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TRANSFORMATION DIAGRAMS OF SELECTED STEEL GRADES WITH CONSIDERATION OF DEFORMATION EFFECT

The aim of this article was to assess the effect of previous plastic deformation on the transformation kinetics of selected steels with a wide range of chemical composition. Transformation (CCT and DCCT) diagrams were constructed on the basis of dilatometric tests on the plastometer Gleeble 3800 and metallographic analyses supplemented by measurements of HV hardness. Effect of previous deformation on transformation was evaluated of the critical rate of formation of the individual structural components (ferrite, pearlite and bainite) in the case of formation of martensite respect to M_s temperature. Previous plastic deformation accelerated especially diffuse transformations (ferrite and pearlite), temperature of M_s was lower after previous plastic deformation and bainitic transformation was highly dependent on the chemical composition of steel.

Keywords: transformation diagrams of steels, phase transformation, plastic deformation, dilatometric tests, Gleeble 3800

1. Introduction

Knowledge of the kinetics of transformation of steel during cooling belongs to its principal characteristics, without which it would be impossible to suitably control the thermomechanical processes during forming processes, as well as the resulting structural characteristics and hence the mechanical properties of the final products [1-3]. For a description of the kinetics of transformations during cooling of steel, the transformation diagrams of the type TTT (Time Temperature Transformation) and CCT (Continuous Cooling Transformation) are used as the best instrument. Transformation diagram can be constructed either on the basis of physical tests (mostly dilatometry) or with the use of mathematical modelling in specialised software (JMatPro, QTSteel and others) [2,4-6]. The TTT diagrams are used in heat treatment processes associated with the isothermal conditions, whereas the CCT diagrams are used to describe the transformation kinetics during anisothermal conditions, more specifically during cooling at constant cooling rates. However, both the aforementioned diagrams are especially useful for heat treatment operations, which do not directly follow the operations of hot forming (forging, rolling, etc.) [1,7]. For a description of transformation kinetics during cooling immediately following the forming operations, a modified CCT diagram is used, which takes into account also the influence of deformation. These diagrams are referred to as DCCT (Deformation Continuous Cooling Transformation) [2,8]. Kinetics of steel transformation is influenced by many parameters. Chemical composition is primarily the main and essential parameter influencing the kinetics of transformations. However, thermomechanical factors have a significant influence on the transformation kinetics, which includes particularly the austenitization temperature, dwell at this temperature and the magnitude of deformation and strain rate [2,8-11]. This paper is focused namely on the assessment of the impact of deformation on the kinetics of individual transformations in different types of steels with a wide range of chemical composition.

2. Experimental description

The experiment was performed for a total of five different grades of steel, which are presented in Table 1 together with their chemical composition. The range of the chemical composition varied for carbon from approx. 0.2 to 0.8 wt. %, for manganese from approx. 0.6 to 1.4 wt. %, for chromium content from approx. 0.3 to 1.3 wt. %; molybdenum, vanadium, nickel or boron appeared in some steels as alloying elements.

On the basis of dilatometric tests that were performed on the dilatometric module of the plastometer GLEEBLE 3800, transformation diagrams of the type CCT and DCCT were constructed for the aforementioned steels. For dilatometric tests without deformation, the samples of special design were used, which had hollow head parts with the diameter of 10 mm and reduced

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Chemical composition of selected steels in wt. %

| Steel grade	20MnCrS5	32CrB4	42CrMo4	51CrV4	Rail Steel
C	0.17-0.22	0.30-0.34	0.38-0.45	0.47-0.55	0.74-0.84
Mn	1.10-1.40	0.60-0.90	0.60-0.90	0.70-1.10	0.75-1.25
Cr	1.00-1.30	0.90-1.20	0.90-1.20	0.90-1.20	max. 0.30
Si	max. 0.40	max. 0.30	max. 0.40	max. 0.40	0.10-0.60
V	—	—	—	0.10-0.25	max. 0.01
Ni	—	—	—	—	max. 0.25
Mo	—	—	0.15-0.30	—	max. 0.06
B	—	0.001-0.005	—	—	—
S	0.02-0.04	max. 0.025	max. 0.035	max. 0.035	max. 0.02
P	max. 0.035	max. 0.025	max. 0.025	max. 0.025	max. 0.02
Norm	EN 10084-1998	EN 10263-4	EN 10083-3	EN 10083-3	—
	[12]	[13]	[14]	[14]	[15]

