Journal of Achievements in Materials and Manufacturing Engineering
VOLUME 49
ISSUE 2
December
2011

Critical points of hypoeutectoid steel - prediction of the pearlite dissolution finish temperature Ac_{1f}

B. Pawłowski*
Faculty of Metals Engineering and Industrial Computer Science,
AGH University of Science and Technology,
Al. Mickiewicza 30, 30-059 Kraków, Poland
* Corresponding author: E-mail address: bpawlow@agh.edu.pl

Received 12.09.2011; published in revised form 01.12.2011

Analysis and modelling

ABSTRACT

Purpose: of this work is to present possibility of calculation of pearlite dissolution finish temperature Ac_{1f} during heating of hypoeutoctoid steels.
Design/methodology/approach: The presented multiple linear regression equations for calculating the Ac_{1f} temperature are based on experimental data set containing chemical composition and values of critical temperatures obtained by use of the dilatometric technique at the own laboratory only.
Findings: The elaborated multiple linear regression equations for calculating the critical temperatures are an alternative to dilatometric examinations to obtain data necessary for proper heat treatment conditions planning.
Research limitations/implications: All presented equations for calculating pearlite dissolution finish temperature are limited by range of mass concentrations of elements which is a consequence of limited data set used for elaboration of these equations. The obtained relationships do not concern other factors influencing Ac_{1f} temperature such as heating rate, grain size and interlamellar spacing of pearlite.
Practical implications: Broadening the knowledge on the chemical composition influence on the critical temperatures, which will help in designing heat treatment conditions, especially of the Dual Phase steels.
Originality/value: An attempt was made to find out a multiple linear regression formula between chemical composition and the pearlite dissolution finish temperature of hypoeutectoid steels.
Keywords: Critical temperatures; Linear regression; Dilatometry; Pearlite dissolution finish temperature

Reference to this paper should be given in the following way:
B. Pawłowski, Critical points of hypoeutectoid steel - prediction of the pearlite dissolution finish temperature Ac_{1f}, Journal of Achievements in Materials and Manufacturing Engineering 49/2 (2011) 331-337.

1. Introduction

The Fe-Fe_3C phase diagram refers only to the iron-carbon binary alloys and does not fully apply to the steels i.e. iron base alloys (by a definition with the carbon content) containing other elements. For example, all modern steels contain manganese (used as an alloying element because however much of its ability to bind sulphur as manganese sulphide MnS) and low levels of the impurity atoms of sulphur and phosphorus. In the iron-carbon binary system eutectoid reaction (under equilibrium conditions) takes place at 727 °C and eutectoid point has a composition of 0.77%C [1]. Steels contain alloying elements and impurities (such as sulphur and phosphorus) that modify the positions of the eutectoid point (both temperature and composition). In addition, contrary to the iron-carbon binary system, eutectoid transformation (during cooling) or

pearlite to austenite transformation (during heating) does not take place at constant temperature but at the certain temperature range. According to the EN 10025 standard, for the hypoeutectoid steels following transformation temperatures (critical points) during heating can be distinguished: Ac_1 - temperature at which austenite begins to form and Ac_3 - temperature at which ferrite completes its transformation into austenite. Consequently, during cooling temperatures Ar_3 - temperature at which ferrite begins to form and Ar_1 - temperature at which austenite completes its transformation into ferrite or ferrite and cementite can be determined. The formation of austenite in the hypoeutectoid steels consists of two phenomena: pearlite dissolution and hypoeutectoid ferrite to austenite transformation. The temperatures of austenite formation during continuous heating used to be determined by dilatometric analysis. Modern high-resolution dilatometers allows in some cases to accurate identification of the finishing temperature of pearlite dissolution process and this temperature is variously designated, for example T_C (Fig. 1) [2,3], Ac_{1e} (Fig. 2) [4], Af (Fig. 3) [5], Ac_Θ (Fig. 4) [6] or A_{pf} [7].

