# The analysis of solidification process of ferritic-austenitic cast steel

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## Abstract

One of the most common defects leading to the rejection of faulty castings made of duplex cast steel is hot cracking. Hot cracking – differently from cold cracking which occur on cooling, when the material exhibits already distinct elastic properties – proceeds in the semi-solid state, particularly when the temperature of solidifying casting is close to the equilibrium solidus point. There exist a range of temperatures in the vicinity of the solidus point within which the solidifying metal shows very small deformation ability and small strength. Therefore even little stresses occurring at the solidification stage and caused by density difference between ferrite and austenite, or restricted shrinkage, or various temperature gradients, can be the reason of hot cracking. Copper addition, as it is used in cast steel grades implemented in Polish power industry applications, decreases the temperature of the end of solidification, thus affecting beneficially the surface reproduction quality, but on the other hand it can promote, along with several other elements contained in duplex cast steel, the peritectic transformation during the last stage of solidification. The presence of peritectic solidification, i.e. strictly speaking the structural stresses accompanying that process, is the well-known and significant reason of the increased steel defectiveness in the continuous steel casting (CSC) technology if the steel with carbon content promoting the peritectic transformation is processed.

The authors have presented the examination results of the solidification phenomenon for two duplex cast steel grades – one without copper addition, and the other with addition of about 3.0% Cu.

**Keywords:** Innovative foundry materials and technologies; Duplex cast steel; Solidification; Segregation; DDTA

## 1. Introduction

Castings made of duplex cast steel with copper addition are used in Polish national power industry due to their increased corrosion-erosion resistance, higher than this of the cast steel without copper addition [1,2]. Therefore an attempts of making massive castings of GX2CrNiMoCuN25-6-3-3 grade cast steel have been undertaken in Poland.

The possibility of increasing the hardness of the copper-containing alloy by ageing has made it reasonable to choose cast steels with copper addition for castings working under corrosive-erosive conditions, such as elements of pump casing, impellers, connector pipes, guide vanes, etc [3]. But the quantity of defected castings (due to hot cracking) and the difficulty with the copper-containing scrap management at piece production have resulted in the fact that Polish power industry still uses imported elements [4].

It seems that one of the factors promoting hot cracking of the duplex cast steel castings is the possibility of occurring of the peritectic transformation during the last stage of solidification, proceeding in fact under the non-equilibrium conditions. The negative influence of the effects of the peritectic transformation during the solidification of carbon steels, particularly those cast with use of the CSC technology, is well-known and results in the increased quantity of defects [5-9]. The verification – based on the analysis of the duplex type cast steel solidification – if it is reasonable to speak about a peritectic transformation in relation to GX2CrNiMoCuN25-6-3-3 cast steel has been recognized as important. Chemical compositions of ferritic-austenitic cast steel grades given by the PN-EN 10283:2004 Standard provide for ferritic solidification. It is confirmed by the data calculated according the formulae shown in Table 1 [10].

It should be stressed that in ferritic-austenitic cast steel there occur as many as five elements (Ni, Cu, N, Mn, and C) able to enter the peritectic reaction with iron during the solidification of the alloy. It seems that the synergetic effect of their interaction with respect to this reaction can be expected. The authors do not

know the extent of the phenomenon of hot cracking for duplex cast steel castings not containing copper. The examined massive castings have been made exclusively of the cast steel with about 3% copper addition [11-13].

The work undertakes a trial of assessment of the solidification process for duplex type cast steel which deals with two grades: GX2CrNiMoN25-6-3 and the alloy with copper addition i.e. GX2CrNiMoCuN25-6-3-3.

