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PHASE TRANSFORMATION AND COOLING CURVES OF THE MILD STEEL INFLUENCED BY PREVIOUS HOT ROLLING

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Rods from mild steel S235JR were intensively rolled in the laboratory continuous mill. Specifically defined temperature of phase transformation A_r was determined from the free cooling curves measured by the temperature scanner. The A_r value increased from 763 to 786 °C with rolling temperature descending from 1 200 to 800 °C. The value of A_r = 730 °C was obtained at free cooling of the non-deformed rod of the same diameter 9,8 mm from heating temperature 1 000 °C. The obtained results were compared with continuous cooling transformation (CCT) and deformation continuous cooling transformation (DCCT) diagrams based on the dilatometric tests.

Key words: mild steel, rolling, temperature, phase transformation, dilatometric test

INTRODUCTION

Cooling of the material after hot rolling in conjunction with the finish-rolling temperature plays a key role for achievement of the final structure and mechanical properties. In the case of rolling of steel characterised by phase transformation (e.g. austenite/ferrite) the difference between the temperature of finish-rolling and the transformation temperature during cooling of the finished product is very important. If the finish-rolling temperature is considerably higher, after the last reduction austenitic grain elongated by deformation has time to re-crystallise and to become even coarser before the phase transformation, which will negatively result in grain coarseness of the resultant structure (composed e.g. of ferrite and pearlite) [1,2].

Finish-rolling just above the transformation temperature can in turn cause an acceleration of the corresponding phase transformation due to non-recovered share of the strain hardened structure [1-4].

Diagrams of anisothermal austenite (CCT), designed most frequently with use of dilatometry for specific material, help to resolve this complicated issue [3,5].

The experiments conducted previously on the dilatometric module of the plastometer GLEEBLE 3800 at the VSB - TU Ostrava revealed some principal problems at interpretation of the results of such tests, especially during the construction of transformation diagrams with the influence of previous deformation (DCCT) [2]. It does not concern only the magnitude of the applied deformation, but also the deformation temperature and size of the initial austenitic grain (variable by heating parameters prior the testing) [6-12].

The combination of findings about the phase transformation kinetics for the given steel is therefore of utmost importance (see decay diagrams) with the data about the real cooling rate at the temperatures associated with the start of these transformations. The performed experimental works suitably combine the advantages of plastometric investigations with the application possibilities of laboratory semi-continuous rolling mill of bars at the VSB - TU Ostrava with the analyses of cooling curves obtained on rolled products by measurements and registration of their surface temperatures by thermal scanners. The aim was to quantify the impact of previous temperature-deformation conditions on the kinetics of austenite decay during cooling of the rolled products made of non-alloyed high quality structural steel grade S235JR.

EXPERIMENTAL PROCEDURE

The tested low carbon steel had the following chemical composition in wt.%: 0,085 C – 0,68 Mn – 0,22 Si – 0,028 P – 0,012 S – 0,004 Al. Round bars of 20 mm diameter were after heating to the temperature of 1 050 °C first rolled to bars of 15,8 mm diameter, namely by two reverse passes on a roughing mill with roll pass flat oval/circle.

The rolled products were after partial cooling cut to bars 0,9 m long, preheated for 30 minutes at the temperature of 1 000 °C in an electric resistance furnace and then (after optional cooling controlled by pyrometer) they were transferred to the second furnace of similar type, heated to the specific temperature *T*a /°C. The

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equalising dwell at the given temperature (800 to 1 000 °C) was then followed by rolling of the given bar by four passes in the continuous sequence of the laboratory rolling mill. Each finished rolled product – bar of nominal diameter of 9,8 mm - was directed to the section of free cooling on the roller conveyor, where at the place unaffected by cold rollers its surface temperature was measured by the temperature scanner LandScan, and thus was obtained the cooling curve up to the temperature of approx. 400 °C.

ANALYSIS OF COOLING CURVES

The registered time dependence of the temperature obtained at cooling of individual bars were then smoothed and derived in the software Origin. The cooling rates at any moment, ranging approximately from 0,5 to 14 °C/s were thus calculated by the first derivative - see e.g. Figure 1. The temperature A_r /°C at the place of the derivative local maximum was determined for each curve. Thus defined temperature achieved under the given conditions the values between the temperatures A_{r3} and A_{r1} and its advantage is the accuracy and objectivity, with which it is possible to determine it (unlike the A_{r3} and A_{r1} own temperatures, which, however, have more explicit physical meaning).