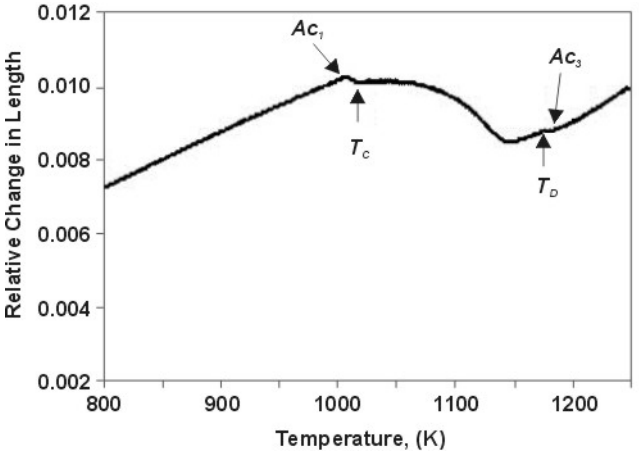

Fig. 1. Experimental dilatation curve, average of four identical dilatometric tests for heating rate of 0.05 $K \cdot s^{-1}$ [2, 3]

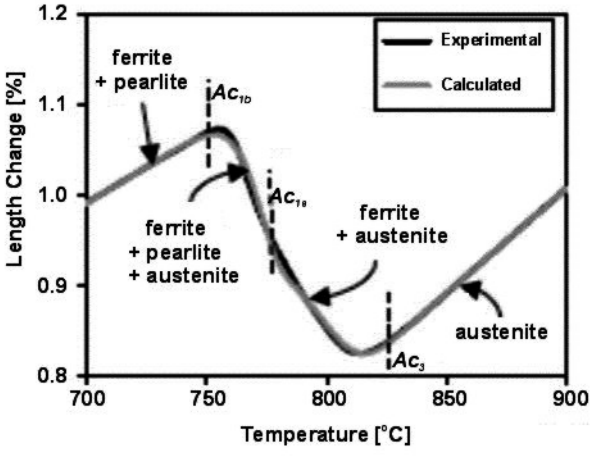

Fig. 2. Phase transformation of AISI 5120 steel during continuous heating (heating rate 0.05 $K \cdot s^{-1}$) [4]

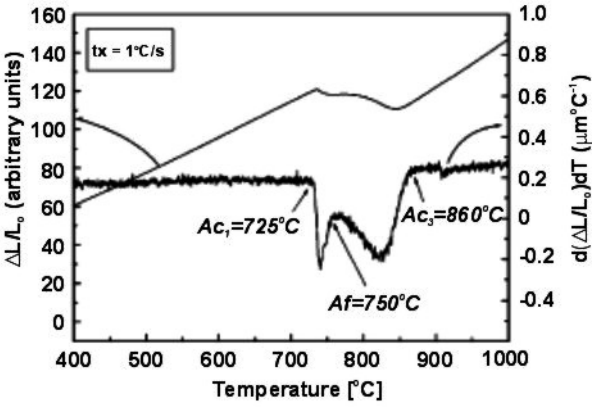

Fig. 3. Dilatometric curve of length change as a function of temperature and its corresponding derivative , for the heating rate of 1 $K \cdot s^{-1}$) [5]

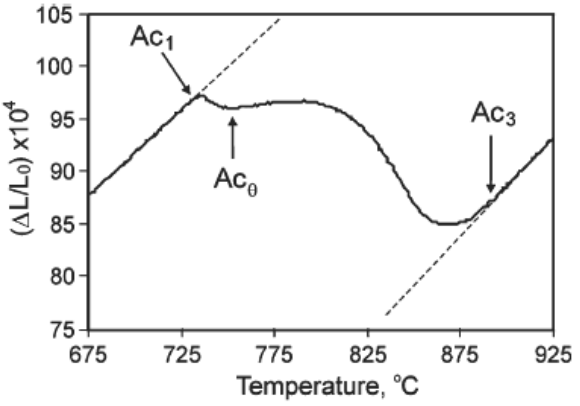

Fig. 4. Dilatometric curve for heating at 0.05 $K \cdot s^{-1}$ [6]

In this work, the finishing temperature of pearlite to austenite transformation will be described as Ac_{1f} (f = finish) according to Wever and Rose nomenclature (Ac_{1e} where e = ende) [7].

Similarly to the martensite start and finish temperatures (M_s and M_f), pearlite dissolution start temperature could be marked as Ac_{1s} but this temperature is commonly marked as Ac_1.

