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The change of solidification mechanism of ferritic-austenitic cast steel

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ABSTRACT

Purpose: The paper presents the results of research on the microstructure changes of two grade of duplex cast steels with a varying carbon, with and without addition of copper.

Design/methodology/approach: The addition of copper have a significant effect on the microstructure of analyzed cast steels. The changes in the mechanism of solidification was also observed during numerical simulation made in the FactSage softwares.

Findings: The cause for undertaking the research were technological problems with hot cracking in bulk castings of duplex cast steel with a carbon content of approx. 0.06%.

Practical implications: The research has shown a significant effect of increased carbon content on the ferrite and austenite microstructure morphology, while exceeding the carbon content of 0.06% results in a change of the shape of primary grains from equiaxial to columnar.

Originality/value: Among the steel and cast steel resistant to corrosion most modern and dynamically developing group are ferritic-austenitic alloys, commonly known as duplex. Higher than austenitic steels, mechanical properties and good corrosion resistance in both overall and pitting make duplex steels irreplaceable material in the petrochemical industry, power, pulp and paper, food.

Keywords: Duplex cast steel; Microstructure; Primary structure; Numerical solidification simulation

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MATERIALS

1. Introduction

Cast steels, similarly as other multi-component metal alloys, have got a dendritic structure after solidification. The primary and secondary dendrite axes form in the initial grain solidification phase, and the further solidification only involves the thickening of the secondary arms. Due to alloy additions and admixtures occurring in steel, which have distribution coefficients, the ratio of solid phase concentration to liquid phase concentration, of $k < 1$, as the dendrite arms get thicker, the element concentrations increase the more rapidly, the lower the distribution coefficient values are. In the final solidification phase, the residual liquid phase solidifies between the dendrite arms and between the adjacent grains. If the concentration of elements and admixtures in the residual liquid phase reaches a saturation state, carbides, nitrides and sulphides will separate from it in the form of eutectics. They can also alter the solidification mechanisms, which in the view of the authors of [1-4] takes places in corrosion-resistant ferritic-austenitic steels. Due to the inability to feed the solidifying contraction, shrinkage micro-pores form in the residual liquid phase. The distribution of micro-segregation in grains is determined by the distances between secondary dendrite arms. On a logarithmic scale, a linear relationship between the solidification rate and/or the local solidification time and the magnitude of secondary dendrite inter-arm [5,6] distance is confirmed in metals and their alloys. This relationship can be used:

- in cast steels, for determining the optimal duration of homogenizing treatment, whose main purpose is to reduce the dendritic segregation for obtaining a uniform structure in heat treatment operations to provide the optimal mechanical properties. The smaller secondary dendrite inter-arm distances, the shorter the necessary treatment duration, because the paths of diffusion of elements for equalizing the chemical composition are shorter;
- the proper arrangement of chills and riser heads to ensure the optimal process of solidification of complex shaped castings.

An example of material, whose scale of difficulty has prevented the production of elements irreplaceable in power engineering wet combustion gas desulfurization systems from starting up in Poland, is the ferritic-austenitic (F-A) cast steel, known also as the duplex cast steel. A recent declaration by Poland's major foundry to undertake the production of duplex cast steel justifies the continuation of this research problem. Previous research [7-11] has shown a negative influence of the increased carbon content and the presence of copper on the increased tendency to cracking, especially for bulk, slow-cooling castings. The present paper has focused on disclosing differences in the microstructure resulting from the variable carbon content. In the researches were also taken to account the influence of copper, especially in conjunction with higher carbon content, on the solidification of analyzed materials.

2. Research material and methodology

The subject of the research was cast steel in the GX2CrNiMoCuN25-6-3-3 and GX2CrNiMoCuN25-6-3 grades according to PN-EN 10283:2010, with a varying carbon content with and without addition of copper. The research material were specimens used in thermal-derivative analysis (TDA) and a bulk (approx. 1500 kg) casting of GX2CrNiMoCuN25-6-3-3 cast steel with a carbon content higher, however, than required by the standard. Chemical composition of the cast steel is summarized in Table 1.

