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# Critical points in solid-state phase transformation of a steel with 0.087% C and 0.511% Mn, determined through dilatometric analyses

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This article contains the results of dilatometric analyses carried out on a hypoeutectoid steel with 0.087% C and 0.511% Mn (Si, Cr, Ni, Mo, Al, Cu, V and W below 0.1%) in order to determine the temperatures that correspond to critical points in solid-state phase transformation, analyses carried out at continuous heating regime with different heating rates (between 1 and 30 °C/min). The eutectoid transformation (the pearlite dissolution into austenite) was carried out in a temperatures interval, ranging between pearlite dissolution start temperature ($Ac_1$) and pearlite dissolution finish temperature (denoted $Ac_{fp}$ in this article). Increasing the heating rate determined a displacement of the critical points in solid-state phase transformation to higher temperatures; these displacements were more significant for the $Ac_{fp}$ point, than for the critical points $Ac_1$ and $Ac_3$. Raising of the temperatures of the critical points $Ac_{fp}$ and $Ac_3$, with the increase of the heating rate led to the decreasing of the temperatures range ($Ac_{fp}$ - $Ac_3$), which is important for the dual-phase steels production technologies. In addition, the authors calculated the temperatures of the critical points $Ac_1$ and $Ac_3$ using mathematical models (provided by literature) and determined the differences between the values obtained through dilatometric analyzes and and those determined with mathematical models.

**Keywords:** critical point, dilatometric analysis, heating rate, dual-phase steel

## INTRODUCTION

According to the Fe-C equilibrium diagram, a hypoeutectoid Fe-C binary alloy has two important critical points in solid-state phase transformation: the point or temperature $Ae_1$ at which the dissolution of the pearlite (P) in austenite ($\gamma$) occurs, process which represents an eutectoid transformation ($P \rightarrow \gamma$) and the point or temperature $Ae_3$ where the allotropic transformation of proeutectoide ferrite ($\alpha$) into austenite ends ($\alpha \rightarrow \gamma$); under equilibrium conditions, the pearlite dissolution (the eutectoid transformation, $P \rightarrow \gamma$) takes place at a constant temperature (at 727 °C), and the completion of allotropic transformation ($\alpha \rightarrow \gamma$) occurs at a temperature that decreases progressively with the increase in the percentage of carbon in the alloys. During the heating and cooling cycles of a Fe-C binary alloy a thermal hysteresis appears and for this reason, for the same critical point, three values correspond, namely: *Ac* for heating, *Ar* for cooling and *Ae* for equilibrium conditions; it should be emphasised that the *Ac* and *Ar* values are sensitive to the rates of heating and cooling. These critical points in solid-state phase transformation can be easily detected by dilatometric analysis [1-3].

In the case of commercial steels, that are Fe-C alloys and with other chemical elements in composition (like alloying elements or impurities), the Fe-C equilibrium diagram does not fully apply. The alloying elements and impurities in the chemical composition of commercial steels change the position of critical points (both temperature and carbon composition); in addition, unlike in the case of the binary system, the pearlite dissolution into austenite (eutectoid transformation, $P \rightarrow \gamma$) no longer occurs at constant temperature, but in a temperatures range, namely, between pearlite dissolution start temperature ($Ac_1$ critical point) and pearlite dissolution finish temperature (denoted $Ac_{fp}$ in this article). The temperature $Ac_{fp}$ indicates the beginning of ferrite and austenite coexistence range during heating (beginning of the allotropic transformation of ferrite into austenite, $\alpha \rightarrow \gamma$), range that stretches up to the temperature of the $Ac_3$ point, the determination of this range of coexistence of the ferrite and austenite ($Ac_{fp}$ - $Ac_3$) being of great importance for the technologies of manufacturing dual-phase steels [1-5]. These steels are alloys with a low carbon content, which have a structure consisting of a soft and ductile ferrite matrix in which are homogeneously dispersed, martensite (10 to 35 %) and a small amount of residual austenite (1 to 2 %). For dual-phase steels the stress-strain curve is continuous, without yield; they have a low yield strength and a high tensile strength ($R_{p0,2}/R_m$ ratio is about 0.5), and to small stresses their work hardening is very fast. The dual-

