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The influence of austenitization on grain size and mechanical properties of regenerative G21CrMoV4–6 cast steel

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ABSTRACT

Purpose: Influence of austenitiziation parameters (temperature and time) on grain size and mechanical properties of low alloy cast steel have been investigated.

Design/methodology/approach: The grain size of former austenite was determined by Image Pro Plus software and its distribution by STATISTICA software. The fractography was characterized using TEM. Moreover, mechanical properties (impact energy and hardness) have been measured.

Findings: What has been evaluated is the optimum range of austenitization temperatures making it possible to obtain fine austenite grain in the Cr–Mo–V cast steel. Received mechanical properties (after various austenitization parameters) revealed an advantage of tempered bainitic – ferritic structure over the ferritic – pearlitic one (after full- and under-annealing).

Practical implications: The established heat treatment parameters can be useful for preparation of regenerative heat treatment technology of Cr–Mo–V casts steels.

Originality/value: The relationship between the austenitization parameters, grain size and mechanical properties in G21CrMoV4–6 cast steel was specified.

Keywords: Metallic alloys; Mechanical properties; Quantitative metallography

PROPERTIES

1. Introduction

Long-term operation of steel casts under creeping conditions causes degradation of the structure through: privileged carbides' precipitation on grain boundaries, segregation of phosphorus to grain boundaries, as well as disintegration of pearlite areas or/and bainite areas.

Processes of structure degradation contribute to: decrease of impact energy often to the level of 4-6 J and increase of NDT temperature. Significant decrease of crack resistance is accompanied by slight decrease of mechanical properties - larger in the case of yield point than tensile strength [1-4].

Degradation of steel casts' structure does not exclude the possibility of their further safe operation. Extension of casts' operation time (expected time is up to 300 000 hours) is connected with the process of revitalization. Such a process consists in regenerative heat treatment whose task is to get "new", regenerated structure, which would enable impact energy increase above 27J, NDT temperature decrease and yield point growth [5, 6]. In order to obtain required mechanical properties, mostly impact energy, the following changes in the structure degraded by long-term service are necessary: grain size reduction, dissolving of carbides in austenite and elimination of brittleness of grain boundaries caused by phosphorus segregation [7, 8].

Regenerative heat treatment, applied in industry, consists in normalization/full-annealing of the steel casts with subsequent tempering/under-annealing. Ferritic – pearlitic structure, obtained through such a treatment, ensures required impact energy with mechanical properties similar to those after service [9].

Self study [9, 10] of the cast steels after long-term operation at elevated temperatures revealed that decrease of impact energy is the least in the case of cast steels with bainitic and bainitic – ferritic structure with around 5% ferrite content.

The aim of the work was to determine influence of austenitizing parameters (temperatures and times) on former austenite grain size and mechanical properties of G21CrMoV4 – 6 cast steel after regenerative heat treatment.

2. Material for research

Material for investigation was low – alloy G21CrMoV4 – 6 (G21) cast steel with chemical composition shown in Table 1. The material was taken from three-valve chamber serviced for over 160 000 hours at the temperature of 535 ^{o}C and pressure 2.05 MPa.

Table 1.
Chemical composition of the investigated cast steel, %wt.

C	Mn	Si	P	S	Cr	Mo	V
0.21	0.46	0.25	0.009	0.013	0.94	0.58	0.28

After operation the investigated cast steel revealed ferritic – pearlitic – bainitic structure. Prevailing phase in the structure was quasi-polygonal ferrite. Pearlite was precipitated mainly on ferrite grain boundaries. In pearlite and bainite full spheroidization of carbides could be observed. On grain boundaries there were some single, large precipitations noticed (Fig. 1). The size of ferrite and pearlite grain amounted to 31.2 - 44.2 μm, which corresponds to the size of 7/6 according to ASTM. After operation the cast steel was characterized by impact energy of 10J and hardness 160HV30.

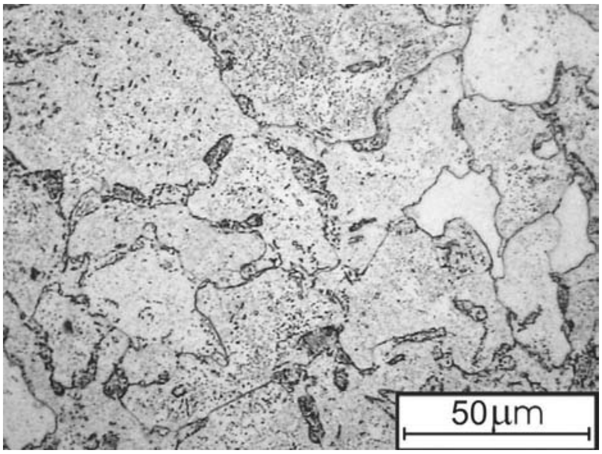

Fig. 1. Structure of the investigated cast steel after operation, nithal etched

3. Methodology of research

By means of optical dilatometer LS – 4 (according to [11]) critical temperatures A_{c1} and A_{c3} were determined and they amounted to 785 and 900 ^{o}C respectively.

