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VERIFICATION OF THE VALIDITY OF THE COMMON PHENOMENOLOGICAL MODELS FOR LOW-ALLOYED TRIP STEEL

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ABSTRACT
During the development of the heat or thermomechanical treatment of new steel types it is necessary to know the characteristic temperatures of phase transformations under various cooling conditions. These include especially the starting and the final temperature of the austenitization interval, the starting temperature of the austenite to ferrite transformation and the starting temperatures of the bainite and martensite transformations. Necessary information can be obtained using dilatometry measurements or computations based on phenomenological models. In the experiment a dilatometry measurement was carried out on low-alloyed TRIP steel. The austenitized samples with and without deformation at a temperature of 910°C were cooled at various cooling rates. The CCT and CCCT graphs were projected based on the results from dilatometric and metallographic evaluation. With the aid of models describing the transformation, the characteristic transformation temperatures were calculated. The model accuracy for this steel was tested by comparison of the calculated values with experimental results.
Keywords: dilatometry, CCT graph, CCCT graph, transformation model

1. INTRODUCTION

When designing heat and thermomechanical treatment of various material types, it is convenient to know the chemical composition as well as the phase transformation temperature. In our experiment low-alloyed TRIP steel with addition of manganese and silicon was investigated (Table 1). Manganese and silicon play a very important role in the control of phase transformations and retained austenite stabilization. [1]

Table 1: Chemical content of low-alloyed TRIP steel

C	Mn	Si	P	S	Cr	Ni	Cu	Al	Nb	Mo	V	W
0,21	1,42	1,85	0,007	0,005	0,007	0,07	0,06	0,006	0,002	0,02	0,004	0,02

TRIP steels are multiphase steels, which are used in the automotive industry because of their high strength, good formability and low strain hardening coefficient. Their typical microstructure consists of polygonal ferrite, bainite and retained austenite, whose content in the structure is from 10 to 14% [2],[3]. This combination of high strength and ductility is achieved through the TRIP effect (TRansformation Induced Plasticity). The TRIP effect is the transformation of retained austenite to deformation induced martensite during plastic deformation [3], [4].
TRIP steels represent just the kind of steels where the knowledge of precise temperature dependencies of the formation of individual phases is very important to achieve the required final properties in production. Especially during cooling it is necessary to avoid the pearlite nose. Pearlite is undesirable

in the TRIP structure, because it decreases the carbon content in retained austenite, which then decreases its stability Pearlite also has a negative impact on ductility and formability [1].

2. EXPERIMENT

Experimental detection of phase transformation temperatures was carried out through dilatometric measurement on the Bähr dilatometer in an inert atmosphere. Test specimens were cylindrical with a diameter of 5 mm and length of 10 mm. The temperature course consisted of heating to 950°C, a holding time of 30 sec, temperature drop to 910°C and cooling to room temperature. In the case of a measurement with deformation, the specimen deformation $\varphi = 0.7$ with a strain rate of $10s^{-1}$ was carried out before cooling to room temperature. Phase transformation temperatures were detected from the cooling curves. Samples were documented metallographically on an optical microscope.