central part with the diameter and length of 5 mm. The advantage of these special samples is the possibility of application of high cooling rates, permitting even cooling rate exceeding 100 °C/s. However, the design of these samples does not allow to apply deformation on these samples, whereas dilatometric tests with an impact of the previous deformation were performed on simple cylindrical samples of the SICO type, which had a diameter of 6 mm and an overall length of 86 mm. The samples of the SICO type make it possible to apply compressive deformation, however, their cooling rate is limited by the rate of approx. 40 °C/s, exceptionally up to 65 °C/s [8, 16]. Both types of the samples are shown in Figure 1.

The dilatometric tests were carried out by heating at the heating rate of 10°C/s to the austenitization temperature, which was for all steels uniform 850°C, with the exception of the rail steel (860°C). These temperatures were selected in accordance with practical experiences. This temperature selection in combination with chosen dwell was a guarantee of full structure austenitization of the selected steels [6,8,15]. This was followed by a dwell at this temperature for 300 seconds. Next procedure was different in dependence on the creation of DCCT or CCT diagram. In the case of the CCT diagram a cooling to the room temperature at constant cooling rates followed. The cooling rates were selected in a range, that would make it possible to describe all the transformations in the selected steels, and they varied from 0.1 to 100°C/s. In the case of the DCCT diagram, a deformation of 0.35 at the strain rate of 1 1/s was included immediately after the dwell and only then the individual samples were cooled down at the constant cooling rates ranging from 0.1 to 40°C/s. For an assessment of transformation changes at higher cooling rates after the applied deformation, a calculation was used based on the simulation software QTSteel 2.3, which enable a calculation of transformation changes also after application of deformation. However, the accuracy of the software is in some cases not fully satisfactory, so this option was used only in inevitable cases [6]. After that, all the samples were subjected to metallographic analyses and measurements of the Vickers hardness HV.

3. Discussion of results

Figures 2-6 show the comparative diagrams of all five steels, which were constructed by combining the CCT and DCCT diagrams for individual steels in order to ease the assessment of the effect of deformation on the transformations. It can be seen from these diagrams that the influence of deformation has a considerable influence on the kinetics of transformation.
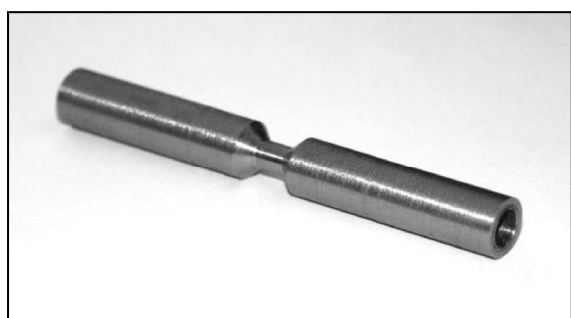
a) Special sample for dilatometric tests without deformation
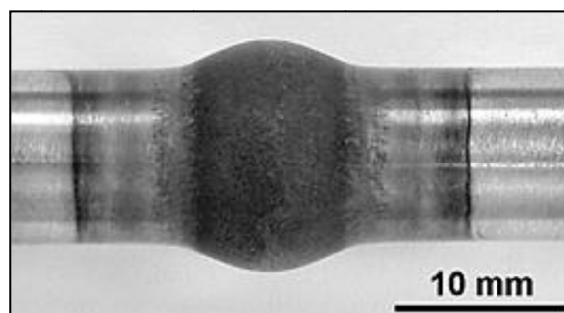
b) SICO sample after deformation