Approaches for predicting austenite start formation temperature Ac_1 or Ae_1 (as well as austenite formation finish temperature Ac_3 or Ae_3) during heating was made by regressing experimentally determined critical temperatures with respect to the steel chemistry in mass percent and some of them are listed below in chronological order:

R.A. Grange – 1961, according to [8]

$$Ae_1\ [°F] = 1333\text{-}25 \cdot Mn + 40 \cdot Si + 42 \cdot Cr - 26 \cdot Ni \quad (1)$$

$$Ae_3\ [°F] = 1570\text{-}323 \cdot C - 25 \cdot Mn + 80 \cdot Si - 3 \cdot Cr - 32 \cdot Ni \quad (2)$$

K.W. Andrews – 1965 [9]

$$Ae_1\ [°C] = 723\text{-}16.9 \cdot Ni + 29.1 \cdot Si + 6.38 \cdot W - 10.7 \cdot Mn + 16.9 \cdot Cr + 290 \cdot As \quad (3)$$

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

G.T. Eldis – 1978, according to [8]

Ae_1 [°C] = 712-17.8·Mn-19.1·Ni+20.1·Si+11.9·Cr+9.8·Mo (5)

Ae_3 [°C] = 871-254.4·√C-14.2·Ni+51.7·Si (6)

H.P. Hougardy – 1984, [10]

Ac_1 [°C] = 739-22·C+2·Si-7·Mn+14·Cr+13·Mo-13·Ni (7)

Ac_3 [°C] = 902- 255·C+19·Si-11·Mn-5·Cr+13·Mo -20·Ni+55·V (8)

O.G. Kasatkin, B.B. Vinokur – 1984 [11]

Ac_1 [°C] = 723-7.8·Mn+37.7·Si+18.1·Cr+44.2·Mo +8.95·Ni+50.1·V+21.7·Al+3.18·W+297·S -830·N-11.5·C·Si-14·Mn·Si-3.1·Si·Cr -57,9·C·Mo-15.5·Mn·Mo-5.28·C·Ni-27.4·C·V +30.8·Mo·V-0.84·Cr^2-3.46·Mo^2-0.46·Ni^2-28·V^2 (9)

Ac_3 [°C] = 912-370·C-27.4·Mn+27.3·Si-6.35·Cr-32.7·Ni +95.2·V+190·Ti+72·Al+64.5·Nb+5.57·W+332·S +276·P+485·N- 900·B+16.2·C·Mn+32.3·C·Si +15.4·C·Cr+48·C·Ni+4.32·Si·Cr-17.3·Si·Mo +18.6·Si·Ni+4.8·Mn·Ni+40.5·Mo·V+174·C^2 +2.46·Mn^2-6.86·Si^2+0.322·Cr^2+9.9·Mo^2+1.24·Ni^2 -60.2·V^2 (10)

W.L. Roberts – 1988 (Ae_3 only), according to [8]

Ae_3 [°C] = 910-25·Mn-11·Cr-20·Cu+60·Si+700·P -250·Al-Fn (F_n depends of carbon content) (11)

S.H. Park – 1996 (Ae_3 only), according to [8]

Ae_3 [°C] = 955-350·C-25·Mn+51·Si+106·Nb+100·Ti+68·Al -11·Cr-33·Ni-16·Cu+67·Mo (12)

J. Trzaska, L.A. Dobrzański – 2007 [12]

Ac_1 [°C] = 739-22.8·C-6.8·Mn+18.2·Si+11.7·Cr-15·Ni-6.4·Mo -5·V-28·Cu (13)

Ac_3 [°C] = 937.3-224.5·√C-17·Mn+34·Si-14·Ni+21.6·Mo +41.8·V-20·Cu (14)

These empirical equations (mainly linear regression) are very convenient to use but sometimes may cause severe errors in predicting critical temperatures Ac_1 and Ac_3. A better agreement between predicted and experimental values could be obtained by use of the artificial neural network technology (ANN) [13-16]. The neural network method is a kind of a regression method of which linear regression is a subset [14].

An examples of artificial neural network application for estimation of the Ac_1 and Ac_3 temperatures are shown in Figure 5 and Figure 6.

The value of the Pearson' correlation coefficient r for the neural network models presented in work [15] was 0.804 and 0.925 for the predicting of the respectively Ac_1 and Ac_3 temperatures. The Pearson' correlation coefficients for these temperatures calculated using the Andrews formula [9] was 0.788 and 0.790, using the same data set as for the neural network models.

It should be noted here, that one of the most important variable that could have effect on the artificial neural network prediction quality is the number of collected data set, containing the chemical compositions and the critical temperature values. This remark applies also to the regression methods. In work [15] authors collected from literature data more than 400 charges of the structural hypoeutectoid steels.

