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PHYSICAL AND NUMERICAL MODELLING OF HEAT TREATMENT THE PRECIPITATION-HARDENING COMPLEX-PHASE STEEL (CP)

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The article presents the results of physical and numerical modelling of the processes of thermo- plastic treatment of an experimental complex-phase (CP) steel. Numerical tests were carried out using a commercial software program, ThermoCalc. Based on the obtained test results, the austenitization temperature was established. Physical modelling was performed using a DIL 805A/D dilatometer and the Gleeble 3800 system. The characteristic temperatures of the steel and the primary austenite grain size were determined. The test pieces were also subjected to metallographic examinations and Vickers hardness tests. The obtained results served for building an actual CCT diagram for the steel tested.

Key words: CP steels, microstructure evolution, physical modelling, CCT diagrams

INTRODUCTION

The development of the automotive industry urges designers to focus their activities on reducing the mass of cars to be manufactured, resulting in a significant reduction of fuel consumption and emissions of harmful exhaust gas to the atmosphere. The consequence of this is searching for new constructional materials for the manufacture of sheet metal of high strength and engineering deformability, which will assure lightweight and tough car bodies to be obtained [1 - 2]. This direction is consistent with the general trend development of metallurgy in Poland [3]. Among modern car body steels, two group of steels can be distinguished. The first group is made up of conventional High-Strength Steels (HSS).

This includes: Interstitial-Free (IF) steels, Isotropic Steels (IS), Bake Hardened (BH) steels, C-Mn (carbon-manganese) steels, and High-Strength Low-Alloy (HSLA) steels. The second group consists of Advanced High-Strength Steels (AHSS): Dual Phase (DP) steels; Complex Phase (CP) steels; TRIP (Transformation Induced Plasticity) steels; and TMS (martensitic steels) [4 - 8].

CP steels are characterized by their tensile strength at a level of approx. 800 MPa, and quite often even more. The high strength of steel is achieved due to the contents of fine-grained ferrite and interstitial bainite in the microstructure and the dispersion hardening by precipitates of carbides and nitrides. To obtain fine-grained precipitates, additions of niobium, titanium or vanadium are used. Steels of this type are distinguished by good deformability and high capability to absorb energy during a collision. Thanks to these properties, CP steels find application as a material for production of construction elements absorbing the energy of collisions, especially side crashes.

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TEST MATERIAL AND TESTING METHODOLOGY

Tests were carried out on an experimental complex phase steel, whose chemical composition is given in Table 1.

Table 1 **Chemical composition of the steel / wt %**

C	Mn	Si	Cr	Ni	Ti	Cu	N
0,08	1,5	0,4	0,3	0,2	0,10	0,2	0,003

The melt was made under laboratory conditions in a VSG100S vacuum furnace with a crucible capacity of 100 kg, and was cast in vacuum into a 100 x 100 mm inner cross-section ingot mould. The obtained ingot was forged into square and round bars and then softening heat treatment was carried out.

Numerical studies were carried out using the Thermo-Calc program. The austenitizing temperature of the test steel, which assured the dissolution of alloy additions in the solution, was determined based on the chemical composition using this program. On this basis, the diagram of equilibrium of the test steel with the carbon content varying in the range of 0 - 0,12 % and variation in the contents of individual phases as a function of temperature was plotted.

For carrying out physical simulations of heat treatment, a DIL 805A/D dilatometer was used. For the tests 10 mm-long and 5 mm-diameter cylindrical samples

were used. In the first place, the effect of austenitizing temperature on the primary austenite grain size was examined. To this end, the samples were heated up to a temperature in the range of 900 – 1 250 °C with a step of 50 °C and at a rate of 5 °C/s, soaked at that temperature for 30 minutes, and then rapid cooling was applied to assure that the structure was frozen. The austenite grain size on samples was determined by a comparative method using the normalized standard scale conforming to standard PN-EN ISO643:2003.

The values of the characteristic temperatures A_{c1}, A_{c3}, A_{r1} and A_{r3} during heating and cooling were determined. The samples were heated up and cooled down in a continuous manner at a constant rate of 3 °C/min. The analysis of dilatometric patterns recorded during heating and cooling was made following the procedure set out in standard PN-68/H-04500. The determined values of temperatures A_{c3} provided a basis for establishing the value of austenitizing temperature during conducting the dilatometric tests.