Fig. 1. Types of samples for dilatometric tests: a) without deformation; b) with deformation [16]
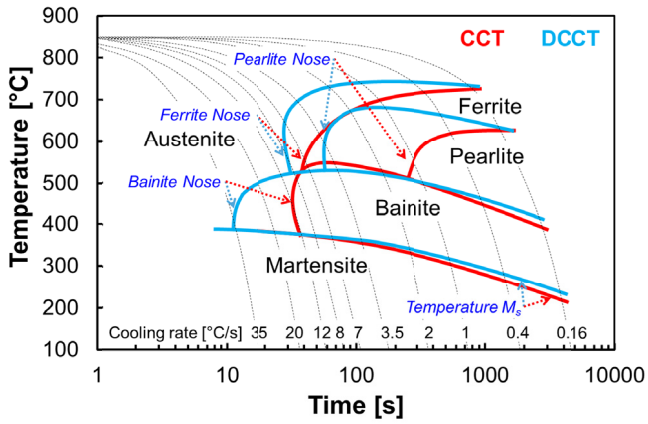
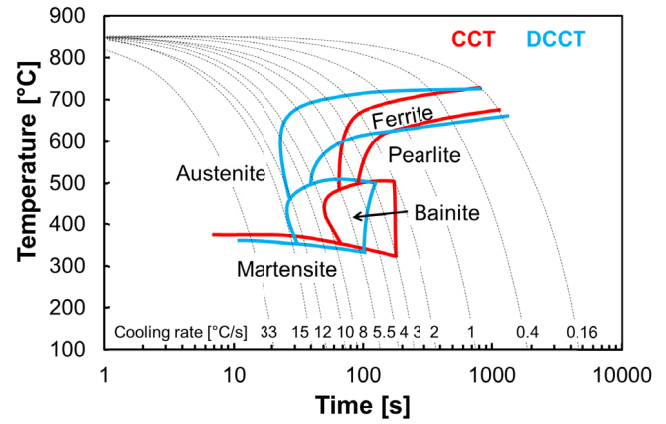Fig. 2. Comparison of CCT and DCCT transformation diagrams of steel 20MnCrS5

Fig. 3. Comparison of CCT and DCCT transformation diagrams of steel 32CrB4
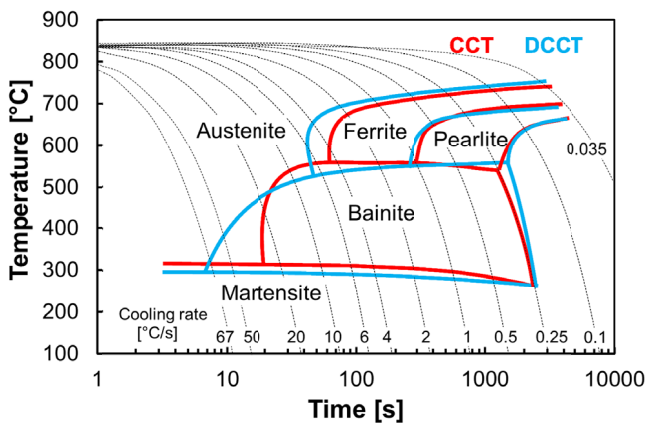

Fig. 4. Comparison of CCT and DCCT transformation diagrams of steel 42CrMo4
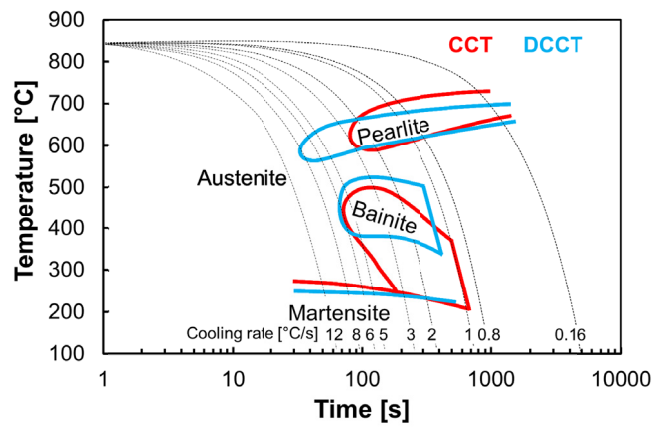

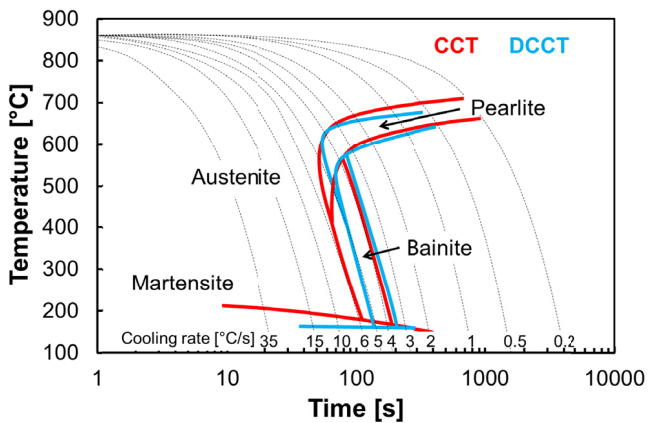Fig. 5. Comparison of CCT and DCCT transformation diagrams of steel 51CrV4

