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THE INFLUENCE OF A COOLING RATE ON THE EVOLUTION OF MICROSTRUCTURE AND HARDNESS OF THE STEEL 27MnCrB5

The aim of the performed experiments was to determine the influence of a cooling rate on the evolution of microstructure and hardness of the steel 27MnCrB5. By using dilatometric tests performed on the plastometer Gleeble 3800 and by using mathematical modelling in the software QTSteel a continuous cooling transformation diagram for a heating temperature of 850°C was constructed. Conformity of diagrams constructed for both methods is relatively good, except for the position and shape of the ferrite nose. The values of hardness, temperatures of phase transformations and the volume fractions of structural phases upon cooling from the temperature of 850°C at the rate from 0.16°C · s^{-1} to 37.2°C · s^{-1} were determined. Mathematically predicted proportion of martensite with real data was of relatively solid conformity, but the hardness values evaluated by mathematical modelling was always higher.

Keywords: Steel 27MnCrB5, continuous cooling transformations diagrams, dilatometric tests, plastometer Gleeble 3800, software QTSteel

1. Introduction

For achievement of the desired structural and mechanical properties of the hot formed products, it is possible to use a progressive method of thermo-mechanical forming of materials [1-3]. All of the hot formed articles (for example seamless pipes, forgings made by free forming or by die forging) cannot be, however, processed by this advanced technology and traditional methods must be used for their production, which is followed by heat treatment, with the use of which the final properties of these products are achieved [4-6]. For this reason, the knowledge of the influence of the austenitization conditions is important and particularly of the cooling rates on the final microstructure and mechanical properties of the heat treated materials [7-9].

The influence of temperature and time on the course of austenite transformation is illustrated by transformation diagrams, the validity of which is determined by the chemical composition and by the conditions of austenitization of the given steel. These transformation diagrams differ from the equilibrium diagrams radically by the fact that they are valid always only for one particular steel. Two basic types of transformation diagrams exist: TTT (time temperature transformation) diagrams and CCT (continuous cooling transformation) diagrams, which are used as a very important basis for the optimisation of heat treatment processes and for better use of the properties of steels. The majority of the heat treatment processes is carried out during continuous cooling, and that is why the CCT diagrams have therefore in practice greater importance [10-12].

The CCT diagrams are usually plotted using physical methods, and one of the most widely used methods is the dilatometric analysis [13-15]. Other possibilities for their plotting consist in the use of special computational computer programs, such as for example JMatPro software, EWI software or QTSteel software [16-18], the advantage of which lies in obtaining information on the structural condition of the investigated material within a few seconds after entering the chemical composition, conditions of austenitization and cooling rates.

The aim of the realised experiments was to determine the influence of the heating temperature on the size of the austenitic grain, and namely to determine the influence of the cooling rate on the evolution of microstructure and hardness during the continuous cooling of boron-alloyed steel 27MnCrB5, which is intended for heat treatment, and which is used especially for the production of machine parts (e.g. shovels for dredgers, sprockets wheels, etc.). The experimental works were carried out on the plastometer GLEEBLE 3800, which is characterised by its versatility as regards the possibility of performed tests [19-21], and which is among others equipped with a dilatometric module [22-23].

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2. Experimental description

The experimental works were divided into two stages. In the first stage, the influence of the heating temperature on the austenite grain size was investigated, while in the second stage, the influence of the cooling rate on the final microstructure and hardness of the examined steel, the chemical composition of which is documented in Table 1, was investigated.

TABLE 1

The chemical composition of steel 27MnCrB5 in wt. %

C	Mn	Si	P	S	Cr	B
0.292	1.15	0.187	0.012	0.004	0.57	0.004

Cylindrical samples with a diameter of 6 mm and a length of 60 mm, were prepared from the examined steel for determination of the influence of the heating temperature on the size of austenite grains. These samples were heated by electric resistance heating implemented on the plastometer GLEEBLE 3800 to the selected temperature of 830°C, 850°C, 870°C, 900°C or 930°C and after the dwell time of 120 second at this temperature they were rapidly cooled down with water to 25°C. After that, these samples were subjected to metallographic analyses.

