Austenite – ferrite transformation temperature regression equations for low carbon steels with cooling rate account

P. Záhumenský, I. Kohútek* and J. Semeňák
U. S. Steel Košice, 044 54 Košice, Slovak Republic
*Corresponding author: ikohutek@sk.uss.com

Abstract. The austenite-ferrite transformation temperatures evaluated by dilatometry using thermo-mechanical simulator Gleeble 1500D are investigated in this paper. The effect of cooling rates 1, 5, 10 and 15°C/s on the upper and lower critical transformation temperatures was evaluated for 30 specimens of six material groups. Considering the cooling rate from dilatometry tests and chemical composition (C ≤ 0.2%, Mn ≤ 2%, Si ≤ 0.26%) of particular specimens, the regression equations for both transformation temperatures were derived. These relations have to be satisfied to avoid the crack formation during continuous casting, as well as to provide the hot rolling control. The proposed regression equations are compared with 32 similar ones adopted from 1961 to 2017 and exhibit a good conformity and accuracy.

1. Introduction
For the improvement of the surface quality of continuously cast steels, it is important to study the hot ductility behavior of steels considering their solidifying thermal history along with crack formation during casting. It has been reported [9] that there exist three temperature regions where typical embrittlement is observed in the carbon steels, i.e., drop from the melting temperature (Tm) to 1200°C (I), decrease from 1200 to 900°C (II), and cooling from 900 to 600°C (III). The cause of embrittlement in region (I) is the existence of residual liquid film along the dendritic interfaces. The ductility was found to be independent of the strain rate. In region (II), the precipitation of finely distributed oxy-sulfides at the austenite grain boundary weakens the boundary strength, and therefore such treatments as slow cooling, holding for certain time, or low-rate straining should be used to improve the ductility. On the other hand, the embrittlement in region (III) is manifested by a lower rate of straining. Controlling factors of this embrittlement are grain boundary sliding and the localization of strain to the pro-eutectoid ferrite film along the austenite grain boundary, which is invoked by the γ→α (austenite to ferrite) transformation [3], 5, 10, 11].

The present work provides a tool to calculate the austenite-ferrite transformation temperatures with the account of the effect of chemical composition of low carbon steels.

2. Methods
Using a Gleeble 1500D thermal deformation simulator of physical processes, the temperature range of γ→α transformation was defined for the steels and four different cooling rates corresponding approximately to those of slabs, transfer bars (i.e., semi-products during hot rolling between roughing mill and finishing mill), and hot rolled sheets. Standard size tensile specimens with dimensions of ∅10×110 mm taken from transfer bar were used in the experiment. The specimens were heated with heating rates of 25°C·s⁻¹ and 10°C·s⁻¹ to 1200°C and 1250°C, respectively. The austenitization temperature of 1250°C with holding time of 30 s was applied before cooling to room temperature by cooling rates of 1, 5, 10, and 15°C·s⁻¹, as shown in figure 1. The temperature range of γ→α
transformation during cooling was identified using dilatometry for the four different cooling rates. Although two methods (intersectional and tangential) were used for estimation of the upper (Ar$_1$) and lower (Ar$_3$) critical transformation temperatures in °C, only the results obtained by the intersectional one were used for the regression curve construction and estimation of transformation temperatures, which are plotted in figure 2. Due to a problem with accurate estimation of transformation temperatures for grades with high Si content (e.g., dynamo, non-oriented electrical steels and/or some HSLA specimens), specimens with Si > 0.3% were excluded from the analysis. Moreover, Ar$_1$ values for steels with carbon content below 0.05% were also excluded, since the eutectoid transformation was not considered to occur for such low carbon content.

The chemical composition of the steels has been determined using a LECO analyzer by Optical Emission Spectral Analysis. Full spectra of 22 chemical elements were measured in total.

3. Material
In total, 30 specimens of 6 material groups were tested, as shown in Table 1.

| Group No | Material group                  | Short description | Number of specimens |
|----------|---------------------------------|-------------------|---------------------|
| 1        | C-Mn                            | C-Mn              | 9                   |
| 2        | Drawing                         | Draw              | 9                   |
| 3        | High-Strength Low-Alloy         | HSLA              | 5                   |
| 4        | Interstitial Free               | IF                | 3                   |
| 5        | Dual-Phase                      | DP                | 3                   |
| 6        | Transformation-Induced Plastic  | TRIP              | 1                   |
|          | Total                           |                   | 30                  |

The contents of C, Mn, and Si (in weight %) for the evaluated materials are depicted in figures 3, 4, and 5, respectively, while the histogram of cooling rates is plotted in figure 6.
et of independent variables consists of cooling rate as well as HSLA, DP, TRIP. From the set of examined specimen components were examined to eliminate mutual dependences between components required for all variables in every equation. Three types of multi-regression were used: stepwise forward (starting with all variables, testing the addition of each variable using a chosen model fit criterion), stepwise backward (starting with all variables, testing the deletion of each variable using a chosen model fit criterion), and regression with fixed set of variables. P-values less than 0.05 of all components were required for all variables in every equation, and correlation between pairs of components were examined to eliminate mutual dependences between chemical elements. Note that in specimens measured in this investigation, an unexpected dependence among Mn, Ti and Nb was discovered, so that only Mn is present in the final equation. Moreover, the distribution of Al content in the set of examined specimens was revealed to be abnormal, and so Al (Al sol) was also excluded from the regression analysis. Thus, although the above elements are very important from the metallurgical point of view, they had to excluded from the final equations due to statistical reasons.