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phase steels products worldwide have, generally, a percentage of carbon less than 0.12 %, a content of manganese between 1.0 % and 3.5 %, whereas elements such as V, Cr, Mo and, Nb, are to be found in chemical composition in proportions situated below 1%; in the last few years there have been carried out studies on steels in which the content of manganese is even less than 1 % (0.5 ÷ 1 % Mn) [6-10]. The main technology of producing these steels consists of quenching at temperatures in the intercritical range ($\alpha + \gamma$); the structure obtained, for a given chemical composition, is the result of combined action of heating temperature and the cooling rate, the influence of these two technical parameters on the structure of the material being directly reflected on its properties. The mechanical properties of a dual-phase steel are fundamentally influenced by the volume fraction of martensite in the structure, by the morphology and the distribution of this phase, structural characteristics which, in their turn, are affected, particularly, by the heating temperature in the range ($\alpha + \gamma$). For this reason, the heating temperature represents an essential technological parameter in the process of making such a steel, determining the volume fraction of austenite and finally, after cooling, the volume fraction of martensite formed into an alloy with a certain chemical composition [6-9]. Therefore, for designing and developing a dual-phase steel production technology, it is necessary to know the temperatures of the critical points $Ac_1$, $Ac_{fp}$ and $Ac_3$. A quick and convenient method for determining the temperatures of critical points in solid-state phase transformation when heating a steel lies in the use of mathematical models that take into account the chemical composition (equations obtained by statistical processing of experimental results), but these equations can generate severe errors [1, 2, 11]. A high precision in finding these temperatures is obtained by dilatometric analysis; modern dilatometers, conected to computerised systems, collect the signals of change in the length of a specimen as a function of temperature, plot a dilatometric curve, calculate and generate its corresponding derivative and allow the identification of both the critical points $Ac_1$ and $Ac_3$, as well as the pearlite dissolution finish temperature (the $Ac_{fp}$ point) and therefore, the determination of the temperatures range ($Ac_{fp}$ - $Ac_3$) [2, 5, 12, 13].

This article describes some of the researches carried out at "Stefan cel Mare" University of Suceava, Romania, for obtaining and characterization of dual-phase steels with low manganese content (below 1% Mn). The results of the dilatometric analyses performed on specimens made of a commercial steel, used in industry, mainly, for electrodes and welding wires, are presented. As a result of these researches, the temperatures of the critical points in solid-state phase transformation were identified, the influence of the heating rate on these temperatures was established and a comparison was made between the values determined by dilatometric analyses and those obtained using mathematical models.

## EXPERIMENTAL DETAILS

The chemical composition of the investigated steel was determined with a FOUNDRY-MASTER Xpert spectrometer (Oxford Instruments Analytical GmbH, Germania), and led to the next values (weight %): Fe, 0.087 C, 0.511 Mn, 0.091 Si, 0.0036 P, 0.0039 S, 0.029 Cr, 0.005 Mo, 0.049 Ni, 0.003 Al, 0.082 Cu, 0.003 V, 0.003 W; the initial structure was ferrite-pearlite, consisting of 85.30% ferrite and 14.70% pearlite.

The dilatometric analyses were performed with a DIL 402 Expedis-SUPREME Dilatometer (NETZSCH Gerätebau GmbH, Germany), on cylindrical specimens with a diameter of 5 mm and a length of 25 mm, continuous heated in (30 ÷ 980) $^{\circ}$C temperature range, in nitrogen atmosphere (100 ml/min $N_2$), with a load at the specimen of 200 mN and with the following heating rates: 1, 3, 5, 10 and 30 $^{\circ}$C/min. Three dilatometric analyses were performed for each heating rate (three specimens for each heating rate); finally, the signals provided by the dilatometer were processed with NETZSCH Proteus® Software 7.1.0.