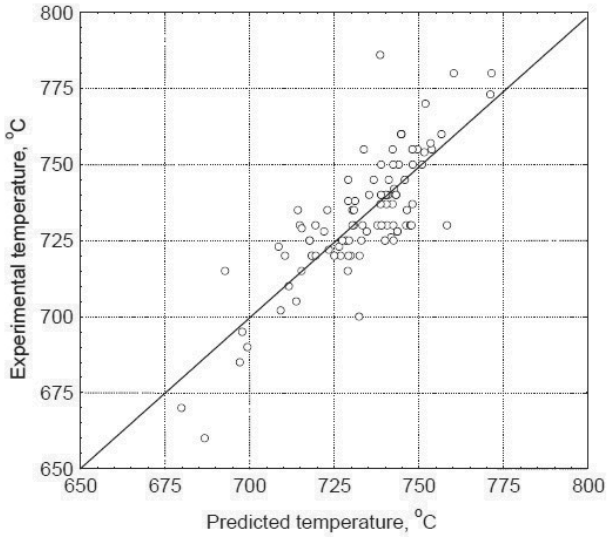

Fig. 5. Comparison of the experimental Ac_1 temperatures with values calculated using the neural network method [15]

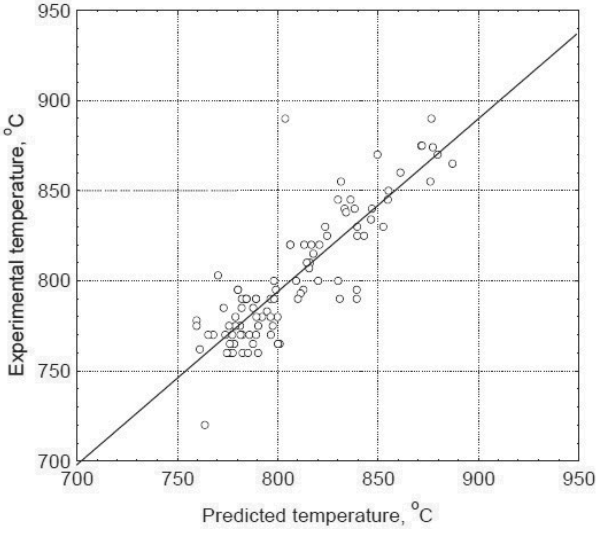

Fig. 6. Comparison of the experimental Ac_3 temperatures with values calculated using the neural network method [15]

Almost identical work as [15] was presented four years later, in 2008 [16], however, containing quotes of publication [15]. The main results of work [16] are presented in Figures 7 and 8.

In work [16] the number of collected data set was 140, from which 120 were used for training and 20 for testing. Similary to Refs. [15] values of Ac_1 and Ac_3 predicted by neural network models was compared with values of these temperatures calculated using Andrews equation (3).

Contrary to Refs. [15] this comparison was worse for artificial neural network model in case of Ac_3 temperature. However, it is to remind that the number of collected data set was almost three times smaller than in work [15].

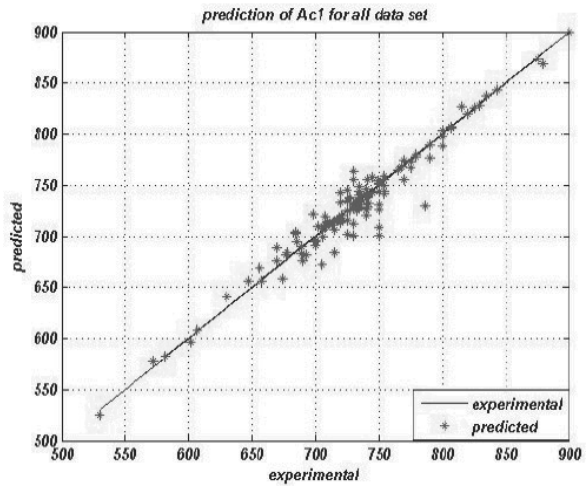

Fig. 7. Comparison of the experimental Ac_1 temperatures with values calculated using the neural network method [16]

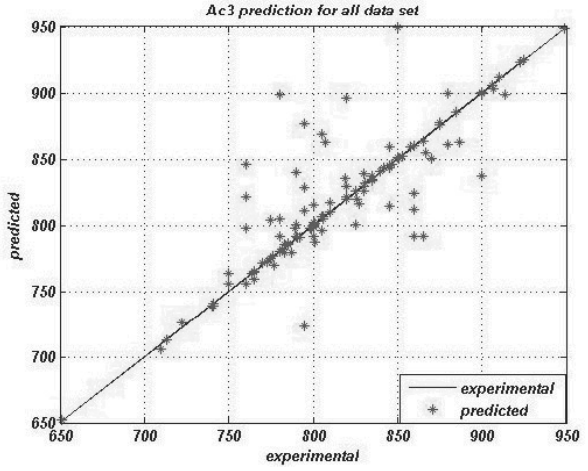

Fig. 8. Comparison of the experimental Ac_3 temperatures with values calculated using the neural network method [16]

2. Pearlite dissolution temperatures

The start temperature of pearlite to austenite transformation (Ac_1 temperature) used to be determined by dilatometric analysis, as it is shown in Figs. 1-4.