Fig. 6. Comparison of CCT and DCCT transformation diagrams of Rail Steel

Nevertheless, for an assessment of the effect of the previous deformation on the kinetics of transformation of steels with the influence of different chemical composition it was necessary to determine the so-called critical cooling rates (CCR) for individual transformations. In the case of ferritic, pearlitic and bainitic transformations the cooling rates were thus determined corresponding to the "nose" of the individual transformations [17]. This is, however, impossible in the case of martensitic transformation, since this is a transformation that takes place namely in the steels with the highest cooling rates and it is therefore impossible to achieve in any case the "nose" of this transformation and therefore to determine the critical cooling rate. For this reason, in the case of martensitic transformation, the temperature of the start of formation of the martensite M_s was monitored, as well as the influence of deformation on it. The system of determination of the critical rates is demonstrated in the comparative transformation diagram for the steel 20MnCrS5 – in Figure 2. The values of the achieved critical cooling rates are in Table 2. For clarity of the influence of the previous deformation on martensitic transformation the table 2 was added with the average values of M_s and of its mean errors. These errors were calculated based on the performed physical experiments (dilatometric tests on the plastometer Gleeble 3800) in the examined range of cooling rates.

For the purpose of a transparent generalising evaluation of the effect of deformation on the kinetics of phase transformations, bar diagrams were constructed for all five investigated steels, which documented the effect of the previous deformation on the value of the critical cooling rate (CCR) for individual transformations. The influence of the previous deformation on the critical cooling rate for formation of ferrite is documented in

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TABLE 2

Values of critical cooling rate and temperature M_s in depending on ferritic, pearlitic and bainitic transformation for investigated steels

Steel	Critical Cooling Rate – CCR [°C/s]					
	Ferrite		Pearlite		Bainite	
	CCT	DCCT	CCT	DCCT	CCT	DCCT
20MnCrS5	7	8	1	3.5	12	35
32CrB4	5.5	12	4	8	8	15
42CrMo4	4	6	1	1.5	20	67
51CrV4	—	—	3	8	6	6
Rail Steel	—	—	5	5	6	5
Steel	Average Temperature M_s [°C]					
	Martensite					
	CCT			DCCT		
	M_s		Mean Error	M_s		Mean Error
20MnCrS5	351.4		10.5	353.5		10.7
32CrB4	354.9		6.1	347.4		3.0
42CrMo4	298.2		6.2	290.9		3.3
51CrV4	249.6		6.8	241.9		3.5
Rail Steel	176.0		5.7	163.0		0.9

Figure 7. In two steels it was impossible to detect the formation of ferrite, since their composition was close to that of eutectoid steel (51CrV4), or it corresponds to the hyper-eutectoid steel (rail steel). It is obvious that the previous deformation accelerated the ferrite transformation in all hypo-eutectoid steels (20MnCrS5, 32CrB4 and 42CrMo4). An assumption that embedded deformation accelerates the ferrite transformation controlled by diffusion was confirmed. The deformation increases the number of lattice defects, which promote the diffusion of all atoms in solid solution, which thus leads to a more rapid nucleation and growth of nuclei of a newphase [2, 9, 10].

The influence of plastic deformation to a shifting of the pearlitic nose is documented in Figure 8, from which it is evident that deformation never resulted in a deceleration of this transformation. In the steels 20MnCrS5, 32CrB4, 42CrMo4 and 51CrV4 this transformation was accelerated due to the previous deformation. In the case of the rail steel the deformation had no effect on the critical rate of formation of pearlite. As demonstrated by studies of the authors [2,9], relatively long time intervals between the start of the deformation and the start of the formation of pearlite

can lead to a suppression of the effects of deformation. It means that no considerable acceleration of the pearlite transformation may take place, but that on the contrary, it may be even slightly delayed, however, the resulting pearlite should be finer [9,11]. An evidence of this assumption is microstructure of the rail steel after the cooling by the rate of 3°C/s (Fig. 9).