## RESULTS AND DISCUSSION

During austenite formation, the local changes in the crystal structure conducted to a macroscopic volume contraction of the specimen; these changes can be detected and quantified by dilatometric analysis. The volume contraction has two main contributions: I) the difference in specific volume between the phases involved in the transformation (austenite, ferrite and cementite) and II) the variation of the austenite specific volume due to the carbon enrichment or depletion [3, 14]. Thus, at continuous heating of a hypoeutectoid Fe-C binary alloy, the critical points $Ac_1$ and $Ac_3$ appear on a dilatometric curve which plots the variation of the relative length of a specimen on temperature, $\Delta L/L_o$

= f (T), and the two critical points can be determined from changes in the slope of the dilatometric curve (Fig.1). The critical point $Ac_1$ is defined as the temperature at which the linear thermal expansion (graphically represented by the $\Delta L/L_0=f(T)$ function) has the first deviation from linearity; this behaviour is caused by the volume contraction associated with the austenite formation, which first compensates, and then reverses the normal expansion of the specimen due to the increase in temperature. The location of the point at which the deviation occurs is obtained by extrapolating the linear portion of the dilatometric curve. The critical point $Ac_3$ is defined as the temperature at which the thermal expansion begins again to depends linearly on temperature; likewise, this point is determinated by extrapolating the linear portion of the dilatometric curve after transformation [2-5, 14].

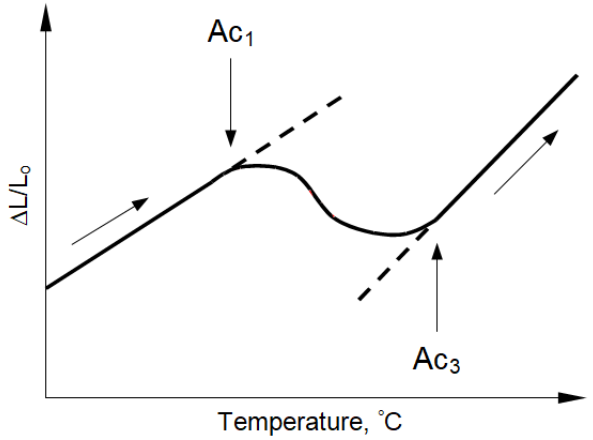


**Fig.1.** Schematical variation of the relative change of length as a function of temperature during continuous heating of a hypoeutectoid Fe-C binary alloy specimen [4]

The signals of change in the length of the steel specimens characerised by 0.087% C and 0.511% Mn, depending on the temperature, collected during dilatometric analyses with the computerised systems of the DIL 402 Expedis-SUPREME Dilatometer, have led to the plotting of the dilatometric curves, as well as to the calculation and graphic representation of their first derivative. Fig.2 shows the dilatometric curve and its corresponding derivative, for a heating rate of 3 °C/min.

Normally, no difference between the pearlite dissolution process (P → γ) and the allotropic transformation of ferrite into austenite (α → γ) is detected on the continuous heating dilatometric curve obtained for a hypoeutectoid Fe-C binary alloy (Fig.1). However, all the dilatometric curves drawn for the investigated steel (regardless of the heating rate), present an unusual anomaly at the onset of the austenitization; this obvious anomaly, highlighted by other researchers as well [2-5, 12-