Diagram in Figure 2 shows that with the decreasing rolling temperature (herein defined as *T*a, which is strictly speaking the temperature of heating and of the beginning of rolling) the A_r temperature increases. This demonstrates the combined effect of the smaller size of initial grains and of strain hardening on acceleration of the austenite decay. The value of A_r, measured for the *T*a = 1 000 °C without previous deformation, is completely beside this trend.

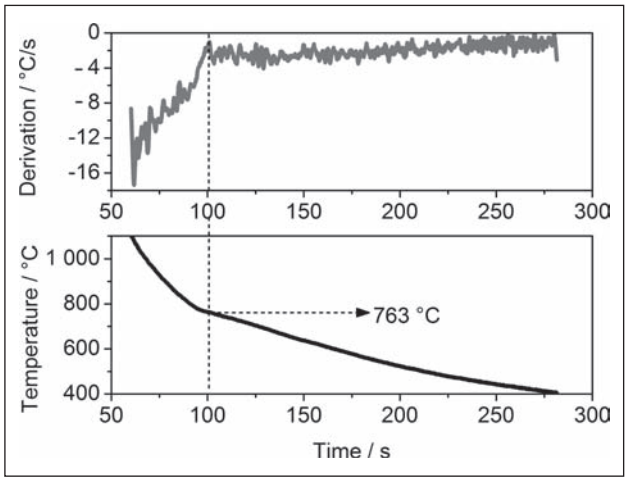


Figure 1 Analysis of the cooling curve (rolling at the temperature of 1 200 °C)

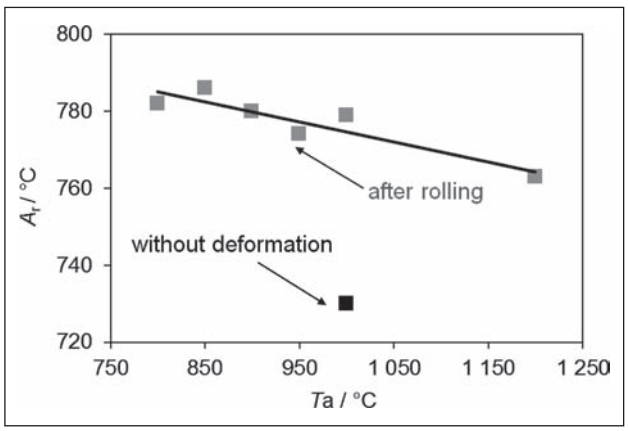
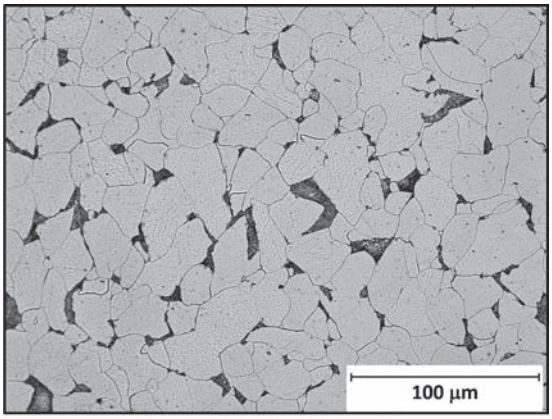


Figure 2 Influence of rolling temperature *T*a on the phase transformation temperature A_r

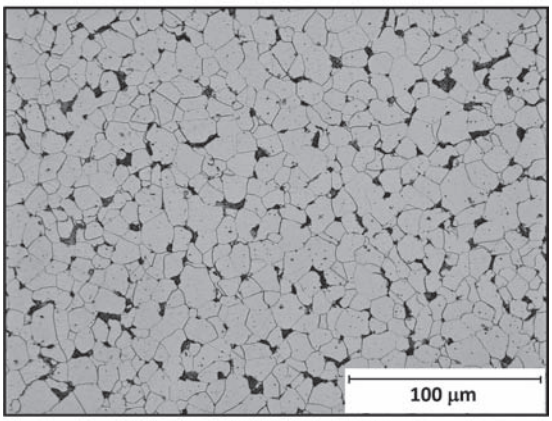
RESULTING GRAIN SIZE

Due to the chemical composition and hence to the low hardenability of the investigated steel it is practically impossible to determine the size of austenitic grain entering the phase transformation during cooling. However, it was easy to determine the size of the resultant ferrite grains, by the linear intersectional method with use of metallographic images of microstructure of individual bars (in the axis of the cross section) - see Figure 3.