To determine the CCT diagram, the samples were heated up to a temperature of 940 °C at a heating rate of 3 °C/s, soaked at that temperature for 300 s and then cooled down to ambient temperature at varying cooling rates. The outcome of the tests is a series of dilatometric patterns illustrating the variation of sample length as a function of temperature. After the heat treatment physical simulations, the samples were subjected to metallographic examination to disclose the structure formed, and then Vickers hardness tests were performed.

To determine the effect of temperature and strain rate on the yield stress of the steel, a high-temperature compression test was carried out. The tests were conducted using a simulator of metallurgical processes Gleeble. The σ-ε curves were determined for the actual strain of ε = 1. The samples were resistance heated in vacuum to a temperature of 1 150 °C at a heating rate of 5 °C/s, soaked at that temperature for 60 s, and then cooled down to a plastic strain temperature of 850 - 1 150 °C. The compression of the samples was conducted at a strain rate of ε = 0,1; 1,0 and 10 s^{-1}, respectively.

TEST RESULTS AND THE DISCUSSION

Based on the chemical composition, the austenitizing temperature of the test steel was determined. For this purpose, the Thermo-Calc program was used. The program served for constructing the diagram of equilibrium of the steel with carbon content varying in the range 0 - 0,12 % (Figure 1).

The data in Figure 1 shows that up to a temperature of approx. 880 °C, a multi-component structure exists in the steel. It is composed of ferrite, austenite, cementite, MC-type carbides and manganese sulphide. Above that temperature, only austenite and manganese sulphide occur in the structure.

The austenite grain size in the initial state was determined by a comparative method using the normalized

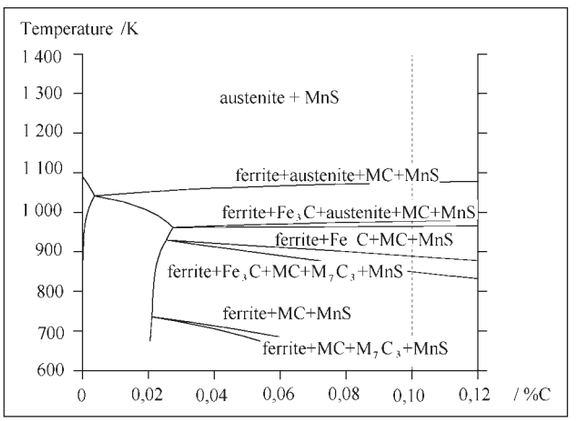

Figure 1 Equilibrium diagram for steel with carbon content varying in the range of 0 – 0,12 %

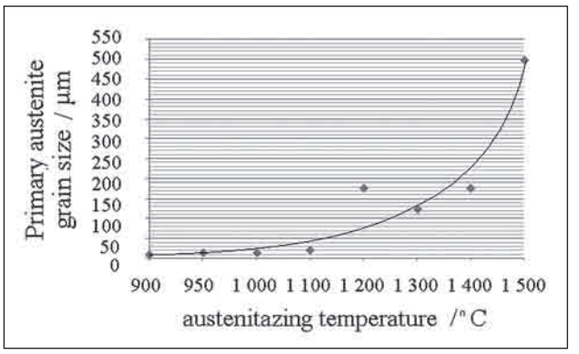

Figure 2 Effect of austenitizing temperature on the primary austenite grain size

scale of standards in accordance with standard PN-EN ISO 643:2003, and was found to be 9 µm.

The results of tests for the effect of austenitizing temperature in the range of 900 – 1 250 °C on the γ phase grain growth are illustrated in Figure 2.

Figure 3 shows the revealed primary austenite grain boundaries in the test steel, as quenched from a temperature of 1 200 °C and 950 °C, respectively.

The performed tests found that samples austenitized in the temperature range of 900 - 1 050 °C were characterized by fine austenite grains from 11 to 22 µm in size. This indicates that for austenitizing temperatures below 1 050 °C the steel maintains a fine-grained structure. For a sample austenitized at 1 100 °C, the austenite grain size was determined to be 117 µm, which definitely deviates from the remaining determined sizes. As indicated by the data in Figure 3, the accelerated austen-