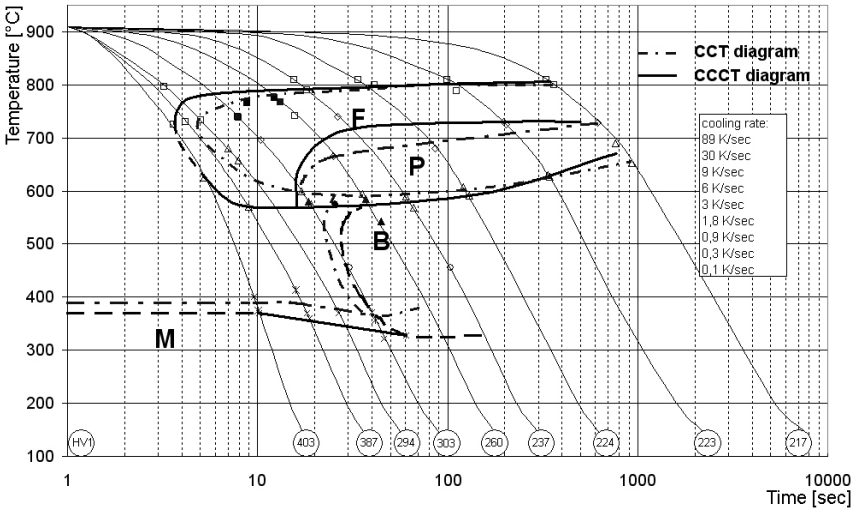

Figure 1: CCT and CCCT diagrams

From a comparison of the CCT and the CCCT diagrams (Figure 1) it is obvious that deformation significantly shifts the start of ferrite transformation to higher cooling rates. The bold ferrite islands in the martensite matrix were observed in the deformed samples with the cooling rate of 90 Ks^{-1} (Figure 2). In the samples without deformation before cooling, the volume fraction of ferrite was remarkably lower (Figure 3). Moreover, the deformation accelerates the pearlite transformation, which leads to an extension of the time and the temperature interval for pearlite transformat-ion. For martensite transformation the phenomenon was reversed. The transformation begins at lower temperatures due to deformation. In these diagrams the bainite range is only marked for guidance, because no bainite forms in this kind of steel during dilatometry measurement with continual cooling.

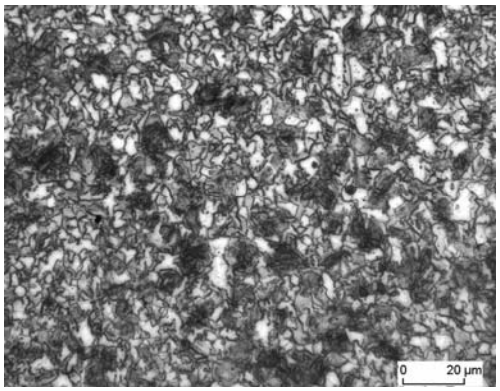

Figure 2: Martensite-ferrite structure with deformation, cooling rate 90 Ks^{-1}

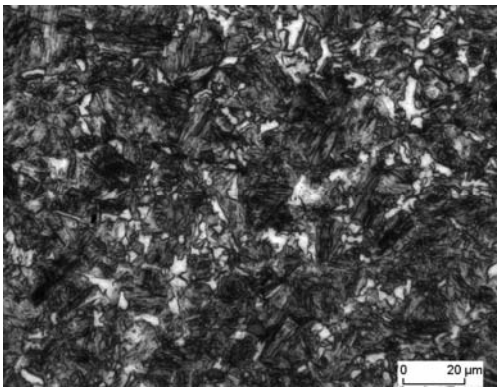

Figure 3: Martensite-ferrite structure without deformation, cooling rate 90 Ks^{-1}

3. PHENOMENOLOGICAL MODELS

The mathematical description of a phenomenological model is usually built on the basis of parametric equations, where multiples of weight contributions of individual alloying elements are added or subtracted according to their influence on a given type of transformation. These empirical models are determined either experimentally, based on the measurement of many specimens with similar chemical compositions, or they are compiled using statistical information from various material sheets. In general, phenomenological models have a strictly defined interval of validity. The interval boundaries are derived from the type of steel and the processing methods for which it was developed. This

limitation can be given by a series of parameters, e.g. chemical composition, cooling rate, material thickness etc.