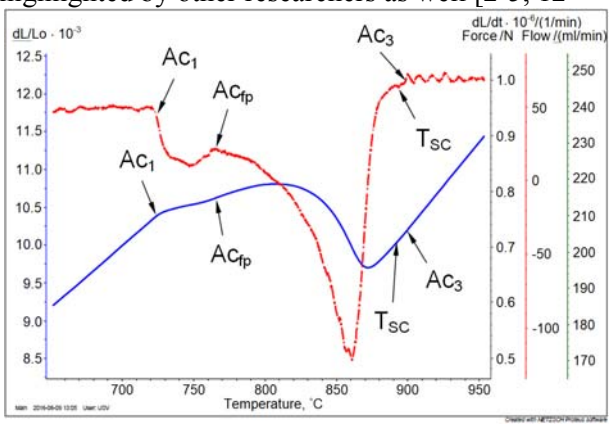


**Fig.2.** The dilatometric curve (continuous line) and its corresponding derivative, for the heating rate of 3 °C/min

15], is a contraction associated to the pearlite dissolution (Fig.2). The possibility to be able to precisely highlight the two processes that take place when heating a hypoeutectoid steel (the pearlite dissolution into austenite and the allotropic transformation of ferrite into austenite) by means of high resolution dilatometry permits the determination of the $Ac_{fp}$ temperature (the pearlite dissolution finish temperature) as well. $Ac_{fp}$ is the temperature at which the first contraction on the dilatometric curve, due to the pearlite dissolution into austenite (P → γ), finishes; it is also a transition temperature between the two transformations, (P → γ) and (α → γ) [2, 5, 12-15]. This point is less obvious on the dilatometric curve, $\Delta L/L_o = f(T)$, but easier to determine from the first derivative curve, $d(\Delta L/L_o)/dT = f(T)$. Thus, first derivative curve shows two peaks which indicate the contraction caused by (P → γ) and (α → γ) transformations (Fig.2, dashed line); the critical temperatures $Ac_1$ and $Ac_3$ were chosen as points of decrease of first derivative curve below the minimum value found in the section where the derivative is approximately constant, whereas the pearlite dissolution finish temperature, $Ac_{fp}$, was chosen at the point where the sloping-up part of the first derivative curve starts to bend to the right [2, 12, 13, 16, 17]. Immediately after finishing pearlite dissolution (P → γ), the allotropic transformation of ferrite in austenite (α → γ) begins, transformation which determine also a decrease in the specific volume (a contraction); after achieving a minimum in the changing of the relative length of the specimen, on the dilatometric curves, at a

temperature noted $T_{SC}$ in Fig.2, there is a small contraction which is better highlighted on the first derivative curves, which have a small peak at $T_{SC}$ temperature. This modification of the volume is difficult to explain; perhaps, the phenomenon was caused, either through the formation (almost instantaneously) of austenite from a ferrite that remains untransformed in structure [3, 15], either through a diffusion of carbon from rich-carbon austenite (formed of pearlite) in the less-carbon austenite (formed of ferrite) [17]. Tab.1 shows, depending on the heating rate, the temperatures of the critical points in solid-state phase transformation of a steel with 0.087% C and 0.511% Mn. Results were obtained through processing with NETZSCH Proteus® Software 7.1.0. the signals of change in the length of the specimens provided by the dilatometer, during the tests.

**Table 1.** Results of the dilatometric analyses

| Heating rate | $Ac_1$ | $Ac_{fp}$ | $Ac_3$ | ($Ac_{fp}$ - $Ac_3$) |
|---|---|---|---|---|
| ˚C/min | ˚C | ˚C | ˚C | ˚C |
| 1 | 723.40 | 764.70 | 898.90 | 134,20 |
| 3 | 724.00 | 765.60 | 899.40 | 133,80 |
| 5 | 724.90 | 767.30 | 901.10 | 133,80 |
| 10 | 727.60 | 770.50 | 904.20 | 133,70 |
| 30 | 737.30 | 784.20 | 908.50 | 124,30 |