The Laboratory of Phase Transformations, Department of Physical and Powder Metallurgy, (AGH University of Science and Technology, Faculty of Metal Engineering and Industrial Computer Science), since several years, is able to determine by dilatometric analysis the finishing temperature of pearlite dissolution process, which is marked as Ac_{1f} (Figs. 9, 10), using high resolution Adamel Lhomargy DT1000 dilatometer and recently ultra-high resolution dilatometer RITA L78.

In some cases, dilatometric curves obtained by use of high resolution dilatometer do not allow for identification of the finishing temperature of pearlite dissolution process as it is shown in Figure 11.

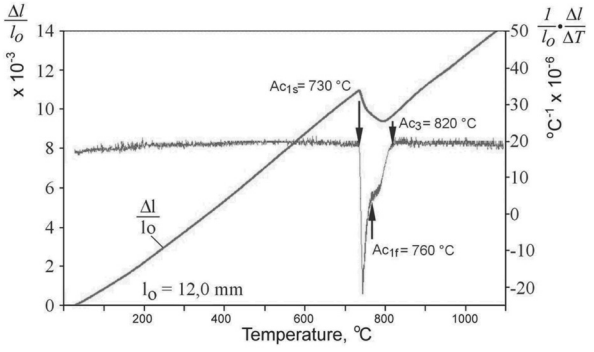

Fig. 9. Typical dilatometric curve of hypoeutectoid steel and its derivative. Heating rate 0.05 K/s, high resolution Adamel Lhomargy DT1000 dilatometer [17]

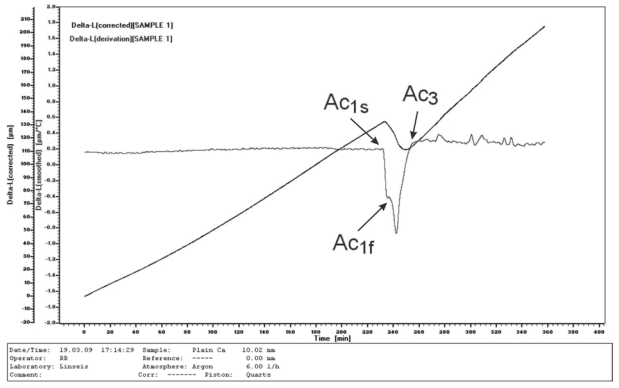

Fig. 10. Dilatometric curve of C56 hypoeutectoid steel and its derivative with the clear pearlite dissolution finish temperature. Heating rate 0.05 K/s, ultra-high resolution RITA L78 dilatometer [18]

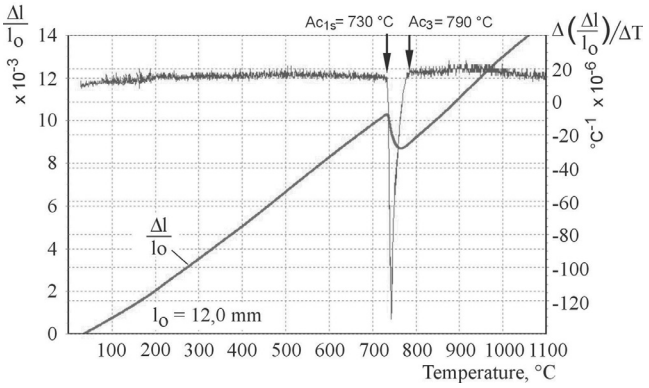

Fig. 11. Dilatometric curve of C56 hypoeutectoid steel and its derivative without the clear pearlite dissolution finish temperature. Heating rate 0.05 K/s, high resolution Adamel Lhomargy DT1000 dilatometer [18]

Neither the Polish Standard PN EN 10052:1993 nor the standards of other European Union countries (e.g. British BS EN BS EN 10052:1994) define pearlite to austenite transformation start and finish temperatures in steels. Thus, there is a lack of standard validations of the temperature determining the start of the coexistence range of ferrite and austenite during heating as well as the temperature determining the finish of this range, during cooling, in hypoeutectoid steels. Knowledge of such temperature range in the steel structure is very important e.g. during a thermo-mechanical treatment of DP steel (dual phase) [18]. Problems of lacking the proper definitions of phase transformation temperatures in steels was broadly discussed in Refs. [19].