As it is evident from Figure 10, for the steels 20MnCrS5, 32CrB4 and 42CrMo4 previous deformation caused even an acceleration of the bainite transformation, the kinetics of which depended primarily on the chemical composition of the material. For steel 51CrV4, the influence of deformation did not cause any significant shift of the bainitic nose. It seems that the value of CCR for the bainitic transformation mostly decreases with the increasing carbon content [9,18,19].

Since in the case of martensitic transformation no analogous comparison was possible, in this case, a bar diagram was constructed in Figure 11 comparing the impact of the embedded deformation on the average value of the temperature of the start of martensitic transformation M_s of the investigated steels, including the scatter of the measured values. What concerns
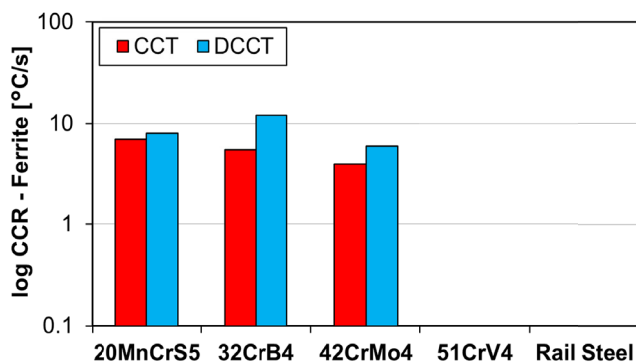

Fig. 7. Effect of plastic deformation on critical cooling rate for ferrite transformation of investigated steels
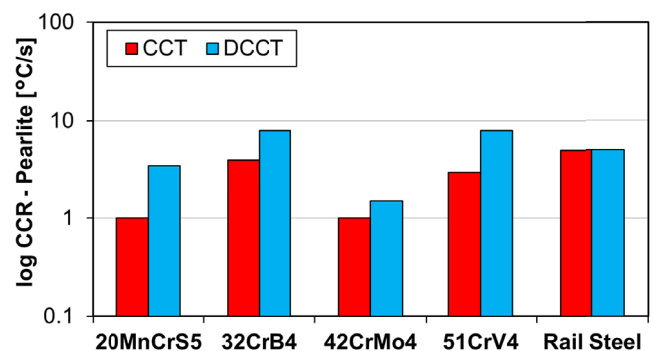

Fig. 8. Effect of plastic deformation on critical cooling rate for pearlite transformation of investigated steels

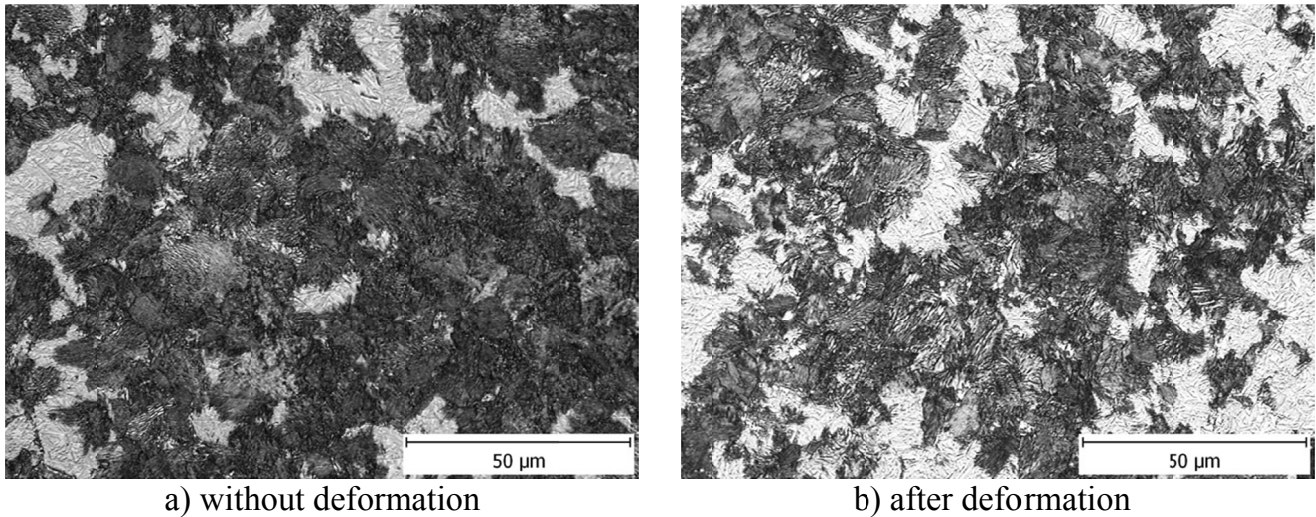a) without deformation   b) after deformation