Data in Tab.1 demonstrate that when increasing the heating rate, the critical points in solid-state phase transformation ($Ac_1$, $Ac_{fp}$ and $Ac_3$) are moving toward higher temperatures (Fig.3). At low heating rates (1 ˚C/min and 3 ˚C/min) the differences between temperatures of the same critical points are very low, less than 1 ˚C (0.60 ˚C for $Ac_1$, 0.90 ˚C for $Ac_{fp}$ and 0.50 ˚C for $Ac_3$). Raising the heating rate has led to an increase in these differences between the temperatures of the critical points; for example, between the temperatures obtained at heating rates of 10 ˚C/min and 30 ˚C/min, the differences were 9.70 ˚C for $Ac_1$, 13.70 ˚C for $Ac_{fp}$ and 4.30 ˚C for $Ac_3$. Increasing the heating rate from 1 to 30 ˚C/min determined a displacement with 19.50 ˚C, of the critical point $Ac_{fp}$ toward higher temperatures (from 764.70 to 784.20 ˚C); the displacement of critical points $Ac_1$, and especially the $Ac_3$ is smaller, that is with 13.90 ˚C for $Ac_1$ (from 723.40 ˚C to 737,30 ˚C) and with 9.60 ˚C for $Ac_3$ (from 898.90 ˚C to 908.50 ˚C). The displacements of the critical points in solid-state phase transformation with the increase of the heating rate led to the decreasing of the temperatures range ($Ac_{fp}$ - $Ac_3$), Tab.1. Raising the heating rate from 1 to 10 ˚C/min caused an insignificant decrease, of less than 1 ˚C (from 134.20 ˚C for 1 ˚C/min, to 133.80 ˚C for 3 ˚C/min and 5 ˚C/min and at 133.7 ˚C for 10 ˚C/min). However, increasing heating rate from 10 to 30 ˚C/min led to a decrease with 9.40 ˚C of the temperatures range ($Ac_{fp}$ - $Ac_3$), from 133.70 to 124.30 ˚C; between the values obtained for this temperature range at heating speeds of 1 and 30 ˚C/min, the difference is 9.90 ˚C (from 134,20 to 124,30 ˚C).

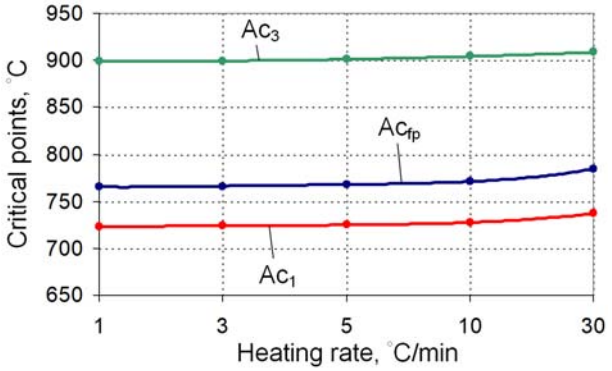


**Fig.3.** The influence of the heating rate on the temperatures of the critical points

Over the years, many researchers have developed mathematical models, that could estimate, through statistical processing of experimental results, depending on the chemical composition (in mass percent), the temperatures of the critical points in solid-state phase transformation; some of these mathematical models (equations) are listed below (in chronological order):

- *R.A. Grange* (1961) [1, 11]

$$Ae_1 = 1333 - 25 \cdot Mn + 40 \cdot Si + 42 \cdot Cr - 26 \cdot Ni \quad (1)$$

$$Ae_3 = 1570 - 323 \cdot C - 25 \cdot Mn + 80 \cdot Si - 3 \cdot Cr - 32 \cdot Ni \quad (2)$$

($Ae_1$ - lower equilibrium temperature between ferrite and austenite, ˚F; $Ae_3$ - upper equilibrium temperature between ferrite and austenite, ˚F);

- *K.W. Andrews* (1965) [1, 11]

$$Ae_1 = 723 - 16.9 \cdot Ni + 29.1 \cdot Si + 6.38 \cdot W - 10.7 \cdot Mn + 16.9 \cdot Cr + 290 \cdot As \quad (3)$$

$$Ae_3 = 910 - 203\sqrt{C} + 44.7 \cdot Si - 15.2 \cdot Ni + 31.5 \cdot Mo + 104 \cdot V + 13.1 \cdot W - 30 \cdot Mn + 11 \cdot Cr + 20 \cdot Cu - 700 \cdot P - 400 \cdot Al - 120 \cdot As - 400 \cdot Ti \quad (4)$$