Table 1.
Chemical composition of the examined cast steel grades

No.	C, %	Cr, %	Ni, %	Cu, %	Mo, %	Mn, %	Si, %	S, %	P, %	N, %	Potting Temperature, °C
1	0.025	26.80	6.48	0.03	3.00	1.19	1.04	0.011	0.008	0.25	1547
2	0.060	26.32	6.93	0.03	3.08	0.98	0.99	0.010	0.008	0.27	1550
3	0.10	25.99	6.58	0.03	3.15	0.94	0.99	0.010	0.008	0.26	
4	0.024	25.62	6.52	2.55	2.98	0.97	0.86	0.010	0.008	0.25	1536
5	0.063	25.44	6.49	2.69	3.12	0.81	0.81	0.010	0.007	0.24	1556
6	0.10	25.18	6.50	2.62	3.11	0.84	0.79	0.009	0.007	0.24	1529
cast	0.0613	23.38	8.58	2.41	2.94	0.063	1.07	0.0331	0.0262	0.064	

The presented results comprise metallographic examinations performed on microsections obtained from specimens cut along the diameter. The microstructural analysis was made using Olympus GX-41 and Nikon Eclipse MA-200 optical microscopes, while the fractographic examination was performed with an Olympus SZ-61 microscope. Very similar pouring temperatures, identical cooling conditions and the fixed location of the area of performing microstructural examinations provided a basis for determining the differences in the solidification pattern. The basic variable is the carbon content and, within the grades, the addition of copper, whose presence allows the service properties to be enhanced by means of ageing. The primary structure, both on the microsections and on the fracture, was revealed with the Oberhoffer reagent (2 hrs. at a temperature of 55°C), while the microstructure with the Mi21Fe reagent (30 g potassium ferricyanide, 30 g potassium hydroxide and 60 g distilled water). The numerical simulation of solidification for different chemical composition were made using FactSage software programs. The software use the Scheil'a model during calculation.

3. Results and discussion

The bulk casting of approx. 1500 kg made from the GX2CrNiMoCuN25-6-3-3 cast steel have a carbon content higher, than required by the standard. Figure 1 shows a fracture of a bulk F-A cast steel casting cracked during production, with the composition from Table 1. This typical hot cracking mode of bulk F-A cast steel castings was the cause of problems and the abandonment of their production in the domestic cast steel foundry. Considerable exceeding of the carbon content compared to the GX2CrNiMoCuN25-6-3-3 is noticeable; however, many standards contain grades with a carbon content of up to 0.08% (e.g. 2A acc. to AISI A995/995M-09). In the fracture of a bulk F-A cast steel casting are very well shown two type of solidification grain morphology, large columnar and smaller equiaxial (Fig. 1).