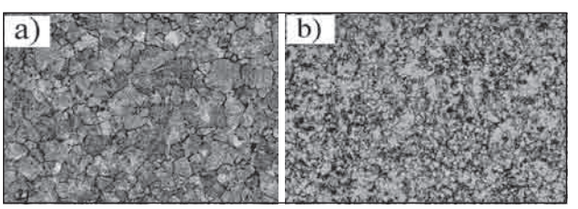

Figure 3 Primary austenite grain boundaries in steel quenched from a temperature of: a) 1 200 °C, 50 x, b) 950 °C, 100 x

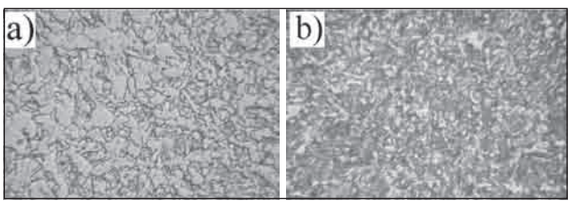

Figure 4 Structure of the test steel: a) ferritic-bainitic, obtained after cooling at a rate of 30 °C/s; b) bainitic-martensitic, with a slight amount of ferrite, obtained after cooling at a rate of 80 °C/s; 1000 x

ite grain growth occurs only after the temperature of 1 100 °C is exceeded.

The characteristic temperatures obtained from the analysis of dilatometric patterns: A_{c1} = 740 °C, A_{c3} = 889 °C, A_{r1} = 655 °C, A_{c1} = 811 °C.

The austenitizing temperature for carrying out physical simulations for the test steel was assumed to be T_A = 940 ºC (A_{c3} + 40 – 50 ºC).

The samples after physical simulations were subjected to metallographic examination to reveal the structure formed (Figure 4).

Vickers hardness tests were also performed (Table 2).

Table 2 **Phase transformation temperatures and the hardness of the test steel as cooled from a temperature of 940 °C**

Cooling rates/ ºC/s	Characteristic temperatures / ºC	Hardness HV
150	F_s = 715, F_f = B_s = 650, B_f = 490, M_s = 411, M_f = 290	321
100	F_s = 712, F_f = B_s = 660, B_f = 4 85, M_s = 410, M_f = 286	317
80	F_s=720, F_f = B_s = 670, B_f = 505, M_s = 410, M_f = 330	257
50	F_s = 733, F_f = B_s = 680, B_f = 479, M_s = 418, M_f = 348	230
30	F_s = 715, F_f = B_s = 650, B_f = 432	188
10	F_s = 800, F_f = P_s = 755, P_f = B_s = 672, B_f = 550	156
1	F_s = 800, F_f = P_s = 745, P_f = 625	151
0,1	F_s = 796, F_f = P_s = 750, P_f = 664	140

The data in Table 2 shows that bainite-containing structures are obtained by cooling at cooling rates of v = 10 – 150 ºC/s. A three-phase structure composed of ferrite, martensite and bainite is obtained by cooling at cooling rates higher than v = 30 °C/s.

Based on the performed analysis and obtained results, a CCT diagram was plotted (Figure 5).

The developed CCT diagram enables the temperatures of the beginnings and ends of phase transformations occurring during continuous cooling of complex-phase steel to be red out with a high accuracy. It provides also the capability to determine the cooling rates that assure the formation of the desirable three-phase structure.

To determine the effect of deformation temperature and strain rate on the yield stress of the test steel, a high-temperature compression test was carried out using the Gleeble 3800 metallurgical process simulator. Figures 6

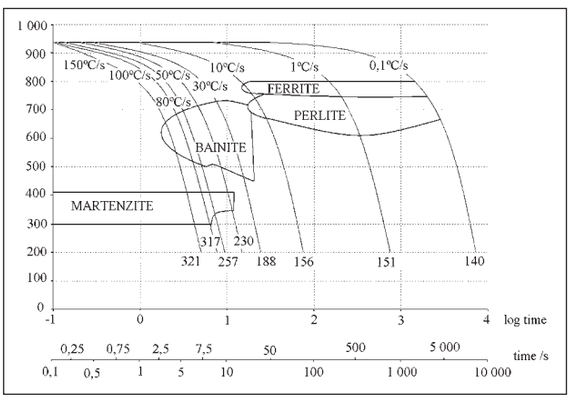

Figure 5 CCT diagram for the test steel

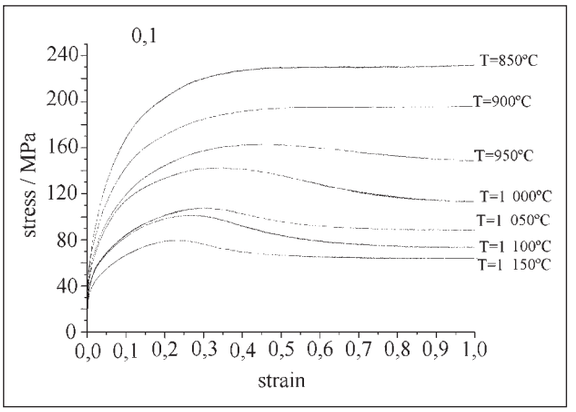

Figure 6 Effect of deformation temperature on the σ-ε curves for the test steel deformed at a rate of 0,1 s^{-1}