($Ae_1$ - lower equilibrium temperature between ferrite and austenite, ˚C; $Ae_3$ - upper equilibrium temperature between ferrite and austenite, ˚C);

- *G.T. Eldis* (1978) [1, 11]

$$Ae_1 = 712 - 17.8 \cdot Mn - 19.1 \cdot Ni + 20.1 \cdot Si + 11.9 \cdot Cr + 9.8 \cdot Mo \quad (5)$$

$$Ae_3 = 871 - 254.4\sqrt{C} - 14.2 \cdot Ni + 51.7 \cdot Si \quad (6)$$

($Ae_1$ - lower equilibrium temperature between ferrite and austenite, ˚C; $Ae_3$ - upper equilibrium temperature between ferrite and austenite, ˚C);

- *H.P. Hougardy* (1984) [1, 11]

$$Ac_1 = 739 - 22 \cdot C - 7 \cdot Mn + 2 \cdot Si + 14 \cdot Cr + 13 \cdot Mo - 13 \cdot Ni \quad (7)$$

$$Ac_3 = 902 - 255 \cdot C - 11 \cdot Mn + 19 \cdot Si - 5 \cdot Cr + 13 \cdot Mo - 20 \cdot Ni + 55 \cdot V \quad (8)$$

($Ac_1$ - lower temperature of the ferrite-austenite field during heating, ˚C; $Ac_3$ - upper temperature of the ferrite-austenite field during heating, ˚C);

- *O.G. Kasatkin, B.B. Vinokur* (1984) [1, 9, 11]

$$\begin{aligned} Ac_1 = {} & 723 - 7.08 \cdot Mn + 37.7 \cdot Si + 18.1 \cdot Cr + 44.2 \cdot Mo + \\ & + 8.95 \cdot Ni + 50.1 \cdot V + 21.7 \cdot Al + 3.18 \cdot W + 297 \cdot S - \\ & - 830 \cdot N - 11.5 \cdot C \cdot Si - 14 \cdot Mn \cdot Si - 3.1 \cdot Si \cdot Cr - \\ & - 57.9 \cdot C \cdot Mo - 15.5 \cdot Mn \cdot Mo - 5.28 \cdot C \cdot Ni - \\ & - 6 \cdot Mn \cdot Ni + 6.77 \cdot Si \cdot Ni - 0.8 \cdot Cr \cdot Ni - 27.4 \cdot C \cdot V + \\ & + 30.8 \cdot Mo \cdot V - 0.84 \cdot Cr^2 - 3.46 \cdot Mo^2 - 0.46 \cdot Ni^2 - \\ & - 28 \cdot V^2 \end{aligned} \quad (9)$$

$$\begin{aligned} Ac_3 = {} & 912 - 370 \cdot C - 27.4 \cdot Mn + 27.3 \cdot Si - 6.35 \cdot Cr - \\ & - 32.7 \cdot Ni + 95.2 \cdot V + 190 \cdot Ti + 72 \cdot Al + 64.5 \cdot Nb + \\ & + 5.57 \cdot W + 332 \cdot S + 276 \cdot P + 485 \cdot N - 900 \cdot B + \\ & + 16.2 \cdot C \cdot Mn + 32.3 \cdot C \cdot Si + 15.4 \cdot C \cdot Cr + \\ & + 48 \cdot C \cdot Ni + 4.32 \cdot Si \cdot Cr - 17.3 \cdot Si \cdot Mo - \\ & - 18.6 \cdot Si \cdot Ni + 4.8 \cdot Mn \cdot Ni + 40.5 \cdot Mo \cdot V + \\ & + 174 \cdot C^2 + 2.46 \cdot Mn^2 - 6.86 \cdot Si^2 + 0.322 \cdot Cr^2 + \\ & + 9.90 \cdot Mo^2 + 1.24 \cdot Ni^2 - 60.2 \cdot V^2 \end{aligned} \quad (10)$$

