) point 1 from Fig. 4b, b) point 2 from Fig. 4b and c) point 3 from Fig. 4b

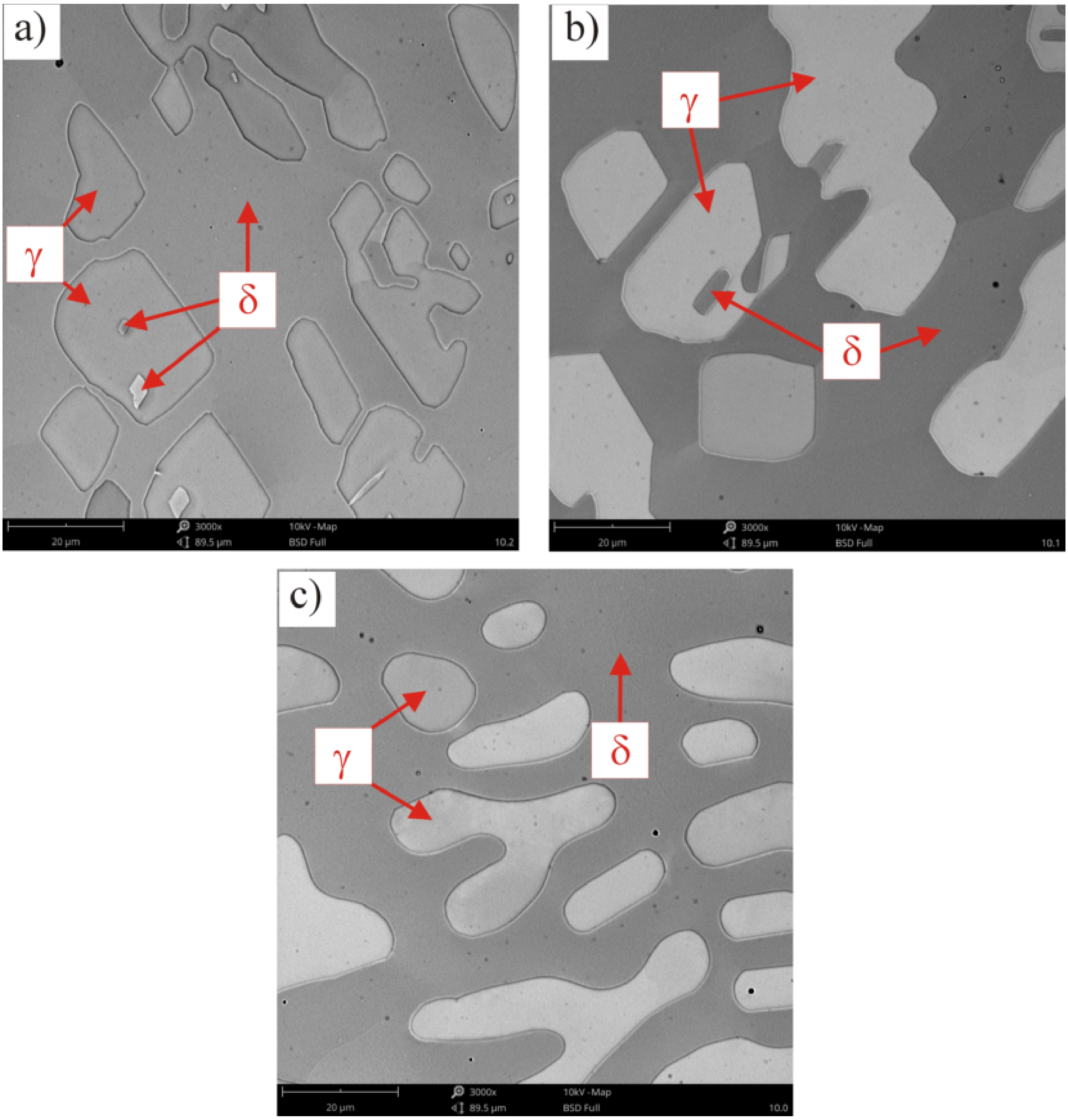

Fig. 6. Example microstructures of duplex cast steel GX2CrNiMoCu25-6-3-3 grade (melt no. 10) after hyperquenching from holding temperature: a) 1100, b) 1125 and c) 1150°C; SEM, mag. 3000×