Table 1. The most commonly used formulae for calculating the so-called chromium equivalent ($Cr_{eq}$) and nickel equivalent ($Ni_{eq}$) along with the predicted "solidification models" for duplex type cast steel

| $N^o$ | Relationships for calculation of $Cr_{eq}$ and $Ni_{eq}$ | Value of $Cr_{eq}/Ni_{eq}$ | Solidification model* |
|---|---|---|---|
| 1. | $Cr_{eq}$= %Cr + %Mo + 1.5%Si + 0.5%Nb<br>$Ni_{eq}$= %Ni + 30%C+ 0.5%Mn | $Cr_{eq}/Ni_{eq} \leq 1.48$<br>$1.48 \leq Cr_{eq}/Ni_{eq} \leq 1.95$<br>$Cr_{eq}/Ni_{eq} \geq 1.95$ | austenitic<br>ferritic / austenitic<br>ferritic |
| 2. | $Cr_{eq}$= %Cr + 1.37%Mo + 1.5%Si + 2%Nb + 3%Ti<br>$Ni_{eq}$= %Ni + 22%C + 0.31%Mn + 14.2%N + Cu | $Cr_{eq}/Ni_{eq} \leq 1.55$<br>$Cr_{eq}/Ni_{eq} \geq 1.55$ | austenitic / ferritic<br>ferritic / austenitic |
| 3. | $Cr_{eq}$= %Cr + 1.37%Mo + 1.5%Si + 2%Nb + 3%Ti<br>$Ni_{eq}$= %Ni + 22%C + 0.31%Mn + 14.2%N + Cu<br>$\varphi = Ni_{eq} - 0.75Cr_{eq} + 0.257$ | $\varphi < 0$<br>$\varphi = 0$<br>$\varphi > 0$ | ferritic<br>ferritic / austenitic<br>austenitic |
| 4. | $Cr_{eq}$= %Cr + 1.5%Mo + 2%Si + 1.75%Nb + 1.5%Ti + 0.75%W + 5%V + 5.5%Al<br>$Ni_{eq}$= %Ni + 30%C + 0.5%Mn + %Co + 0.3%Cu + 25%N | - | - |

# 2. Material and methodology of tests

The object of examination has been the ferritic-austenitic cast steel GX2CrNiMoN25-6-3 and GX2CrNiMoCuN25-6-3-3. Both grades have been taken from industrial heats performed in the medium frequency induction furnace of about 150 kg capacity. A series of test castings has been produced of both cast steel grades in order to assess their technological and working properties. The used specimens have served as a charge for cast steel melting in order to perform derivative differential thermal analysis (DDTA). Melting of small quantities of cast steel (about 400 g) have been done at Częstochowa University of Technology. Small ceramic crucibles placed inside the induction coil powered with the medium frequency current have been used. The process have been held under argon atmosphere. The constant temperature of pouring metal into the DDTA probe has been provided by measuring the temperature of the molten cast steel with PtRh10-Pt thermocouple.

Chemical compositions of the cast steel poured into the DDTA probe has been determined by optical emission spectroscopy methods. The LECO analyser has been used for determining carbon and sulphur content. The results of analyses are gathered in Table 2.

Table 2. Chemical compositions of the examined cast steels (mass %)

| Cast steel | C | Mn | Si | S | P | Cr | Ni | Mo | Cu | N |
|---|---|---|---|---|---|---|---|---|---|---|
| A | 0.021 | 1.46 | 0.93 | 0.012 | 0.008 | 26.70 | 6.48 | 3.10 | 0.02 | 0.23 |
| B | 0.024 | 1.32 | 0.81 | 0.011 | 0.008 | 25.84 | 6.34 | 2.94 | 2.75 | 0.23 |

The solidification process of duplex cast steel has been examined also by analytic method used in ThermoCalc program. The determining of copper influence on the solidification mechanism has been performed both for assumed equilibrium conditions and according to Scheil-Gulliver method which assumes the infinitely fast diffusion in a liquid phase and no diffusion in a solid one. Simulations have been done for cast steel of chemical composition given in Table 2.

The cast steel microstructure has been revealed with Mi21Fe etchant ((30 g of potassium ferrocyanide, 30 g of potassium hydroxide, 60 ml of distilled water).