Influence of austenitization parameters on former austenite grain size was estimated for the following range of temperatures: 910-970 ^{o}C with the „measurement step" – 15 ^{o}C. Assumed holding time at austenitization temperatures was: 3 and 5 hours. Record of the microstructures was carried out by means of Axiovert 25 optical microscope, while research of fractures was done by means of JOEL JSM – 5400 scanning microscope. Computer aided analysis of the image was performed by means of ImagePro Plus program, using 900 - 2000 former austenite grains for calculation.

Taking into account calculated resolving power of the microscope for applied magnifications, its quality and kind of investigated material, all grains with diameter below 2μm were rejected.

In order to determine the character of former austenite grain distribution [12] STATISTICA 8.0 program was used, as well as Kolmogorov test of goodness of fit with normal distribution λ, for logarithmed values. Assumed significance level was $\alpha = 0.01$. By means of chosen stereological parameters: mean diameter and mean surface area of the grain [13, 14], it was possible to describe grain sizes in quantitative way for the applied austenitizing parameters.

Heat treatment of G21 cast steel consisted in:

- full-annealing after 5-hour austenitizing at the temperature: 910 and 970 ^{o}C and subsequent 4-hour under-annealing at the temperature of 800 ^{o}C;
- bainitic hardening after 3- and 5-hour austenitizing at the temperature: 910, 940 and 970 ^{o}C and subsequent 4-hour tempering at the temperature of 720 ^{o}C.

Measurements of impact energy KV and hardness HV30 were taken in accordance with the norms.

4. Results of self study

4.1. Influence of austenitization parameters on the size of former austenite grain

For established logarithm-normal layouts of mean diameters and mean surface areas of former austenite grains, their parameters were calculated on the basis of formulas [13, 14]. Obtained values are presented in Tables 2 and 3.

Selected logarithm-normal layouts of mean diameters and mean surface areas of former austenite grains for austenitization option of 925 ^{o}C and holding time 3 hours, are shown in Fig. 2.

Relations of mean diameters and mean surface areas of former austenite grain to temperature and time of austenitization were described by means of matching curves and corresponding correlation equations – Figs. 3 and 4.

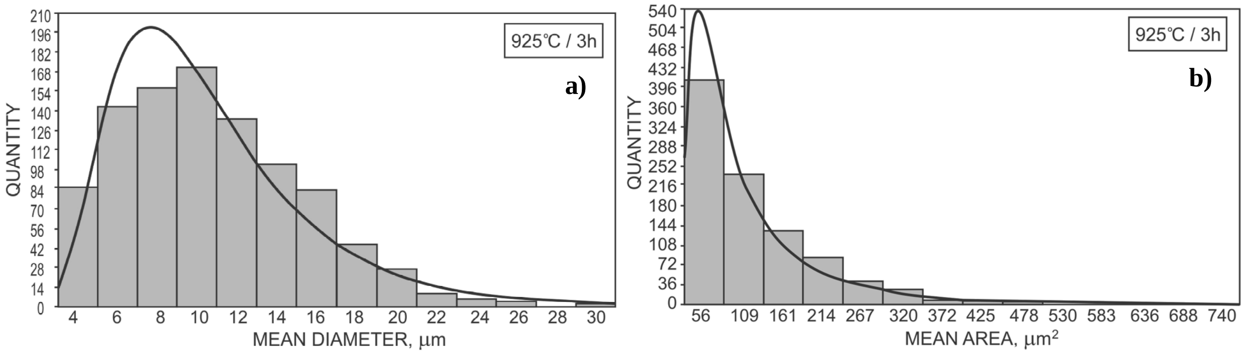

Fig. 2. Logarithm – normal layout of grains for : a) mean diameter; b) mean surface area

Table 2.
Results of measurements and calculations of mean diameters of former austenite grain