Moreover was concluded that after heat treatment, a two-phase (δ + γ) microstructure was obtained for each holding temperature used. According to quantitative analysis with the decrease in holding temperature in hyperquenching process increases the amount of austenite with simultaneous decreases in the amount of ferrite is observed (Fig. 7 and 8). Presented influence of the holding temperature in hyperquenching process on the δ/γ ratio in the microstructure directly effects on the obtained mechanical properties of studied duplex cast steel, as shown above in Figures 2 and 3. Moreover, it was concluded that described above the impact of holding temperature in hyperquenching process on the δ/γ ratio in the microstructure of studied duplex cast steel is conforming with Eq. (3) which is presented in paper [7]. According to Eq. (3) together with increasing in hyperquenching temperature increases the amount of ferrite in the microstructure of duplex cast steel.

3. Conclusions

Based on conducted studies following conclusions have been formulated:

1. The heat treatment of type hyperquenching has a significant impact on the microstructure and mechanical properties of studied duplex cast steel.

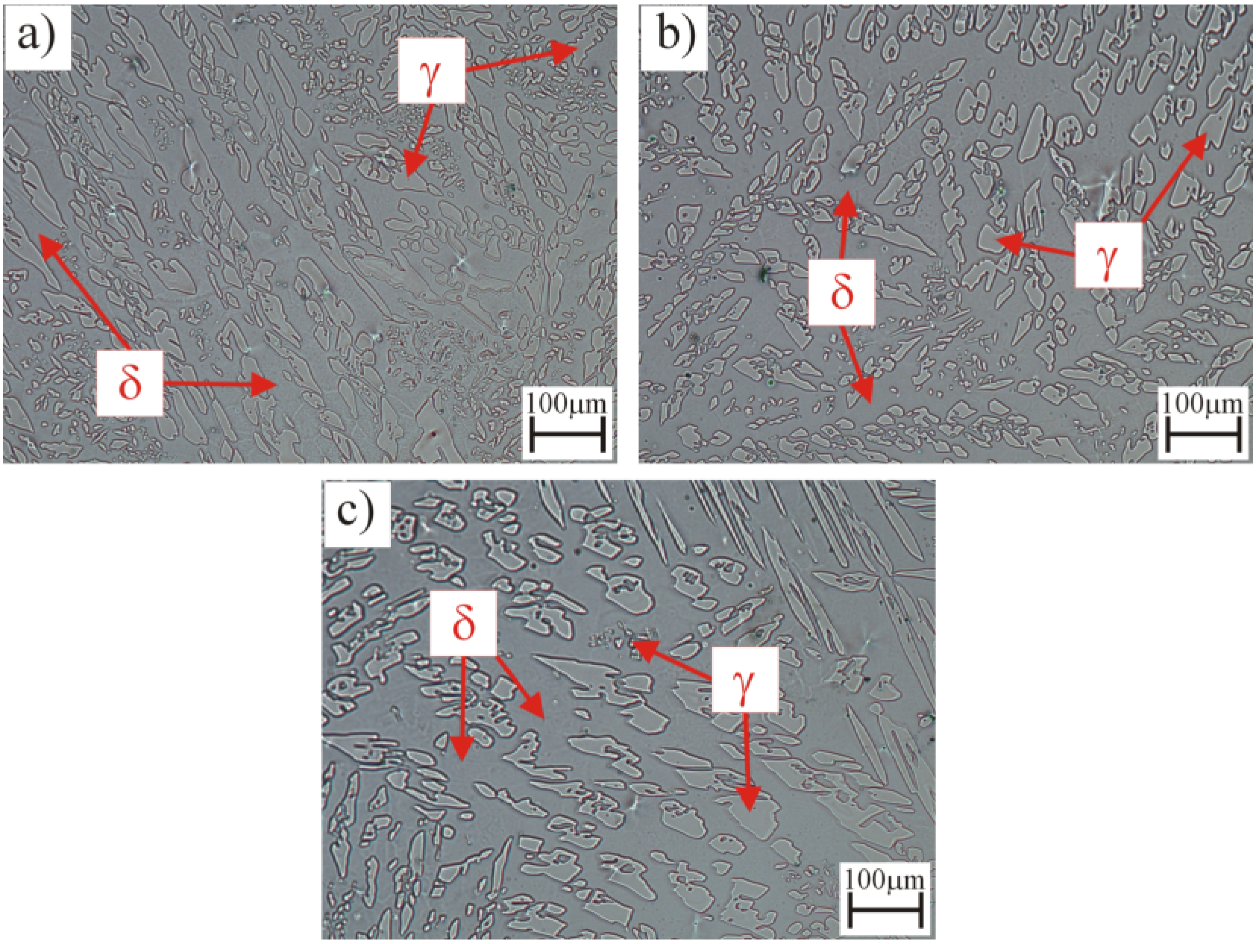