# 3. Examination results

Figure 1 shows the results of the DDTA analysis for both examined grades of cast steel. Figure 2 presents the course of the solidification process determined according to the analytic ThermoCalc method. Table 3 gives temperature ranges of occurring of the individual phases during the solidification. Figure 3 illustrates the microstructure of the examined cast steel. Microsections have been prepared for samples cut out of the ingots cast in DDTA probes.

Table 3. Temperature ranges of occurring of individual cast steel phases during solidification process

| The analysed region | Cast steel grade | |
|---|---|---|
| | GX2CrNiMoN 25-6-3 | GX2CrNiMoCuN 25-6-3-3 |
| L | 1444°C | 1413°C |
| L+BCC | 1444 ÷ 1357°C | 1413 ÷ 1314°C |
| L+BCC+FCC | 1357 ÷ 1300°C | 1314 ÷ 1297°C |
| L+BCC+FCC+HCP | 1300 ÷ 1230°C | 1297 ÷ 1195°C |
| L+BCC+FCC+HCP+$M_{23}C_6$ | − | 1195 ÷ 1172°C |

# 4. Conclusion

Both experimental (DDTA) and analytical results indicate that despite the very small carbon content (0.021 and 0.024) the peritectic transformation occurs in the final stage of ferrite solidification. The copper addition decreases the temperature of beginning of solidification by 4°C and also lowers and widens the temperature range of peritectic reaction. According to the DDTA examination results the range of peritectic solidification covering the A'BC region (Fig. 1) equals to 16°C and 26°C for GX2CrNiMoN25-6-3 and GX2CrNiMoCuN25-6-3-3 cast steel grades, respectively.
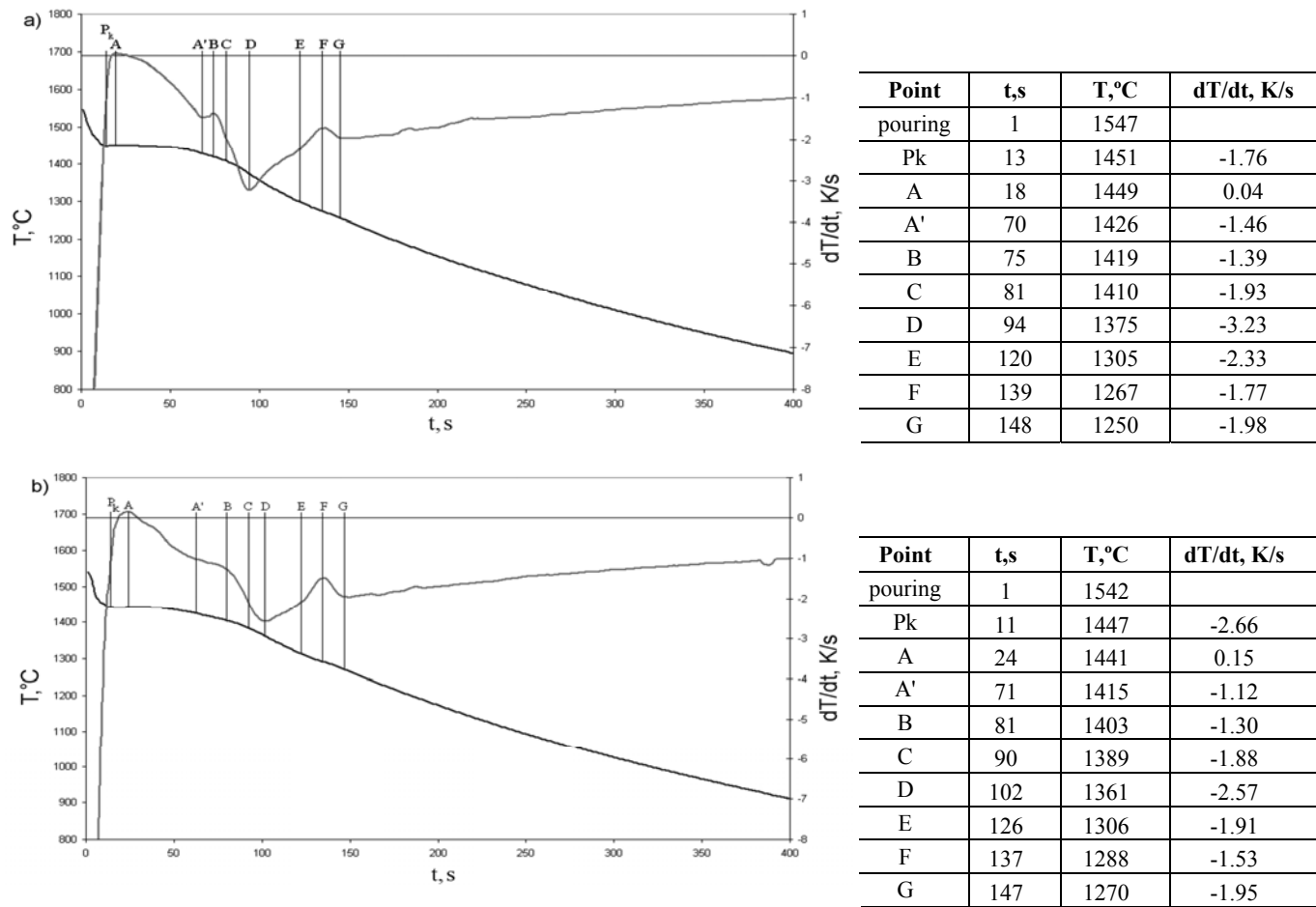
| Point | t,s | T,ºC | dT/dt, K/s |
|---|---|---|---|
| pouring | 1 | 1547 | |
| Pk | 13 | 1451 | -1.76 |
| A | 18 | 1449 | 0.04 |
| A' | 70 | 1426 | -1.46 |
| B | 75 | 1419 | -1.39 |
| C | 81 | 1410 | -1.93 |
| D | 94 | 1375 | -3.23 |
| E | 120 | 1305 | -2.33 |
| F | 139 | 1267 | -1.77 |
| G | 148 | 1250 | -1.98 |