Consequently, there is a lack of empirical equations predicting the pearlite to austenite transformation finish temperature.

In this paper, an attempt was made to find out a regression formula between chemical composition and the pearlite dissolution finish temperature during heating of hypoeutectoid steels.

3. Materials and method

Since there is no many accurate literature data about pearlite dissolution finish temperature, in present work multiple linear regression equations for calculating the Ac_{1f} temperature are based on experimental data set containing chemical composition and values of critical temperatures obtained by use of the dilatometric technique at the Laboratory of Phase Transformations, Department of Physical and Powder Metallurgy, AGH University of Science and Technology. It is obviously limited data set (only 89 charges of the structural hypoeutectoid steels), so the quality level of developed equations will require fine-tuning.

Analogically to the equations (1), (3), (5), (7) and (13) for Ac_1 temperature, identically set of elements was taken into account during elaboration of multiple linear regression equations for calculating the Ac_{1f} temperature, i.e. five different equations for the Ac_{1f} temperature was elaborated, hereinafter called modified Grange, Andrews, Eldis, Hougardy and Trzaska equation. In present work multiple linear regression equations only was elaborated, so there is no modified Kasatkin&Vinokur modified equation.

As it was mentioned above, collected data set contains only 89 charges of the structural hypoeutectoid steels and the range of the mass concentrations elements is presented in Table 1.

Table 1.
Ranges of the concentration of elements

element	mass concentration of element, %	
	min.	max.
C	0.06	0.75
Mn	0.12	2.94
Si	0.07	1.21
Cr	0.01	2.04
Ni	0.00	2.52
Mo	0.00	0.68
W	0.00	0.04
V	0.00	0.77
Cu	0.00	0.25
As	0.00	0.02

The elaborated modified Grange, Andrews, Eldis, Hougardy and Trzaska interrelations describing the influence of chemical composition on the Ac_{1f} critical temperature are presented in Eqs.(15)-(19) as well as Pearson' correlation coefficient and standard estimation error values are added (according to the StatSoft's Statistica ver.9). The comparative plots for the experimental and calculated values of Ac_{1f} temperature are shown in Figs. 12-16.

The modified Grange equation

$$Ac_{1f} = 752.6-5.7\cdot Mn+28.3\cdot Si+17.9\cdot Cr-14.2\cdot Ni \quad (15)$$

Pearson' correlation coefficient r = 0.64
Standard estimation error = 15 °C

The modified Andrews equation

$$Ac_{1f} = 752.6-14.4\cdot Ni+28.4\cdot Si+273\cdot W-5.8\cdot Mn +18.1\cdot Cr+929\cdot As \quad (16)$$

Pearson' correlation coefficient r = 0.65
Standard estimation error = 15 °C

The modified Eldis equation

$$Ac_{1f} = 748.4-2.1\cdot Mn-9.1\cdot Ni+32.1\cdot Si+25.2\cdot Cr-42.6\cdot Mo \quad (17)$$

Pearson' correlation coefficient r = 0.69
Standard estimation error = 14.7 °C

The modified Hougardy equation

$$Ac_{1f} = 752.7+30.7\cdot Si-2.0\cdot Mn+24.6\cdot Cr-42.1\cdot Mo-9.6\cdot Ni \quad (18)$$

Pearson' correlation coefficient r = 0.70
Standard estimation error = 14.7 °C

The modified Trzaska equation

$$Ac_{1f} = 752.7-11.2\cdot C-3.2\cdot Mn+33.2\cdot Si+25.9\cdot Cr-13.4Ni -36.8\cdot Mo-9.9\cdot V+39.9\cdot Cu \quad (19)$$