($Ac_1$ - lower temperature of the ferrite-austenite field during heating, ˚C; $Ac_3$ - upper temperature of the ferrite-austenite field during heating, ˚C; These equations are valid within these composition limits: C ≤ 0.83%, Mn ≤ 2.0%, Si ≤ 1.0%; Cr ≤ 2.0%, Mo ≤ 1.0%, Ni ≤ 3.0%, V ≤ 0.5%, W ≤ 1.0%, Ti ≤ 0.15%, Al ≤ 0.2%, Cu ≤ 1.0%, Nb ≤ 0.20%, P ≤ 0.040%, S ≤ 0.040%, N ≤ 0.025%, B ≤ 0.010%);

- *J. Trzaska, L.A. Dobrzański* (2007) [1, 11]

$$Ac_1 = 739 - 22.8 \cdot C - 6.8 \cdot Mn + 18.2 \cdot Si + 11.7 \cdot Cr - 15 \cdot Ni - 6.4 \cdot Mo - 5 \cdot V - 28 \cdot Cu \quad (11)$$

$$Ac_3 = 937.3 - 224.5\sqrt{C} - 17 \cdot Mn + 34 \cdot Si - 14 \cdot Ni + 21.6 \cdot Mo + 41.8 \cdot V - 20 \cdot Cu \quad (12)$$

($Ac_1$ - lower temperature of the ferrite-austenite field during heating, ˚C; $Ac_3$ - upper temperature of the ferrite-austenite field during heating, ˚C).

Tab.2 gives the temperatures of critical points of the steel with 0,087% C and 0,511% Mn, obtained using the equations mentioned above.

**Table 2.** The temperatures of critical points calculated with mathematical models

| Mathematical models | Critical points | |
|---|---|---|
| *R.A. Grange* Eq.(1) și (2) | $Ae_1$ = 1323.80 ˚F or 717.70 ˚C | $Ae_3$ = 1534.70 ˚F or 834.80 ˚C |
| *K.W. Andrews* Eq.(3) și (4) | $Ae_1$ = 719.90 ˚C | $Ae_3$ = 836.90 ˚C |
| *G.T. Eldis* Eq.(5) și (6) | $Ae_1$ = 704.20 ˚C | $Ae_3$ = 800.00 ˚C |
| *H.P. Hougardy* Eq.(7) și (8) | $Ac_1$ = 733.50 ˚C | $Ac_3$ = 875.00 ˚C |
| *O.G. Kasatkin, B.B. Vinokur* Eq.(9) și (10) | $Ac_1$ = 724.40 ˚C | $Ac_3$ = 877.70 ˚C |
| *J. Trzaska, L.A. Dobrzański* Eq.(11) și (12) | $Ac_1$ = 732.50 ˚C | $Ac_3$ = 863.40 ˚C |

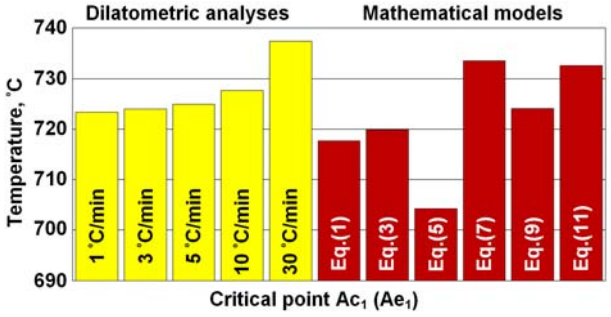


**Fig.4.** Temperatures of critical point $Ac_1$ ($Ae_1$) determined through dilatometric analyses and with mathematical models

The results presented in Tabs.1, 2 show that:

- between the temperatures of critical points determined through dilatometric analyses and those calculated with mathematical models are differences between 0.40 and 33.10 ˚C for the critical point $Ac_1$ ($Ae_1$) and between 21.20 and 108.50 ˚C for the critical point $Ac_3$ ($Ae_3$), Fig.4, 5;

- the lowest errors were generated, for the $Ac_1$critical point, by equations of *O.G. Kasatkin, B.B. Vinokur* (between 0.40 and 12.90 ˚C), *H.P. Hougardy* (between 3.80 and 10.10 ˚C) and *J. Trzaska, L.A. Dobrzański* (between 4.80 and 9.10