| Point | t,s | T,ºC | dT/dt, K/s |
|---|---|---|---|
| pouring | 1 | 1542 | |
| Pk | 11 | 1447 | -2.66 |
| A | 24 | 1441 | 0.15 |
| A' | 71 | 1415 | -1.12 |
| B | 81 | 1403 | -1.30 |
| C | 90 | 1389 | -1.88 |
| D | 102 | 1361 | -2.57 |
| E | 126 | 1306 | -1.91 |
| F | 137 | 1288 | -1.53 |
| G | 147 | 1270 | -1.95 |

Fig. 1. Results of DDTA analysis: a) for GX2CrNiMoN25-6-3 cast steel, b) for GX2CrNiMoCuN25-6-3-3 cast steel
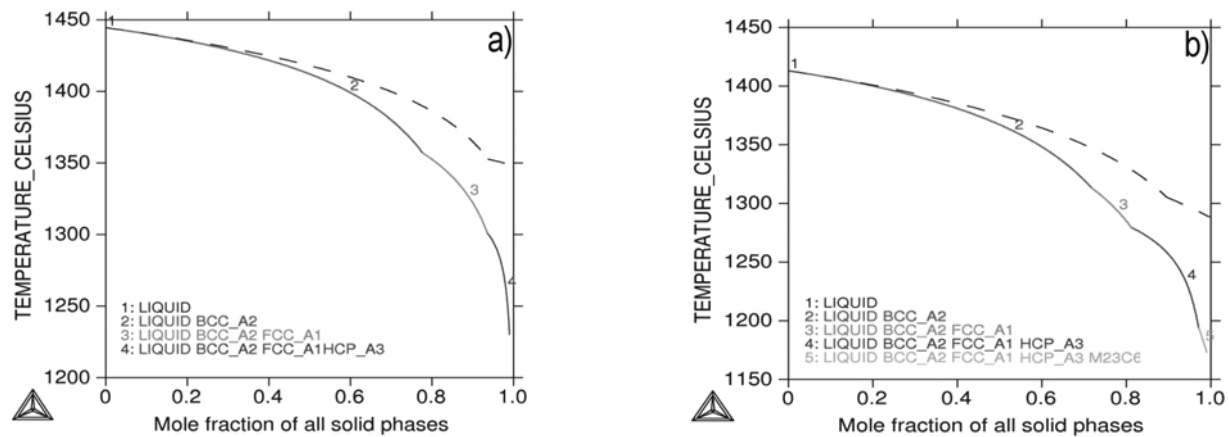