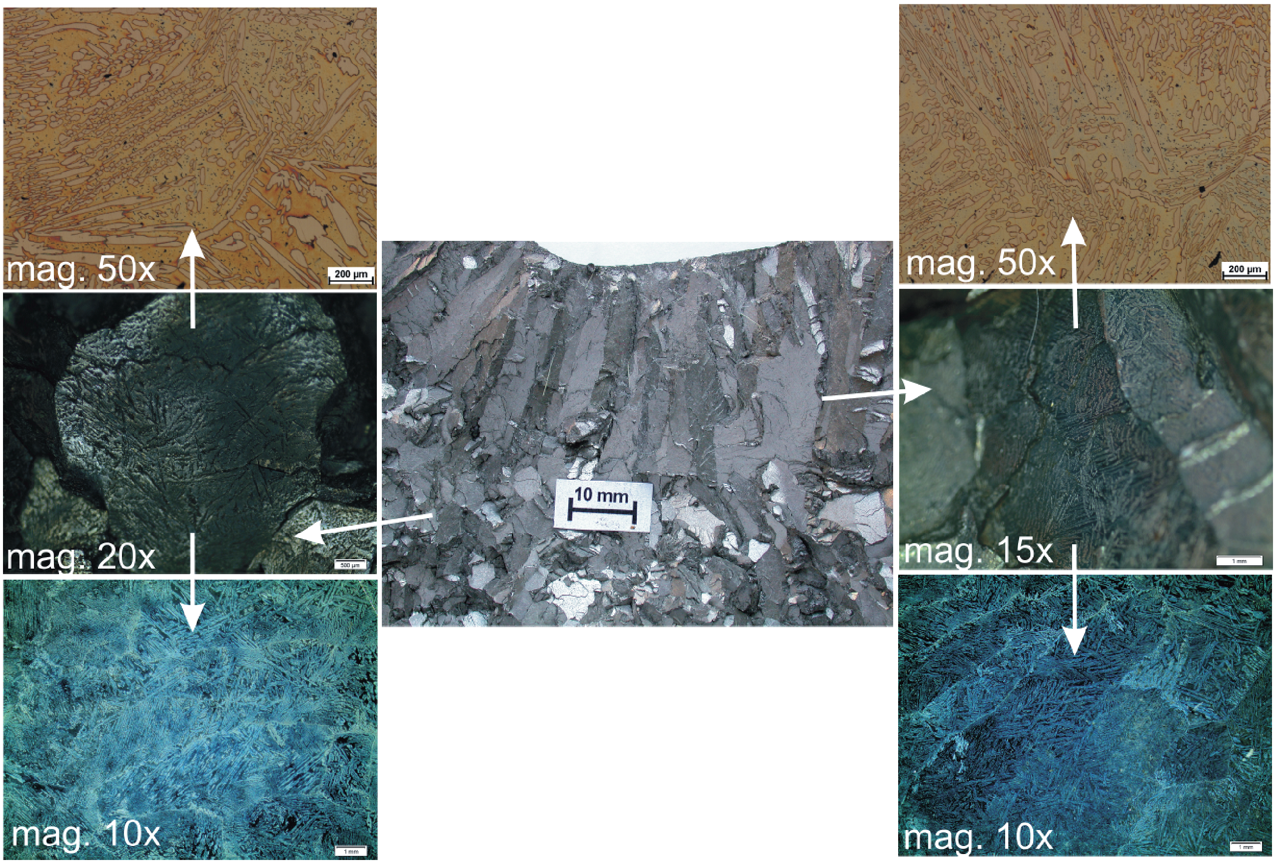

Fig. 1. A fragment of a cracked bulk casting with enlarged columnar crystal zone regions and a primary structure revealed with the Oberhoffer reagent and microstructure etched with Mi21Fe reagent

Very well shown large columnar solidification grains are conspicuous, whose interior has a dendritic structure. The dendritic structure are well presented on both fracture and microstructure revealed with the Oberhoffer reagent. In the microstructure etched with Mi21Fe reagent (Fig. 1) is very well visible change of morphology in different parts of cast. The presence of such differences in solidification grain morphology justifies the undertaking of this problem. To understand what cause such situation were made numerical simulation with use of FactSage software programs and physical tests with use of the TDA specimens of variable carbon and copper contents. The Figures 2 and 3 present results of numerical simulations with the line is marked the GX2CrNiMoCuN25-6-3-3 and GX2CrNiMoCuN25-6-3 chemical composition according to PN-EN 10283:2010 standard. The TDA tests gave the possibility to determine the influence of chemical composition on the microstructure of examined casts steels. As it is presented in Table 1 the potting temperature of all samples are very similar to avoid any influence of initial parameters.

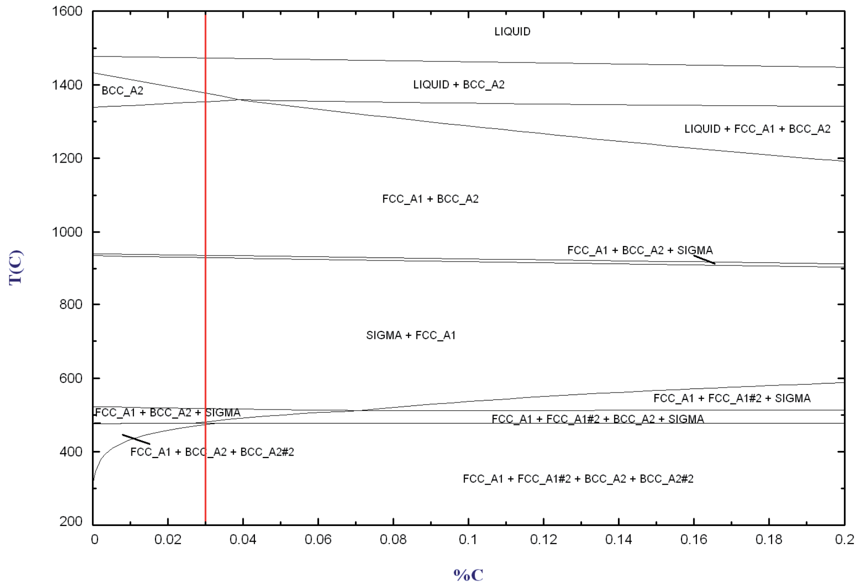

Fig. 2. Results of FactSage software numerical simulation for the GX2CrNiMoCuN25-6-3 with different carbon content