Table 2:Models for determination of transformation temperatures with results

	Model [°C],[F]*)	Result [°C]	Notice
Choquet [5]	$A_{r3} = 902 - 527C - 62Mn + 60Si$	817	- samples cooled directly after hot rolling
Nippon Steel 1 [6]	$A_{r3} = 879{,}4 - 516{,}1C - 65{,}7Mn + 38Si + 274{,}7P$	752	- for cooling rate of 20 Ks^{-1}
	$A_{r1} = 706{,}4 - 350{,}4C - 118{,}2Mn$	467	
Nippon Steel 2	$A_{r3} = 901 - 325C - 92Mn + 33Si + 287P + 40Al - 20Cr$	767	
Andrews [7]	$A_{r3} = 910 - 203\sqrt{C} - 15{,}2Ni + 44{,}7Si + 104V + 31{,}5Mo + 13{,}1W - (30Mn + 11Cr + 20Cu - 700P - 400Al - 120As - 400Ti)$	864	- for steels with carbon content below 0.6%
	$A_{r1} = 723 - 10{,}7Mn - 16{,}9Ni + 29{,}1Si + 16{,}9Cr + 290As + 6{,}38W$	761	
	$M_S = 539 - 423C - 30{,}4Mn - 17{,}7Ni - 12{,}1Cr - 11Si - 7Mo$	387	
Steven [8]	$B_S = 1526 - 486C - 162Mn - 126Cr - 67Ni - 149Mo$ *)	642	
	$B_{50} = B_S - 108$ *)	582	
	$B_{100} = B_S - 216$ *)	522	
Suehiro [9]	$B_S = 718 - 425C - 42{,}5Mn$ *)	570	
Rowland [10]	$M_S = 930 - 600C - 60Mn - 20Si - 50Cr - 30Ni - 20Mo - 20W$ *)	361	
Krauss [11]	$M_S = 561 - 423C - 30{,}4Mn - 17{,}7Ni - 12{,}1Cr - 11Si - 7Mo$	415	

For a comparison of the experiment with the phenomenological models Choquet, Nippon Steel 1, Nippon Steel 2 and Andrews (Table 2), the following austenite transformation temperatures were calculated: A_{r3} – temperature of the beginning of the austenite transformation to ferrite, A_{r1} – temperature of the end of the austenite transformation to ferrite, B_s – temperature of the beginning of the bainite transformation, B_x – required temperature for the transformation of x% of bainite, M_s – temperature of the beginning of the martensite transformation.

The minimum influence of alloying elements occurs in the Choquet equation, which only considers the influence of carbon and silicon as ferrite-formation elements and the influence of manganese content, which assists in austenite stabilization and thereby moves A_{r3} to lower temperatures. In the Nippon Steel 1 model the influence of phosphor is taken into account. In the extended Nippon Steel 2 model the influence of aluminum and chrome as ferrite-formation elements is added as well. In comparison to other models, the Andrews empirical formula includes many alloying elements in the computation, e.g. the influence of titanium and arsenic.

A common complication is that the temperature of the beginning and the end of the austenite transformation to ferrite is mostly computed for the equilibrium state, which means for very low cooling rates. Higher cooling rates are only taken into account in some models.

Besides the Nippon Steel 1 and 2 models, which are determined for the cooling rate of 20 Ks^{-1}, the temperatures from individual computations were compared with the value obtained from the dilatometry measurement at the slowest cooling rate of 0.1 Ks^{-1} (Figure 4, Table 2).

Based on the dilatometry measurement of the examined steel the equilibrium temperature A_{r3}=800°C was determined. With this temperature it is possible to compare the Choquet and Andrews models. The best is the Choquet model, where the value of 816.5°C was obtained. The computation according to Andrews differed by 64°C from the experimentally reached temperature. Better agreement with the Choquet model can be explained by the fact that the steel used in this experiment contains higher contents of manganese and silicon only. And the Choquet model is focused just on these elements.

The Nippon Steel 1 and Nippon Steel 2 models, which focus on the cooling rate of 20Ks^{-1}, are not directly comparable with the experimentally detected values, because the experiment was not carried out for this cooling rate (Figure 4, Table 2).

The temperature A_{r1} was computed according to just two models: Nippon Steel 1 and Andrews. For the Nippon Steel 1 model only the influence of carbon and silicon was considered in comparison with the Andres model, where other alloying elements were included as well (Table 2).

For this kind of steel the computations of the B_s temperature are only meant for orientation. In TRIP steels the bainite transformation generally takes place during the isothermal holding at a temperature of approximately 400°C. This fact was not taken into account during the computation. To determine the M_s temperature three models were applied: Andrews, Rowland and Krauss. In all these models the C, Mn, Ni, Cr, Si and Mo elements are used. The highest emphasis is put on carbon and manganese. Additionally, the Rowland model includes the influence of vanadium in the computation. The temperature M_s was experimentally determined to be 390 °C. The smallest difference of only 3°C between the computed and the measured temperatures was detected with the Andrews model. With the Rowland model the M_s temperature was almost 30°C lower than the measured temperature. The temperature in the model according to Krauss was about 25°C higher. (Table 2).