Fig. 2. The solidification curve determined by analytic method (ThermoCalc): a) GX2CrNiMoN25-6-3 cast steel, b) GX2CrNiMoCuN25-6-3-3 cast steel
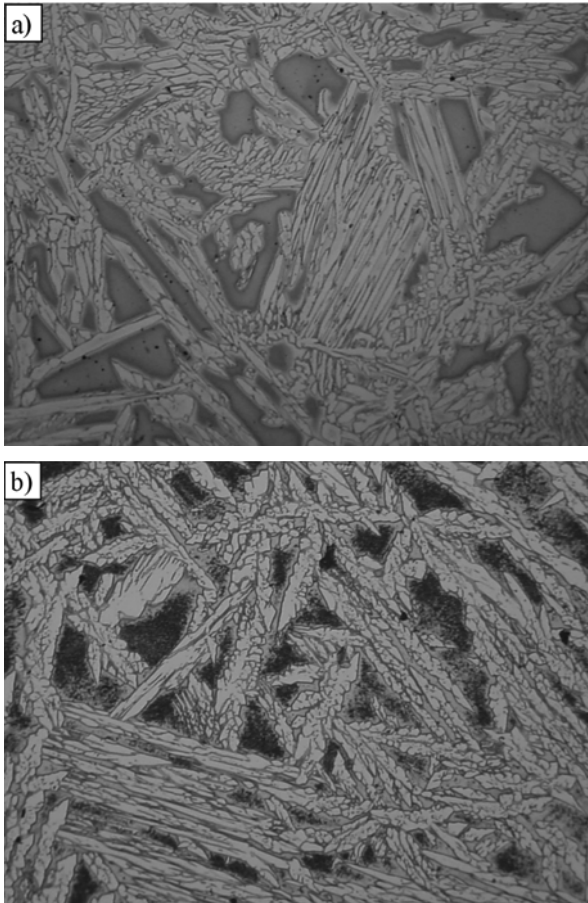
Fig. 3. Microstructure of cast steel: a) GX2CrNiMoN25-6-3 and b) GX2CrNiMoCuN25-6-3-3, magn. 100×

According to the ThermoCalc data the difference between the temperature of the beginning of solidification for both cast steels equals to about 30°C, and the range of peritectic solidification is by several degrees wider for cast steel containing copper. The end of peritectic solidification for the cast iron containing copper, accompanied by precipitation of chromium nitrides of hexagonal structure, occurs at the temperature lower by 35°C than for the other examined cast steel grade. Table 3 indicates that the $Cr_{23}C_6$ carbides should be expected in the quantity of about 2% even at very low carbon content. It is worth noticing that metallographic examination of duplex cast steel with the lowest carbon content (0.021%) have not revealed the presence of carbides.

It should be stressed that, according to the relationships given in Table 1, the solidification character of both of examined duplex cast steel compositions should be pure ferritic. The degree of segregation of the alloying elements resulting from the partition coefficients and empirically determined by EDX method [14], has confirmed the change of the solidification mechanism from pure ferritic to the ferritic-austenitic one only if the relationship (2) is employed. An addition of copper results in occurring the structural constituent of different morphology, which is γ' phase.

The widening of the region of peritectic solidification and the possibility of precipitating of the $Cr_{23}C_6$ carbides can result in increased susceptibility to hot cracking of cast steel containing about 3% copper addition at the final stage of its solidification.

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