The non-deformed sample was characterised by a coarse-grain and heterogeneous structure, in which it was possible to find large nests of hardening phases. It is obvious how essential is the influence of initial the size of austenitic grains (after simple heating or after



a) *T*a = 1 200 °C, rolling



b) *T*a = 800 °C, rolling

Figure 3 Examples of the final microstructure at various temperature-deformation conditions

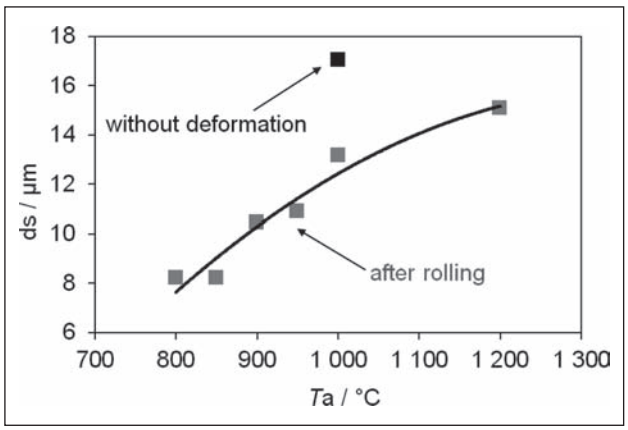


Figure 4 Influence of the rolling temperature on grain size

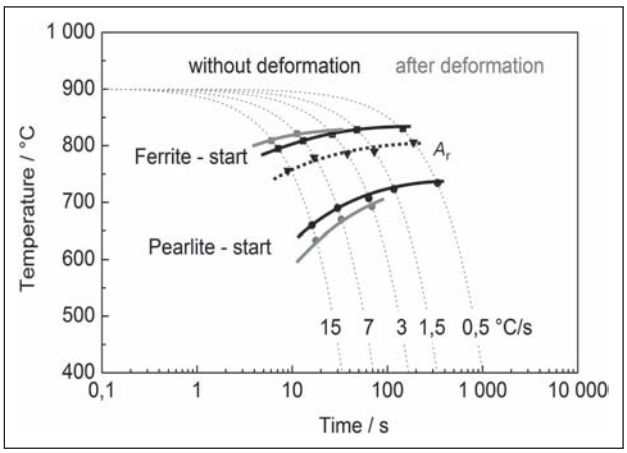


Figure 5 CCT and DCCT diagrams of the tested steel

deformation and recrystallisation) on the kinetics of phase transformations controlled by diffusion. It is possible to present in Figure 4. The point corresponding to the conditions of cooling from the temperature of 1 000 °C without the effect of deformation and refining of austenitic grain by static recrystallisation is beside the unambiguous trend of dependence of the average grain diameter ds /mm on the *T*a temperature, valid for the state after rolling.

DECAY DIAGRAMS

For a limited range of cooling rates from 0,5 to 15 °C/s, achieved during free cooling of the laboratory rolled products, we compiled decay CCT and DCCT diagrams for the investigated steel. The necessary data on temperatures of phase transformations were obtained with use of dilatometric module of the plastometer GLEEBLE 3800, the main advantage of which consists in its the ability to examine on one device a combined effect of the cooling rate and of the defined previous deformation. Cylindrical samples produced from the laboratory rolled products had a diameter of 6 mm and a length of 86 mm. They were uniformly austenitised at the temperature of 900 °C for 120 s, and they were optionally at this temperature deformed by uniaxial pressure by the actual (logarithmic) value of deformation of 0,35 – right before the start of the cooling phase. On the basis of analysis of the dilatation curves we determined the A_r temperatures, similarly as in the case of cooling curves. The A_r values during cooling at the constant cooling rate were between 777 to 806 °C, and they were practically not influenced by the previous deformation, although this was in the case of the Ferrite-start and Pearlite-start slightly manifested, as it is documented in Figure 5.

The increase of the cooling rate leads to an acceleration of the ferritic transformation and vice versa to a shift of the beginning of the pearlitic transformation towards longer times. Previous deformation is probably reflected through the size of recrystallised austenitic grain, rather than through the strain hardening as such, because the austenitising temperature of 900 °C is quite high.

SUMMARY

Continuous rolling of bars with the diameter of 15,8 mm to bars with diameter of 9,8 mm was at different temperatures (from 800 to 1 200 °C) introduced considerable deformation into the low-carbon steel S235JR, manifested by the kinetics of phase transformation of the rolled product during free cooling in air.