Pearson' correlation coefficient r = 0.71
Standard estimation error = 14.5 °C

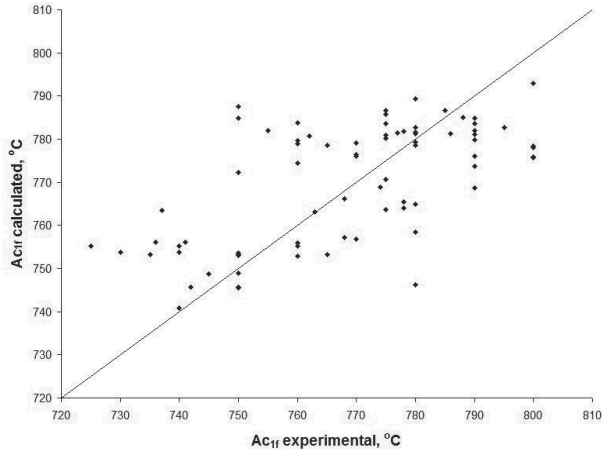

Fig. 12. Comparison of the experimental Ac_{1f} temperatures with values calculated using the modified Grange equation (15)

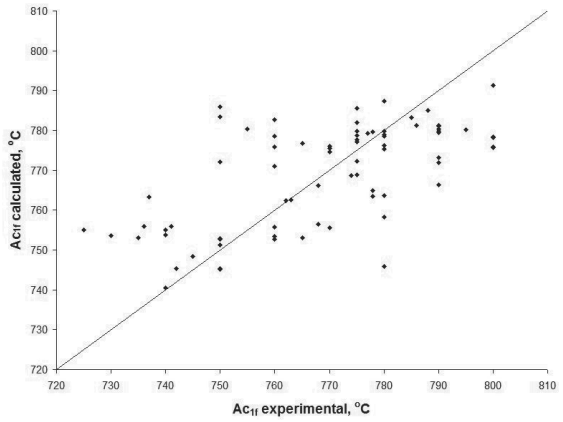

Fig. 13. Comparison of the experimental Ac_{1f} temperatures with values calculated using the modified Andrews equation (16)

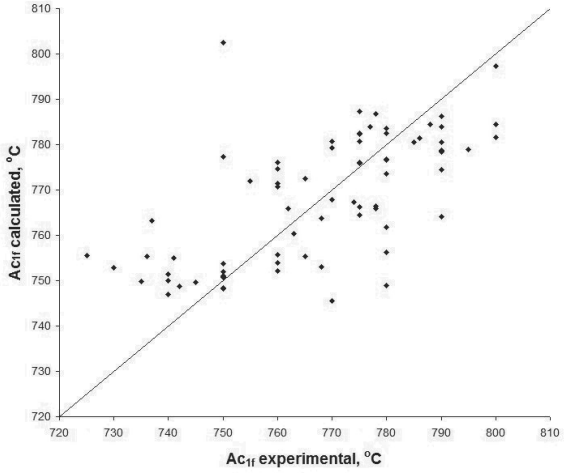

Fig. 14. Comparison of the experimental Ac_{1f} temperatures with values calculated using the modified Eldis equation (17)

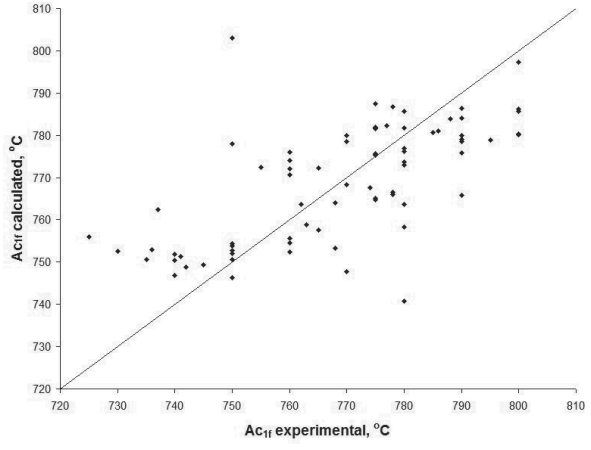

Fig. 15. Comparison of the experimental Ac_{1f} temperatures with values calculated using the modified Hougardy equation (18)

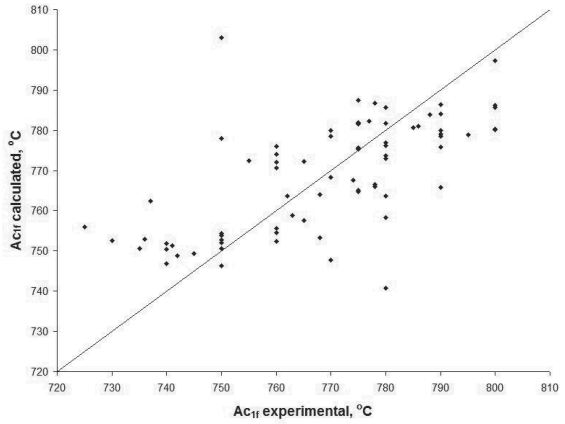

Fig. 16. Comparison of the experimental Ac_{1f} temperatures with values calculated using the modified Trzaska equation (19)

4. Conclusions

The highest Pearson' correlation coefficient value (but this value is still at low level) and lowest standard estimation error (but still high) was obtained by using modified Trzaska equation (eq.19), describing the influence of chemical composition on the Ac_{1f} critical temperature.