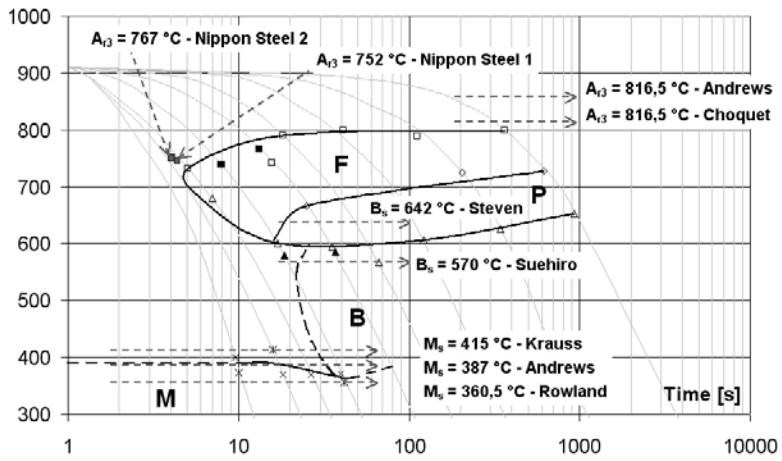

Figure 4. Comparison of the empirical computation and the CCT diagram of 0,2C-1,4Mn-1,8Si TRIP steel without deformation

4. CONCLUSION

The results of the dilatometry measurement were compared with the computed values according to the known models from the literature. The majority of these models are designed for the equilibrium and quasi-equilibrium states. Therefore, the computations were compared to experiments with the same cooling conditions. With the comparison of temperature A_{r3}, the best agreement was achieved with the model according to Choquet, because this model includes the high influence of manganese and silicon. The deviation was +17°C.

To determine the M_s temperature, the model according to Andrews was found to be the most suitable. The difference between the computed value and the experiment was only 3°C.

The experiment implies that for models to be effectively used it is necessary to verify the applicability of the model for each kind of steel as well as to investigate the interval of validity.

5. REFERENCES

[1] Bleck, W.: Using the TRIP effect – the Dawn of a Promising Group of Cold Formable Steels, Proccedings of International Conference on TRIP – Aided High Strength Ferrous Alloys, Belgium, 2002.

[2] Timokhina, I. B.; Hodgson, P. D.; Pereloma, E. V.: Morphology and Stability of Retained Austenite in Thermomechanically Processed C-Mn-Si(-Nb) TRIP Steels, Proceedings of Euromat 2001, Italy, 2001.

[3] Lee, Ch. G.; Kim, S. J.; Lee, T. H.; Lee, S.: Effects of Volume Fraction and Stability of Retained Austenite on Formability in a 0,1C-1,5Si-1,5Mn-0,5Cu TRIP-Aided Cold-Rolled Steel Sheet, Materials Science and Engineering A00, p. 1-8, 2003.

[4] Zou, H. H.; Li, L.; Fu, R. Y.; De Cooman, B. C. a kol.: Effect of Retained Austenite Stability of Si-Mn TRIP Steel on the Product of Strength and Ductility, Proccedings of International Conference on TRIP – Aided High Strength Ferrous Alloys, Belgium, 2002.

[5] Choquet, P. et al.: Mathematical Model for Predictions of Austenite and Ferrite Microstructures in Hot Rolling Processes, IRSID Report, St. Germain-en-Laye, p.7, 1985.

[6] R&D Team of the Kimitsu Steelworks of Nippon Steel, 2003.

[7] Andrews, K. W.: Empirical Formulae for the Calculation of some Transformation Temperatures, Journal of The Iron and Steel Institute, p. 721, 1965.

[8] Steven, W. et al.: Journal of the Iron and Steel Institute, 183, 1956, 349.

[9] Suehiro, M. et al.: Tetsu-to-Hagané, 73, p.1026-1033, 1987.

[10] Rowland, E. S. et al.: Transactions ASM, 37, 1946, 27.

[11] Krauss, G.: Principles of Heat Treatment and Processing of Steels, ASM International, p. 43-87, 1990.