Heat treatment parameters, °C/h	Empirical amount, n	Min. diameter of the grain, µm	Max. diameter of the grain, µm	Mean diameter, µm	Standard deviation	$\frac{\lambda_{emp}}{\lambda_{\alpha=0.01}}$
910/3	976	2	29	11.34	6.36	0.945
925/3	969	2	30	9.84	5.34	0.834
940/3	954	2	31	10.16	6.22	0.957
955/3	964	2	38	14.08	9.34	0.834
970/3	2024	2	297	22.14	17.73	1.387
910/5	946	2	27	9.36	5.70	0.828
925/5	915	2	28	11.00	7.01	0.951
940/5	959	2	32	9.05	5.41	0.816
955/5	937	2	39	12.02	8.37	0.724
970/5	2034	2	324	23.67	18,31	0.877

Table 3.
Results of measurements and calculations of mean surface areas of former austenite grain

Heat treatment parameters, °C/h	Empirical amount, n	Surface area of min. grain μm^2	Surface area of max. grain, μm^2	Mean surface area, μm^2	Standard deviation	$\frac{\lambda_{emp}}{\lambda_{\alpha=0.01}}$
910/3	976	4	695	142.67	204.58	1.067
925/3	969	3	741	104.27	173.60	0.779
940/3	954	3	810	121.34	172.77	0.859
955/3	964	3	1302	187.41	379.31	0.975
970/3	2024	3	95722	812.62	2138.56	1.221
910/5	946	3	608	101.07	162.93	0.656
925/5	915	2	741	144.72	248.95	0.988
940/5	959	3	842	94.03	147.10	0.613
955/5	937	2	1533	391.66	423.09	0.601
970/5	2034	3	102305	915.33	2408.43	0.939

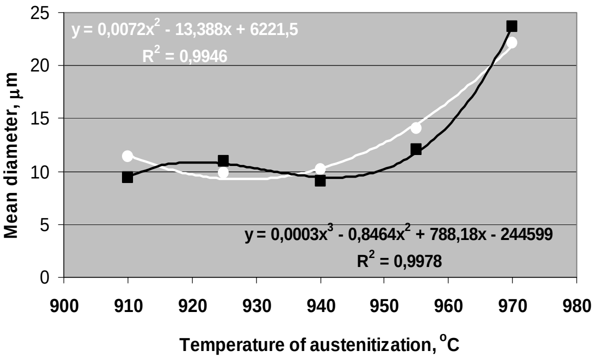

Fig. 3. Influence of austenitization temperature on mean grain diameter depending on the holding time (3 hrs – white, 5 hrs – black)

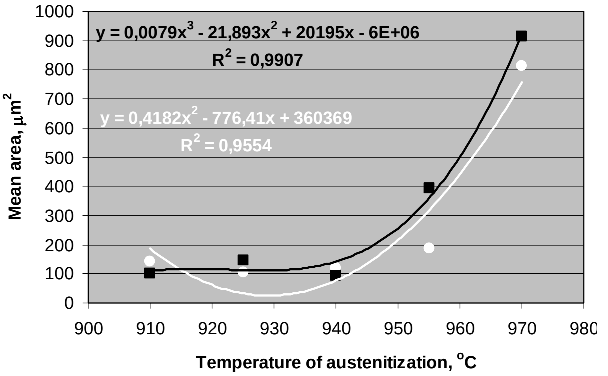

Fig. 4. Influence of austenitization temperature on mean surface area depending on the holding time (3 hrs – white, 5 hrs – black)

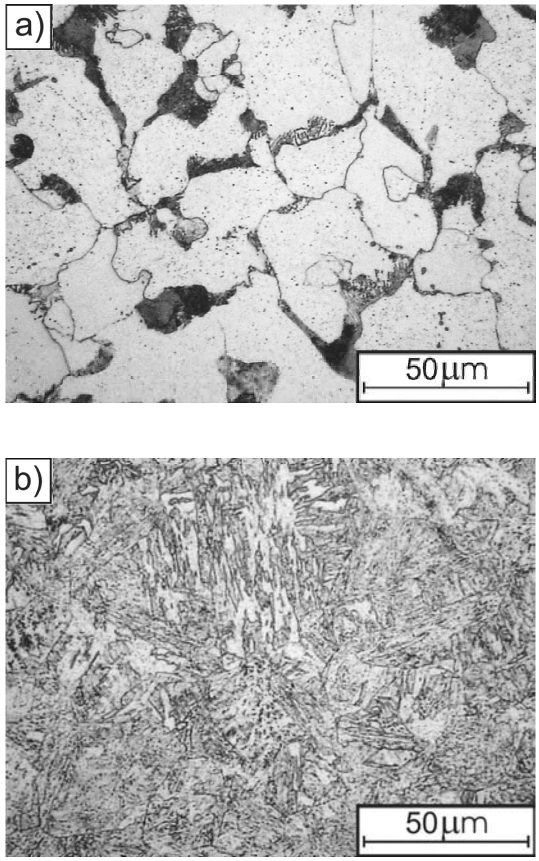

Fig. 5. Structure of G21 cast steel after: a) full-annealing and under-annealing; b) bainitic hardening and tempering; nithal etching