°C), and for the $Ac_3$ critical point, by equations of *O.G. Kasatkin, B.B. Vinokur*, (between 21.20 and 30.80 °C) and *H.P. Hougardy* (between 23.90 and 33.50 °C);

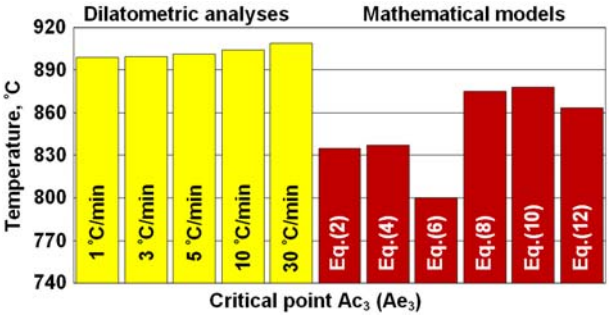


**Fig.5.** Temperatures of critical point $Ac_3$ ($Ae_3$) determined through dilatometric analyses and with mathematical models

- the biggest differences were obtained using the mathematical model developed by *G.T. Eldis* (between 19.20 and 33.10 °C for the $Ac_1$ critical point and between 98.90 and 108.50 °C for the $Ac_3$ critical point);
- unlike the high resolution dilatometry, the mathematical models do not allow the calculation of the pearlite dissolution finish temperature ($Ac_{fp}$) and hence, the determination of the temperatures range ($Ac_{fp}$ - $Ac_3$).

## CONCLUSIONS

The pearlite dissolution into austenite (eutectoid transformation) was carried out in a temperature interval ranging between pearlite dissolution start temperature (critical point $Ac_1$) and pearlite dissolution finish temperature (denoted $Ac_{fp}$ in this article).

The temperatures of the critical points in solid-state phase transformation were influenced by the heating rate, its increase leading to the displacement of critical points to higher temperatures; raising the heating rate caused a more significant displacement for the $Ac_{fp}$ point, than for the critical points $Ac_1$ and $Ac_3$.

The displacements of the critical points $Ac_{fp}$ and $Ac_3$, with the increase of the heating rate, led to the decreasing, up to 9.90 °C, of the temperatures range ($Ac_{fp}$ - $Ac_3$), range which is important for the dual-phase steels production technologies.

The temperatures of the critical points when heating a steel can be determined using mathematical models that take into account the chemical composition; these equations can generate errors and, moreover, do not allow the calculation of the pearlite dissolution finish temperature ($Ac_{fp}$) and, consequently, neither the determination of the temperatures range ($Ac_{fp}$ - $Ac_3$).

For the steel with 0.087% C and 0.511% Mn, between the temperatures of critical points determined through dilatometric analyses and those calculated with mathematical models, depending on the heating rate applied to the specimens during the dilatometric analyses and the mathematical model used, were obtained differences between 0.40 and 33.10 °C for the critical point $Ac_1$ and between 21.20 and 108.50 °C for the critical point $Ac_3$.

## ACKNOWLEDGEMENTS

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## NOMENCLATURE

$Ae_1$ - pearlite dissolution temperature (lower equilibrium temperature between ferrite and austenite), °C;

$Ae_3$ - ferrite to austenite transformation finish temperature (upper equilibrium temperature between ferrite and austenite), °C;

$Ac_1$ - pearlite dissolution start temperature (lower temperature of the ferrite-austenite field during heating), °C;

$Ac_3$ - ferrite to austenite transformation finish temperature (upper temperature of the ferrite-austenite field during heating), °C;

$Ac_{fp}$ - pearlite dissolution finish temperature (ferrite to austenite transformation start temperature), °C;

$T_{SC}$ - small contraction temperature, °C;

$\alpha$ - proeutectoide ferrite;

$\gamma$ - austenite;

P - pearlite.

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