Fig. 9. Influence of deformation on the microstructure of the examined rail steel after the dilatometric tests and the cooling rate of 3°C/s
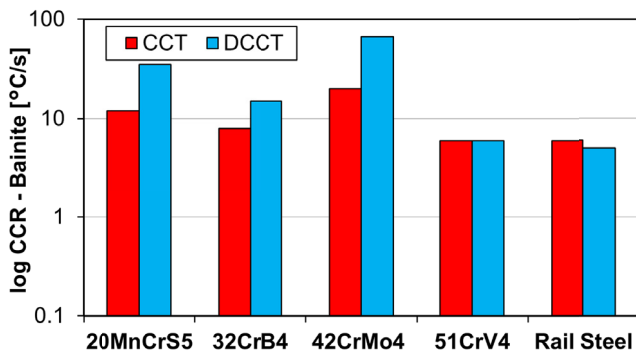

Fig. 10. Effect of plastic deformation on critical cooling rate for bainite transformation of investigated steels
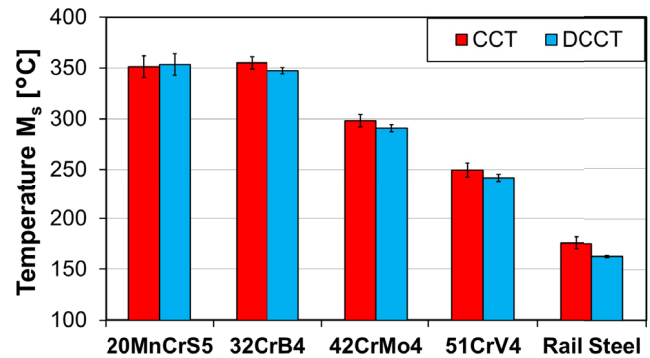

Fig. 11. Effect of plastic deformation on M_s temperature of investigated steels

the influence of deformation on the martensitic transformation, depends mainly on the cooling rate [9,20]. In the case of higher cooling rates a decrease of the temperature of the start of the martensitic transformation occurs, while in the case of slower cooling rates the M_s temperature is compared with the analogous temperature for the non-deformed samples or it even slightly exceeds this temperature. Figure 11 confirms the expected trend of the M_s temperature, which decreases with the increasing carbon content. It also follows from the realised experiments that with the exception of the steel 20MnCrS5 the deformation always resulted in a decrease of the M_s temperature. In four out of five investigated steels an assumption was confirmed that during the deformation of austenite a dense network of dislocations is formed, which hindered a progression of the phase interface. Behaviour of steel 20MnCrS5 rather indicates that as a result of the embedded deformation lattice defects accumulated and formation of martensite was initiated [2,9,20].

4. Conclusions

The influence of the previous deformation on the kinetics of phase transformations in five selected steels with different chemical composition was investigated by dilatometry. It was confirmed that embedded deformation under normal conditions accelerated the formation of structural components controlled by a diffusion mechanism, i.e. by ferrite and pearlite. In the case of bainitic transformation the effect of embedded deformation was manifested in an ambiguous manner, when in the case of the steels 20MnCrS5, 32CrB4 and 42CrMo4 it led to an acceleration of this transformation, in the case of the steel 51CrV4 the kinetics of this transformation remain practically non-influenced, and in the case of the rails steel this transformation was even delayed. It thus confirmed an assumption of a strong influence of the steel chemical composition. It follows from the determined facts that with the decreasing carbon content the probability of an acceleration of bainitic transformation due to deformation increases. The temperature of the start of martensitic transformation M_s decreased significantly with the increasing carbon content ant it was influenced by deformation only slightly. The previous deformation led to a certain decrease of the M_s temperature particularly in the case of higher cooling rates. Nevertheless, it was established in the example of pearlitic transformation, that previous deformation could influence the phase transformations during cooling in principle in two ways. Direct influence is relevant particularly if the strain hardening of the structure