For the purposes of comparison, the obtained cooling curves were derived and at the place of the local maximum of the derivative we determined the A_r temperature, lying between the A_{r3} and A_{r1} temperatures. With the decreasing rolling temperature the A_r value increased almost linearly from approx. 763 to 786 °C, while at free cooling of only heated (i.e. literally non-deformed) bar of the same dimensions from the temperature of 1 000 °C the measured A_r value was 730 °C. This shows an accelerating effect of deformation on the kinetics of anisothermal decay of austenite in the used steel, and it corresponds also to the size of the resulting grain.

Diagrams of anisothermal decay of austenite, constructed for the constant cooling rates of 0,5 to 15 °C/s, as well as with consideration of the previous deformation of 0,35, confirmed the effect of forming on the phase transformation kinetics. Thus obtained A_r values ranged from 777 to 806 °C, and they were therefore higher than in the case of rolling. It can be assumed that the previous deformation influences in such cases the phase transformations mainly indirectly, i.e. through the size of austenitic grain formed by the static recrystallisation during cooling (especially at higher rolling temperatures).

The performed tests document a useful synergy of plastometric and rolling experiments and they show the possibilities of a simple study of anisothermal decay of austenite with the influence of the previous deformation. The cooling rates can be easily changed by dimensions of the rolled products. It should be, however, noted that the described method of analysis of real cooling curves is suitable particularly for materials with significant temperature manifestations at given transformations.

Acknowledgements

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REFERENCES

[1] A. Timoshenkov, P. Warczok, M. Albu, J. Klarner, E. Kozeschnik, G. Gruber, C. Sommitsch, Influence of Deformation on Phase Transformation and Precipitation of Steels for Oil Country Tubular Goods, Steel Research International 85(2014) 6, 954-967. DOI: 10.1002/srin.201300198

[2] R. Kawulok, I. Schindler, P. Kawulok, S. Rusz, P. Opěla, Z. Solowski, K. M. Čmiel, Effect of deformation on the CCT diagram of steel 32CrB4, Metalurgija 54 (2015) 3, 473-476.

[3] M. Opiela, W. Zalecki, A. Grajcar, Influence of plastic deformation on CCT-diagrams of new-developed microalloyed steel, Journal of Achievements in Materials and Manufacturing Engineering 51 (2012) 2, 78-89.

[4] D. Jandová, L.Vadovicová, Influence of deformation on austenite decomposition of steel 0.5C-1Cr-0.8Mn-0.3Si, In: Metal 2004: 13rd International Conference on Metallurgy and Materials. Ostrava: Tanger, (2004), 223.

[5] J. Jech, Tepelné zpracování oceli [Heat treatment of steel], 1st edition. Praha: SNTL (1983) 392.

[6] A. A. Kruglova, V. V. Orlov, E.I. Khlusova, Effect of hot plastic deformation in the austenite interval on structure formation in low-alloyed low-carbon steel, Metal Science and Heat Treatment 49 (2007) 11-12, 556-560. DOI: 10.1007/s11041-007-0102-x

[7] L. X. Du, H. L Yi, H. Ding, X. H. Liu, G. D. Wang, Effects of Deformation on Bainite Transformation During Continuous Cooling of Low Carbon Steels, Journal of Iron and Steel Research 13 (2006) 2, 37-39.

[8] M. Gao, H. Gu, F. Xiao, B. Liao, G. Qiao, K. Yang, Y. Shan, Effect of Hot Deformation on Pearlite Transformation of 86CrMoV7 Steel, Journal of Materials Science and Technology 20 (2004) 1, 89-91.

[9] R. Fabík, P. Kawulok, R. Baron, Mathematical modelling of cooling and prediction of mechanical properties of shapes after hot rolling, In: Metal 2012: 21st International Conference on Metallurgy and Materials. Ostrava: Tanger, (2012), 428-433.

[10] V. M. Khlestov, E. V. Konopleva, H. J. Mcqueen, Effects of deformation and heating temperature on the austenite transformation to pearlite in high alloy tool steels, Materials Science and Technology 18 (2002) 1, 54-60. DOI: 10.1179/026708301125000212

[11] S. B. Yin, X. J. Sun, Q. Y. Liu, Z. B. Zhang, Influence of Deformation on Transformation of Low-Carbon and High Nb-Containing Steel During Continuous Cooling, Journal of Iron and Steel Research 17 (2010) 2, 43-47.

[12] S. J. Lee, Y. K. Lee, Effect of Austenite Grain Size on Martensitic Transformation of a Low Alloy Steel, Materials Science Forum 475-479 (2005), 3169-3172.

Note: Translator responsible for English language is B. Škandera, Frýdek-Místek, Czech Republic