Final equations are as follows:

\[
\begin{align*}
\text{Ar}_3 &= +914 - 6.85 \text{-cooling rate} - 650 \text{-C} - 134 \text{-Mn} + 179 \text{-Si} \quad R^2_{\text{adj}}=0.91 \\
\text{Ar}_1 &= +814 - 9.08 \text{-cooling rate} - 532 \text{-C} - 121 \text{-Mn} + 165 \text{-Si} \quad R^2_{\text{adj}}=0.90
\end{align*}
\]
The comparison of measured temperatures with those estimated via regression equations (1) and/or (2) with an account of chemical composition and cooling rate is shown in Figure 7 (Ar1) and Figure 8 (Ar3). Differences between the measured value and that estimated from regression equation are shown in histograms plotted Figure 9 (Ar1) and Figure 10 (Ar3).

There are many empirical equations to calculate γ→α transformation temperatures derived by several authors for special steel grades and special conditions. The most comprehensive list of them is available in [4], other can be found in [1][2], [6][7]. In [9]total, seven equations for Ar1, as well as 25 equations for Ar3, are compared with equations (1) and (2). Variables in the mentioned equations are of three types: (a) plain linear variable, (b) combination of two chemical elements (8% of Ar3 equations, e.g. Si-Ni) and (c) non-linear function (54% of Ar3 equations - e.g. logarithm, exponent, square root) – see Table 3. The coefficient of particular variable in regression equation (only those which are used in more than 1/3 of equations) are shown in real scale in Figure 11 for Ar1 and in Figure 12 for Ar3: red circle denotes value of coefficients derived for equations (1)-(2) in this paper.

The intercept of all Ar3 equation is between 810°C and 914°C (910°C is known as A3 for ideal equilibrium iron-carbon binary phase diagram), except for that of Yuan [4] for non-deformed austenite (marked as YN in Figure 11), which consists mainly from the combination and/or non-linear functions of variables. The intercept used in all Ar1 – related equations is between 706°C and 814°C. The value of 723°C is referred to as A1 for the ideal equilibrium iron-carbon binary phase diagram.

Table 2. Transformation temperatures of particular grades during cooling

| ID     | Cooling rate 1°C·s⁻¹ | Cooling rate 5°C·s⁻¹ | Cooling rate 10°C·s⁻¹ | Cooling rate 15°C·s⁻¹ |
|--------|----------------------|----------------------|-----------------------|-----------------------|
|        | Ar3 °C | Ar1 °C | Ar3 °C | Ar1 °C | Ar3 °C | Ar1 °C | Ar3 °C | Ar1 °C | Ar3 °C | Ar1 °C |
| C-Mn (a) | 775   | 680   | 725   | 655   | 705   | 635   |
| C-Mn (b) | 650   | 595   | 605   | 520   | 570   | 460   |
| C-Mn (c) | 860   | 735   | 830   | 700   | 660   | 600   |
| C-Mn (d) | 765   | 675   | 780   | 650   | 700   | 625   |
| C-Mn (e) | 815   | 720   | 770   | 675   | 750   | 655   |
| C-Mn (g) | 670   | 630   | 640   | 580   | 620   | 545   |
| C-Mn (i) | 640   | 580   | 605   | 510   | 575   | 475   |
| C-Mn (j) | 650   | 580   | 615   | 530   | 590   | 495   |
| C-Mn (l) | 650   | 595   | 620   | 555   | 600   | 515   |
| DP (a)   | 690   | 640   | 660   | 590   | 635   | 555   |
| DP (b)   | 710   | 630   | 665   | 595   | 640   | 510   |
| DP (c)   | 630   | 560   | 590   | 520   | 570   | 485   |
| Draw (a) | 845   | 790   | 800   | 740   | 765   | 700   |
| Draw (b) | 840   | 795   | 815   | 745   | 795   | 720   |
| Draw (c) | 740   | 620   | 700   | 635   | 685   | 615   |
| Draw (d) | 835   | 755   | 830   | 750   | 820   | 720   |
| Draw (e) | 835   | 795   | 830   | 750   | 820   | 720   |
| Draw (f) | 880   | 780   | 870   | 710   | 865   | 690   | 855   | 680   |
| Draw (g) | 855   | 800   | 830   | 750   | 805   | 715   |
| Draw (h) | 840   | 765   | 810   | 710   | 785   | 690   |
| Draw (i) | 825   | 785   | 780   | 690   | 750   | 670   |
| HSLA (a) | 730   | 605   | 660   | 585   | 645   | 520   |
| HSLA (b) | 835   | 560   | 650   | 595   | 645   | 520   |
| HSLA (c) | 775   | 645   | 690   | 630   | 680   | 620   |
| HSLA (d) | 725   | 560   | 650   | 595   | 645   | 520   |
| HSLA (e) | 770   | 695   | 720   | 610   | 700   | 600   |
| IF (a)   | 860   | 835   | 855   | 805   | 845   | 785   |
| IF (b)   | 910   | 820   | 725   | 695   | 720   | 685   |
| IF (c)   | 745   | 715   | 725   | 695   | 720   | 685   |
| TRIP     | 590   | 550   | 540   | 430   | 460   | 370   | 430   | 370   |
It is generally adopted that the cooling rate affects the transformation temperature, while increasing the cooling rate decreases transformation temperatures – in equations (1) and (2) increasing cooling rate by 1°C·s⁻¹ causes decrease of Ar₁ by 9°C and/or Ar₃ by 7°C. The cooling rate is included in only approx. 1/7 of equations (probably because transformation temperatures were estimated from the process with a very slow cooling – sometimes they are denoted as Ae₁ and/or Ae₃, where "e" stands for equilibrium, see [4]).