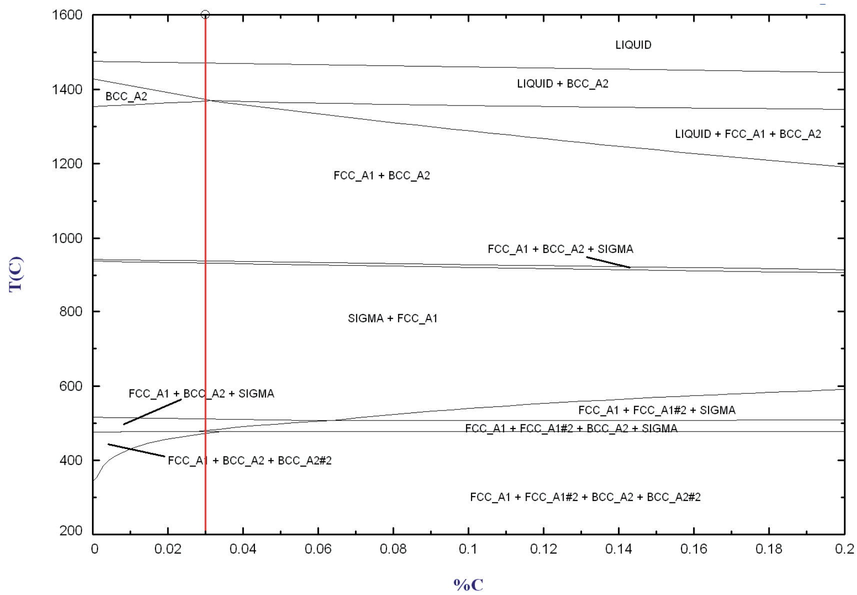

Fig. 3. Results of FactSage software numerical simulation for the GX2CrNiMoCuN25-6-3-3 with different carbon content

Figure 4 (a-f) shows the microstructures of cast steel with variable C and Cu contents. A very strong influence, especially of carbon, on the ferrite and austenite morphology is noticeable. Even with the lowest carbon contents, austenite (the lighter phase) occurs at part of the grain boundaries, with characteristic fragments of dendrite arms. This is indicative of the possibility of this phase separating already during solidification, and not only as a result of the solid-state transition. The amount of thus crystallized phase increases with increasing carbon content.