Fig. 7. Example microstructures of duplex cast steel GX2CrNiMoCu25-6-3-3 grade (melt no. 10) after hyperquenching from holding temperature: a) 1100, b) 1125 and c) 1150°C; OM, mag. 100×

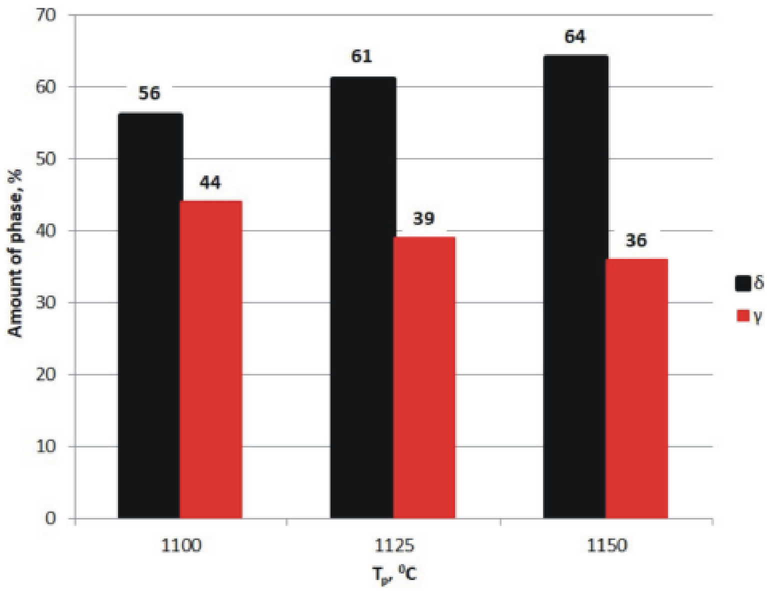

Fig. 8. Influence of hyperquenching temperature T_p on average amount of δ ferrite and γ austenite in microstructure of duplex cast steel GX-2CrNiMoCu25-6-3-3 grade

2. The holding temperature in the heat treatment of type hyperquenching is a parameter that allows effective shaping mechanical properties of duplex cast steel. Increasing the hyperquenching temperature causes increasing in strength and simultaneous decreasing in ductility of studied duplex cast steel GX2CrNiMoCuN 25-6-3-3 grade.

3. For economic reasons in case of GX2CrNiMoCu25-6-3-3 duplex cast steel the hyperquenching temperature equals 1100°C is most suitable, especially since it enables the highest impact strength to be obtained, which is very important for pump systems, not rarely operated under high pressure.
4. Elaborated statistical dependencies i.e. Eq. (6-10), describing the impact of the holding temperature in hyperquenching process on individual mechanical properties can be useful for optimization of heat treatment of duplex cast steel GX2CrNiMoCuN 25-6-3-3 grade.

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