was not sufficiently eliminated by the ongoing static recrystallization. This is possible in the cases when the time between deformation and the start of the relevant phase transformation is comparatively short – for example in the case of controlled rolling with low finish rolling temperature. If the deformation temperature is significantly higher and subsequent cooling to the temperature of phase transformation takes longer time, the deformed structure recrystallizes more or less perfectly and resulting austenitic grain can even get coarser. In that case, the influence of deformation on the kinetics of phase transformations is indirect, it is manifested through the austenite grain size, but this effect would be likely dominant in many processes of hot forming of steel. The performed works clearly demonstrated a high experimental potential in this area of the dilatometric module of the plastometer GLEEBLE 3800 at the VŠB - Technical University of Ostrava.

REFERENCES

[1] J. Jech, Tepelné zpracování oceli [Heat treatment of steel], 1983 SNTL, Prague.

[2] F. Nürnberger, O. Grydin, M. Schaper, F.-W. Bach, B. Koczurkiewicz, A. Milenin, Steel Res. Int. **81** (3), 224-233 (2010).

[3] P. Kawulok, R. Kawulok, I. Schindler, S. Rusz, J. Kliber, P. Unucka, K. M. Čmiel, Metalurgija **53** (3), 299-302 (2014).

[4] E. Rożniata, R. Dziurka, Arch. Metall. Mater. **60** (1), 497-502 (2015).

[5] S. Rusz, T. Kubina, I. Schindler, B. Smetana, P. Kawulok, M. Cagala, Metalurgija **52** (4), 525-528 (2013).

[6] R. Kawulok, I. Schindler, P. Kawulok, S. Rusz, P. Opěla, Z. Solowski, K. M. Čmiel, Metalurgija **54** (3), 473-476 (2015).

[7] S. Rusz, I. Schindler, P. Kawulok, R. Kawulok, P. Opěla, J. Kliber, Z. Solowski, Metalurgija **55** (4), 655-658 (2016).

[8] R. Kawulok, I. Schindler, P. Kawulok, S. Rusz, P. Opěla, J. Kliber, Z. Solowski, K. M. Čmiel, P. Podolínský, M. Mališ, Z. Vašek, F. Vančura, Metalurgija **55** (3), 357-360 (2016).

[9] D. Jandová, L. Vadovicová, in: Metal 2004, Ostrava: Tanger Ltd, paper no. 223 (2004).

[10] V.M. Khlestov, E.V. Konopleva, H.J. McQueen, Mater. Sci. Tech. Ser. **18** (1), 54-60 (2002).

[11] A. Timoschenkov, P. Warczok, M. Albu, J. Klarner, E. Kozeschnik, G. Gruber, Ch. Sommitsch, Steel Res. Int. **85** (6), 954-967 (2014).

[12] ČSN EN 10084-1998, Case hardening steels – Technical delivery conditions, Czech Standards Institute, 2000 Prague.

[13] ČSN EN 10263-4, Steel rod, bars and wire for cold heading and cold extrusion – Part 4: Technical delivery conditions for steels for quenching and tempering, Czech Standards Institute, 2005 Prague.

[14] ČSN EN 10083-3, Steels for heat treatment – Part 3: Technical delivery terms for non alloy steels, Czech Standards Institute, 2006 Prague.

[15] IH class Rail steel, internal documentation of TŘINECKÉ ŽELEZÁRNY, a.s., 2014 Třinec.

[16] I. Schindler, P. Kawulok, Hutnické listy. **66** (4), 85-90 (2013).

[17] M.C. Weinberg, D.R. Uhlmann, E.D. Zanotto, J. Am. Ceramic. **72** (11), 2054-2058 (1989).

[18] L.X. Du, H.L. Yi, H. Ding, X.H. Liu, G.D. Wang, J. Iron Steel Res. **13** (2), 37-39 (2006).

[19] Z. Zhao, C. Liu, Y. Liu, D.O.A. Northwood, J. Mater. Sci. **36** (20), 5045-5056 (2001).

[20] H.Z. Wang, P. Yang, W.M. Mao, F.Y. Lu, J. Alloy. Compd. **558**, 26-33 (2013).