The influence of the cooling rate on the final microstructure and hardness of the examined steel was investigated using dilatometric tests, which were performed on the dilatometric module of the plastometer GLEEBLE 3800. For this purpose, special cylindrical samples with diameter 5 mm were prepared from the investigated steel, with hollow head parts and with the length of the tested part of the sample of 5 mm – see Fig. 1.

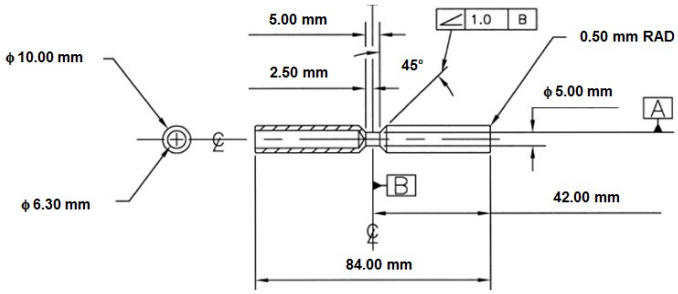


Fig. 1. Drawing of the sample for dilatometric tests

For the purposes of dilatometric tests, we chose on the basis of the results of the previous stage the austenitization temperature of 850°C. The prepared samples were thus heated by electrical resistance on the plastometer GLEEBLE 3800 to the selected temperature and after a dwell time of 120 second at this temperature they were cooled by controlled cooling at selected constant cooling rates down to the temperature of 25°C. Altogether 13 dilatometric tests were performed, wherein the cooling rates were chosen in the range from 37.2°C·s^{-1} up to 0.16°C·s^{-1} in order to enable the most precise possible determination of the areas of individual structural phases. The tested samples were moreover subjected to metallographic analyses and hardness tests.

3. Discussion of results

Photo documentation of the original austenitic grain of the plastometrically tested samples quenched from different heating temperatures is presented in Fig. 2. On the basis of evaluation of metallographic analyses of those samples, it was found that the austenitization temperature of 930°C is not suitable due to selective massive grain coarsening. This results in abnormal heterogeneity of the structure, which becomes evident particularly in direct comparison with the structure obtained after quenching from the temperature of 850°C. The cause consists in some of the austenite grains that grew to the size of approx. 100 μm and fine grains with tenfold smaller size coexisting with them.

After etching of the original austenitic grain from the quenched structure, its dimensions (mean size) was measured by an automated abscissa method, the results of which are summarised in Table 2 and in Fig. 3. Should there not be an abnormal coarsening of some grains at the temperature of 930°C, it would be possible to claim an almost linear relationship between the investigated temperatures of austenitization and grain size.