The coefficients of carbon C, Mn and Ni have the same negative orientation for all equations caused a decrease of transformation temperatures with their increasing contents. The Si coefficients are all positive what is in concordance with expected increasing of transformation temperatures with increasing Si content according to binary Fe-Si diagram. The regression coefficient of chromium (not included in the equations derived in this paper) is mostly negative with 2 exceptions for Ar₃ and positive in all equations for Ar₁.

![Figure 7. Comparison of measured temperatures Ar₃ with those obtained via equation (1)](image1)

![Figure 8. Comparison of measured temperatures Ar₁ with those obtained via equation (2)](image2)

![Figure 9. Histogram of differences between measured Ar₁ and those obtained via regression equation (1)](image3)

![Figure 10. Histogram of differences between measured Ar₁ and those obtained via regression equation (2)](image4)

Given the above discussion, it can be concluded that the obtained results are sufficient for practical purpose of avoiding the crack formation during continuous casting and hot rolling control as well. However, a deeper insight into the embrittlement mechanism requires additional experiments including qualitative and quantitative phase analysis.
Table 3. Number of variables used in the regression by various authors

| Variable | Number of equations | Share of equations in the total scope |
|----------|---------------------|---------------------------------------|
|          | Ar₁                 | Ar₃ (%) from 8 | Ar₃ (%) from 26 |
| Intercept| 8                   | 26            | 100.0          |
| Cooling rate | 1                | 4             | 12.5           |
| C        | 5                   | 20            | 62.5           |
| Mn       | 8                   | 23            | 100.0          |
| Si       | 7                   | 18            | 87.5           |
| Ti       | 3                   |               | 0.0            |
| Nb       | 7                   |               | 0.0            |
| V        | 1                   | 5             | 12.5           |
| Cu       | 7                   |               | 0.0            |
| Al       | 3                   |               | 0.0            |
| Alsol    | 0                   |               | 0.0            |
| Ni       | 5                   | 10            | 62.5           |
| Cr       | 5                   | 13            | 62.5           |
| Mo       | 2                   | 9             | 25.0           |
| P        | 4                   |               | 0.0            |
| W        | 1                   | 2             | 12.5           |
| S        | 2                   |               | 0.0            |
| Zr       | 0                   |               | 0.0            |
| B        | 1                   |               | 0.0            |
| Ca       |                    |               | 0.0            |
| As       | 1                   | 1             | 12.5           |
| Sn       | 0                   |               | 0.0            |
| Sb       | 0                   |               | 0.0            |
| N        | 1                   |               | 0.0            |
| Others – linear combination | 2         | 0.0         | 7.7 |
| Others – non-linear | 14       | 0.0         | 53.8 |

Figure 11. Comparison of regression coefficients of various authors for selected variables in regression equation (1) for Ar₃.
In figure 11, “An” stands for Andrews [4], L1 and L2 mean Lotter A and Lotter B in [4], respectively, “Lu” stands for Lutsenko in [4], and “YN” refers to the equation of Yuan for non-deformed austenite in [4].

In figure 12, “Br” refers to Brandis in [4], Lu to Lutsenko in [4], N2 stands for Proprietary 3 in [4] or Nippon 2 in [9], while S1 stands for Schacht in [4].

**Figure 12.** Comparison of regression coefficients of various authors for selected variables in regression equation (2) for Ar1

6. Conclusions

- The experimental material characteristics can be utilized to avoid crack formation during bending and especially at the unbending section below the caster. This way, the surface quality of the final product can be improved.

- The data and regression equations on the austenite-ferrite transformation temperatures are instrumental for the control of process parameters during hot rolling.

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