The low level of correlation coefficient value and high standard estimation error indicated so big difference between calculated and experimental values of the pearlite dissolution finish temperature Ac_{1f} during heating of hypoeutectoid steels. It is probably due to the not enough quantity of collected data set or multiple regression method is unable to ensure greater correctness of such calculations. It is possible that application of other suitable prediction methods such as artificial neural network models should be more effective.

References

[1] G. Krauss, Steels: Processing, structure and perfor-mance, ASM International, Materials Park, Ohio, 2005, 16.
[2] F.G. Caballero, C. Capdevila, C.G. de Andrés, Modelling of kinetics of austenite formation in steels with different initial microstructures, ISIJ International 41/10 (2001) 1093-1102.
[3] F.G. Caballero, C. Capdevila, C.G. de Andrés, Influence of pearlite morphology and heating rate on the kinetics of continuously heated austenite formation in a eutectoid steel, Metallurgical and Materials Transactions A 39 (2001) 1283-1291.
[4] H. Surm, O. Kessler, M. Hunkel, F. Hoffmann, P. Mayr, Modelling of the ferrite/carbide → austenite transformation of hypoeutectoid and hypereutectoid steels, Journal de Physique 120 (2004) 111-119.
[5] F.L.G. Oliveira, M.S. Andrade, A.B. Cota, Kinetics of austenite formation during continuous heating in a low carbon steel, Materials Characterization 58 (2007) 256-261.
[6] D. San Martín, P.E.J. Rivera-Díaz-del-Castillo, C.G. de Andrés, In situ study of austenite formation by dilatometry in a low carbon micoalloyed steel, Scripta Materialia 58 (2008) 926-929.

[7] F. Wever, A. Rose, Atlas zur Wärmebehandlung des Stähle, Verlag Stahleisen M.B.H., Düsseldorf (in German).
[8] A.A. Gorni, Steel forming and heat treatment handbook, www.gorni.eng.br/e/Gorni_SFHTHandbook.pdf.
[9] K.W. Andrews, Empirical formulae for the calculation of some transformation temperatures, Journal of the Iron and Steel Institute 203 (1965) 721-727.
[10] H.P. Hougardy, Werkstoffkunde Stahl Band 1: Grundlagen, Verlag Stahleisen G.m.b.H. Düsseldorf, 1984, 229.
[11] O.G. Kasatkin, B.B. Vinokur, Calculation models for determining the critical points of steel, Metallovedenie i Termicheskaya Obrabotka Metallov 1 (1984) 20-22.
[12] J. Trzaska, L.A. Dobrzański, Modelling of CCT diagrams for engineering and constructional steels, Journal of Materials Processing Technology 192-193 (2007) 504-510.
[13] L. Gavard, H.K.D.H. Bhadeshia, D.J.C. MacKay, S. Suzuki, Bayesian neural network model for austenite formation in steels, Materials Science and Technology 12 (1996) 453-463.
[14] H.K.D.H. Bhadeshia, Neural networks in Materials Science, ISIJ International 39 (1999) 966-979.
[15] L.A. Dobrzański, J. Trzaska, Application of neural networks for prediction of critical values of temperatures and time of the supercooled austenite transformations, Journal of Materials Processing Technology 155-156 (2004) 1950-1955.
[16] M. Arjomandi, S.H. Sadati, H. Khorsand, H. Abdoos, Austenite formation temperatures prediction in steels using an artificial neural network, Defect and Diffusion Forum 273-276 (2008) 335-341.
[17] B. Pawłowski, P. Bała, A new approach to dilatometric curve and its derivative interpretation, unpublished work.
[18] B. Pawłowski, P. Bała, J. Krawczyk, Some factors influencing the determination of eutectoid start and finish temperatures in hypoeutectoid steels, Metallurgy and Foundry Engineering 35/2 (2009) 121-128.
[19] B. Pawłowski, J. Pacyna, Phase transformation temperatures of steels, Metallurgy – Metallurgical Engineering News 77/3 (2010) 92-96 (in Polish).