4.2. Structure of G21 cast steel after heat treatment

Structures of G21 cast steel after heat treatment are presented in Fig. 5. Fig 5a illustrates structure of the investigated cast steel after full-annealing (holding time at the austenitizing temperature of 970 °C - 5 hours) and under-annealing at the temperature of 800 °C, while Fig. 5b – after bainitic hardening (holding time at the austenitizing temperature of 970 °C - 5 hours) and tempering at the temperature of 720 °C.

4.3. Mechanical properties

Influence of heat treatment parameters on mechanical properties (impact energy and hardness) of the investigated cast steel with ferritic – pearlitic and bainitic – ferritic structure are presented in Table 4.

Influence of austenitizing parameters on mechanical properties of the cast steel with bainitic – ferritic structure are shown in Fig. 6.

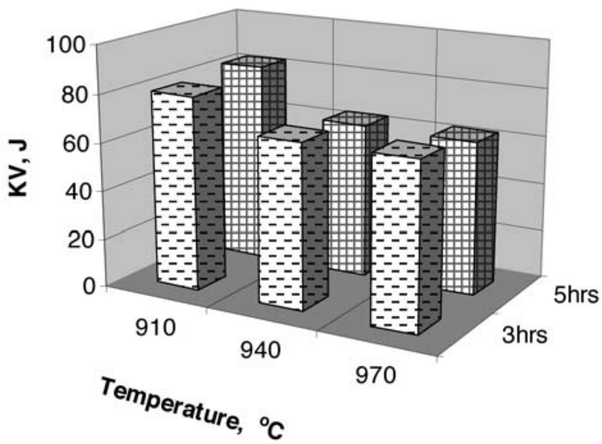

Fig. 6. Influence of temperature and austenitizing time on impact energy of the cast steel with bainitic – ferritic structure after tempering at the temperature of 720 °C

Table 4.
Influence of heat treatment parameters on mechanical properties of G21CrMoV4 – 6 cast steel with ferritic – pearlitic and bainitic structure

Temp. °C	Time, hrs	Ferritic – perlitic structure		Bainitic structure	
		KV J	HV30	KV J	HV30
910	3	---	---	80	231
	5	45	148	83	223
940	3	---	---	68	229
	5	---	---	64	224
970	3	---	---	68	225
	5	28	151	63	221

4.4. Fractography of fractures

Fractography of the investigated cast steel with: ferritic – pearlitic and bainitic – ferritic structure, is illustrated in Fig. 7.

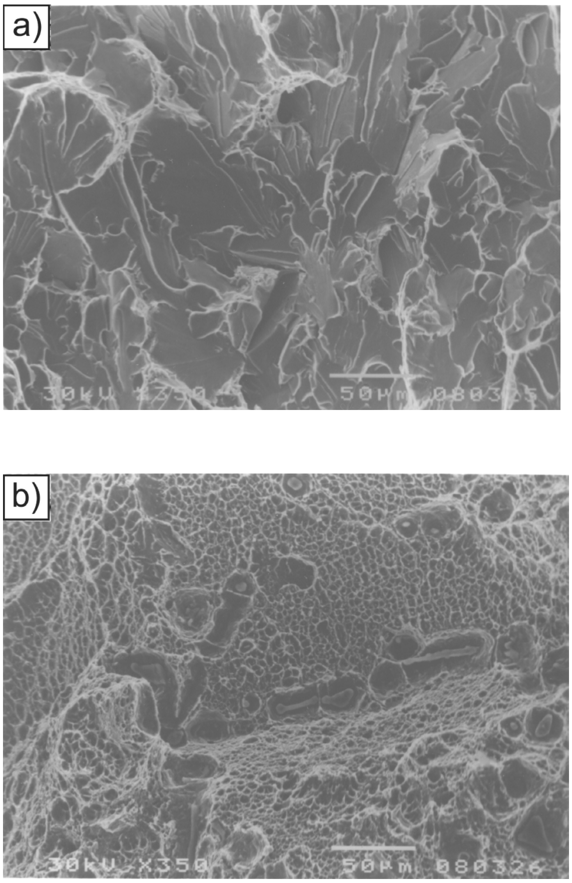

Fig. 7. Fractography of the cast steel with: a) ferritic – pearlitic structure; b) bainitic – ferritic structure