- 8 show diagrams illustrating the effect of deformation temperature on the shape of the σ-ε curves for a varying strain rate of ε = 0,1; 1,0 and 10 s^{-1}, respectively.

The values of strain and yield stress were calculated from relationship (1) and (2), respectively.

$$\varepsilon = \frac{2}{\sqrt{3}}\left|\ln\frac{h}{h_0}\right| \qquad (1)$$

where:
h – height of the sample during plastic deformation,
h_0 – initial sample height.

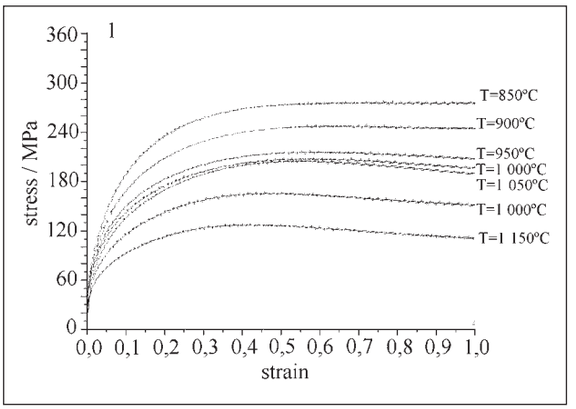

Figure 7 Effect of deformation temperature on the σ-ε curves for the test steel deformed at a rate of 1 s^{-1}

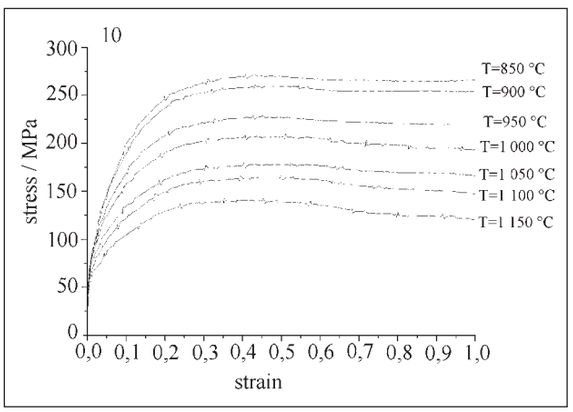

Figure 8 Effect of deformation temperature on the σ-ε curves for the test steel deformed at a rate of 10 s^{-1}

$$\sigma_p = \frac{\sqrt{3}}{2}\frac{F}{wb} \qquad (2)$$

where: F – force measured during the course of plastic deformation, w – anvil width, b – sample width

From the data in Figures 6 - 8 it is found that, for the test steel, the dynamic recrystallization occurs only at a strain rate of 0,1 s^{-1}. It is also fund that, for the steel grade tested (Figures 7 and 8), the effect of strain rate, in the range of values of 1 s^{-1} and 10 s^{-1} and in the temperature range of 850 - 1150°C, on the yield stress is small.

The obtained curves will provide a basis for the development of the technology of rolling sheet metal of the steel grade investigated.

SUMMARY

Based on the investigation carried out, the following findings and conclusions have been made:

- for the steel grade examined, the austenitization temperature equal to T_A = 950 ºC should be assumed;
- the most desirable structures for the steel investigated are the ones containing bainite. During cooling from the austenitization temperature of T_A = 950 ºC, a three-phase structure containing ferrite, martensite and bainite is obtained with cooling at cooling rates in the range of v = 30 – 150 ºC/s;
- the numerical and physical simulations complex-phase steel heat treatment, which were carried out within this study, have enabled the actual CCT diagram to be constructed. This constitutes one of the elements providing the basis for developing the technology of rolling sheet metal of the steel grade investigated.

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Note: The responsible translator for English language is Czesław Grochowina, Poland.