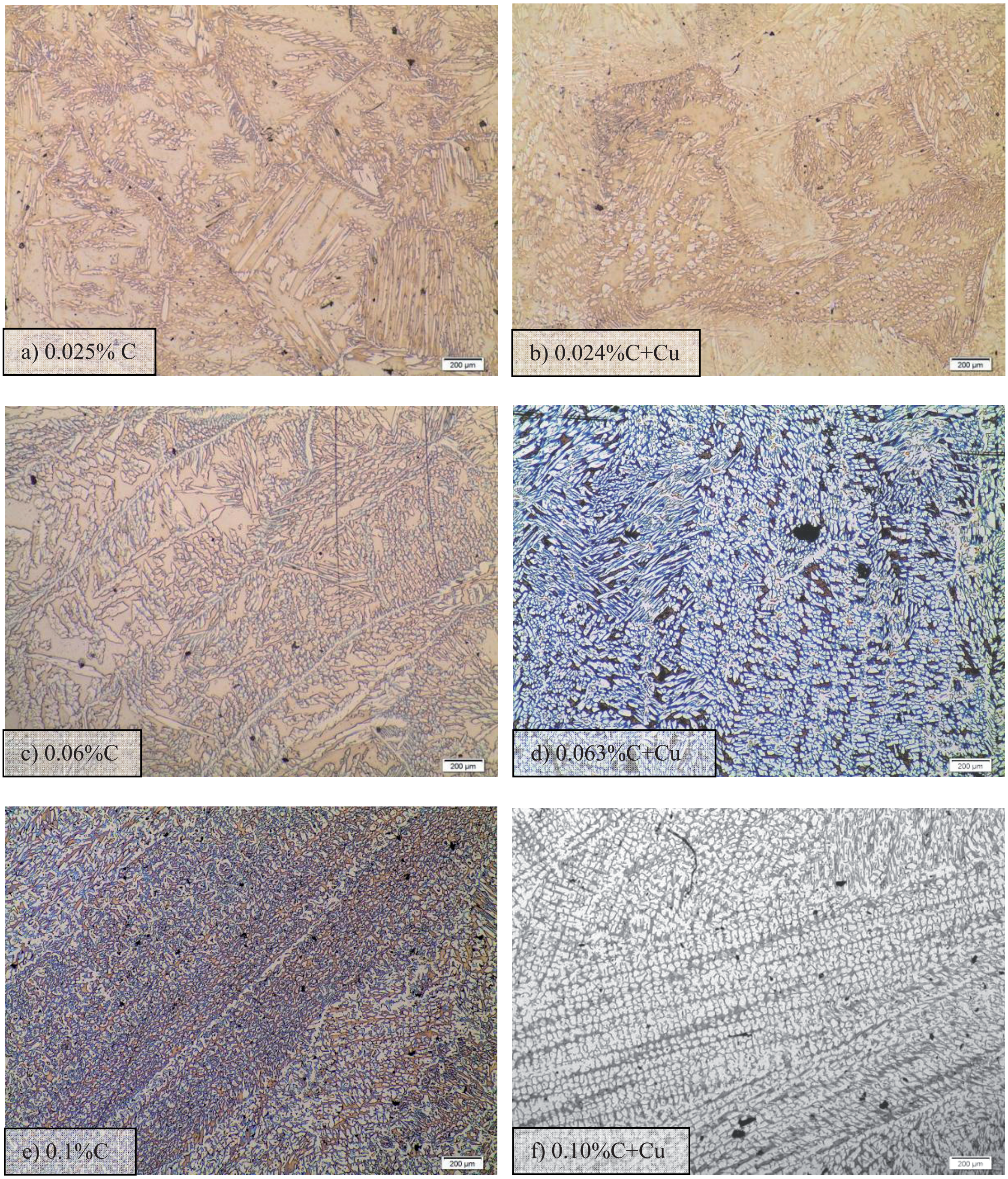

Fig. 4. The microstructure of GX2CrNiMoCuN25-6-3-3 and GX2CrNiMoCuN25-6-3 with varying carbon content

The analysis of the microstructure of TDA specimens with variable carbon and copper contents has shown that the increase of carbon content from approx. 0.06% results in a change of the primary grain shape, as a result of which equiaxial crystals with dendrites along the boundaries are substituted with columnar crystals. The addition of copper to the examined castings containing about 0.06 and 0.1% carbon has a grain refining effect. With a carbon content of about 0.1%C, cast steel both with and without copper, regardless of the apparent grain refining, is characterized by a structure composed of very long columnar dendrites. Similar regions were observed both in the microstructure and on the fracture of the rejected, cracked casting in Figure 1. The primary structure revealed with the Oberhoffer reagent is largely consistent with that observed on the TDA specimens. The possibility of the occurrence of a change in the solidification mechanism from the ferritic to the mixed type – with the peritectic reaction in its final phase for cast steel without copper and with a carbon content above 0.04% and above approx. 0.035% with a 3% copper addition – has been confirmed by the results of numerical analyses using the FactSage software programs, which are presented in Figures 3 and 4.

4. Summary

The research has demonstrated a significant effect of the increase of carbon content on the morphology of ferrite and austenite in castings of duplex cast steel. In TDA specimens cooling down at a rate of approx. 2º/s in the solidification temperature range, a change both in the grain shape and in the shape of the dendritic structure has been found. Increasing carbon content is accompanied by an increased tendency to forming columnar grains, with long dendrites of both phases. The shape of part of the austenite indicates that it has formed in the peritectic solidification reaction rather than in the solid-state transition. The changes in the solidification mechanism have also been corroborated by the results of numerical computations. This fact is quite obvious, because during ferritic solidification, which predominates in the duplex cast steel, an enrichment of the solidification end liquid with austenite-forming elements (Ni, C, N, Cu) takes place, which reduces the solidification end temperature and may result in the peritectic reaction. Exceeding a carbon content of approx. 0.06% C causes a change in the primary grain shape from equiaxial to columnar. Whereas in the microstructure of TDA specimens of a carbon content of approx. 0.06% and without Cu both columnar and equiaxial crystal can be observed (in the central part of the specimen), for the variant with an approx. 3% copper addition (specimen no. 5) only columnar crystals occur within the entire volume. The presence of both columnar and equiaxial crystals in the fast cooling-down casting (at a cooling rate of approx. 2°/s) is reflected in the structure of the copper-containing bulk casting.

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