5. Analysis of the research results

Mean grain diameters and their mean surface areas change continuously and reveal logarithm-normal layouts on the significance level of $\alpha = 0.01$ ($\lambda_{emp.} / \lambda_{0.01} < 1$). The exceptions are the following treatment options: austenitization temperature of 910 °C and time 3hrs for the mean surface area (fulfilled for lower significance level: $\alpha = 0.001$), and temp. 970 °C, time 3hrs for mean diameter as well as for the mean surface area of former austenite grain (Tables 2 and 3). Within the range of austenitization temperatures: 910 - 940 °C for holding times: 3 and 5 hrs, mean diameters and mean surface areas of former austenite grain do not reveal any considerable differences. At the temperature of 970 °C, the largest grain growth could be observed (Tables 2 and 3; Figs. 3 and 4).

The result of full-annealing and under-annealing was ferritic-pearlitic structure obtained in the investigated cast steel, with irregular arrangement of ferrite and pearlite (so-called "flanged" structure). Prevailing phase in the structure of investigated cast steel, similar as in the case of long-term serviced cast steel, was quasi-polygonal ferrite with numerous fine precipitations of carbides inside the grains. Pearlite was arranged mainly on ferrite grain boundaries (Fig. 5a). Applying under-annealing instead of tempering in the case of G21 cast steel results from the need to obtain required impact energy, which tempering could not always guarantee [15]. In the investigated G21 cast steel after bainitic hardening, obtained structure was bainitic – ferritic with about 5% of ferrite content. Tempering at 720 °C caused precipitation of carbides on former austenite grain boundaries as well as inside bainite laths (Fig. 5b). The structure of high-temperature tempered bainite, as proven by the research [16], guarantees optimum combination of mechanical properties and impact energy. Detailed description of the influence of regenerative heat treatment on the structure and properties of G21 cast steel are presented in the works [15-17].

Cast steel with ferritic – pearlitic structure after austenitization at temp. of 910 °C (and under-annealing) was characterized by impact energy of 45 J, however, after austenitization at 970 °C the impact energy decreased by around 40% to the level of 28 J (Table 4). Crack resistance of the cast steel with tempered bainitic – ferritic structure (at the austenitizing temperature of 910 °C) amounted to ca. 80 J. Bainitic hardening from higher austenitizing temperatures, such as: 940 and 970 °C (and tempering) caused decrease of impact energy by about 20% to the level of 63-68 J. Holding time at the austenitizing temperature did not have any significant influence on impact energy (Fig. 6, Table 4). Hardness HV30 of the investigated cast steel for all given structures was comparable, regardless of the temperatures and times of austenitizing (Table 4).

Irrespective of the austenitization temperature, the tempered bainitic – ferritic structure ensures higher crack resistance in comparison with ferritic – pearlitic structure. Cast steel with ferritic – pearlitic structure, in spite of applying under-annealing, was characterized by larger decrease of impact energy (along with the growth of austenitizing temperature) in comparison to the cast steel with bainitic – ferritic structure.

Differences in impact energy of the cast steel after heat treatment were confirmed in their decohesion mechanism. Cast steel with ferritic – pearlitic structure was subject to decohesion through brittle – transcrystalline fissile mechanism with micro-fields of ductile type. On the fracture there were also numerous secondary cracks observed, the so-called "in-depth" cracks (Fig. 7a). The cast steel with bainitic – ferritic structure was subject to cracking through mixed mechanism (Fig. 7b). On the fractures there were three cracking mechanisms noticeable:

- transcrystalline ductile, initiated by fine precipitations of carbides and inclusions of sulfides;
- intercrystalline ductile – initiated by: II-type sulfides (which during heat treatment were subjected to dissolving and then secondary precipitation during cooling, in the form of fine sulfide „colonies"); large primary sulfides and sulfide eutectic,precipitated mainly on former austenite grain boundaries;
- transcrystalline fissile, connected with the occurrence of ferrite in the structure.

6. Conclusions

- It has been concluded that for the range of austenitization temperatures: 910 - 940 ^{o}C and holding times: 3 and 5 hours, sizes of former austenite grain do not reveal any significant differences.
- Optimum range of austenitization temperatures for the investigated G21CrMoV4–6 cast steel amounts to: A_{c3} + 10 - 40 ^{o}C.
- Regardless of the austenitization temperature, the tempered bainitic – ferritic structure ensures higher crack resistance in comparison with the ferritic – pearlitic structure.
- Holding time at a given temperature of austenitizing did not have any considerable influence on impact energy.
- Hardness HV30 of the investigated cast steel for the particular structure cases was comparable, irrespective of the temperatures and times of austenitizing.

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