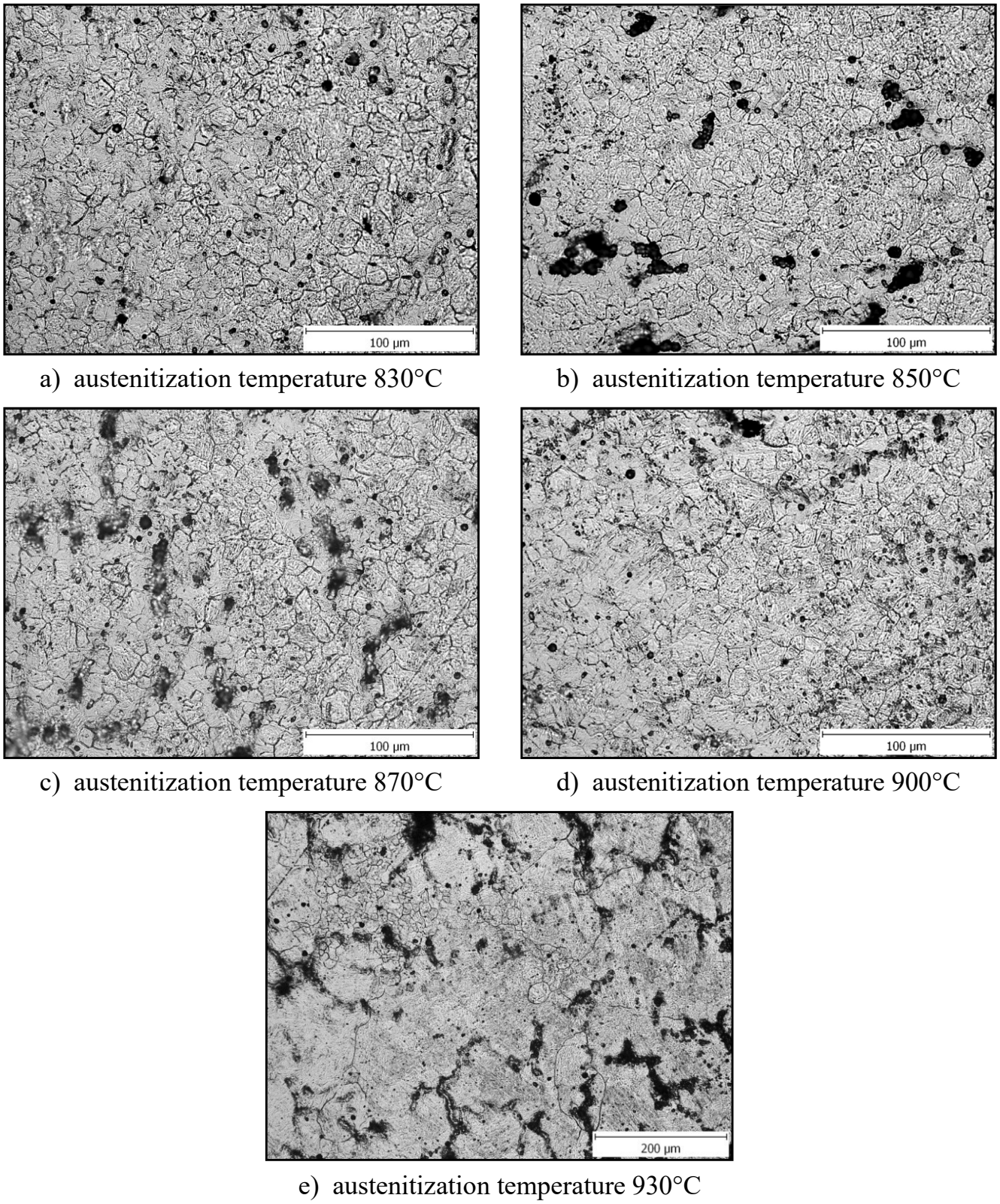
TABLE 2

The mean size of the original austenitic grain in dependence on the heating temperature

Temperature of heating	Mean grain size	Standard deviation
[°C]	[mm]	[mm]
830	8.9	4.5
850	10.3	4.4
870	10.6	4.2
900	10.7	5.1
930	11.5 (fine grains)	6.1
	107 (coarse grains)	40

During dilatometric tests the temperature and the dilatation of the investigated steel were registered in dependence on time. An example of the influence of selected cooling rates on the shape of the dilatation curves is documented in Fig. 4. These data were then analysed in a special CCT software, which enables determination of the temperatures of phase transformations during cooling of the investigated steel and subsequently it is possible thanks to those points to build a transformation diagram of the investigated steel – see Fig. 5.

In the available literature [24,25] it is possible to find a CCT diagram of the investigated steel 27MnCrB5 (see Fig. 6) and this offers us, therefore, a comparison with the CCT diagram determined by dilatometric analysis (see Fig. 5). Unfortunately, no detailed conditions of austenitization are given for the CCT diagram [24,25], which greatly complicates its accurate comparison with the CCT diagram plotted by us. The CCT diagram plotted by the authors [24,25] presented in Fig. 6 shows, in comparison with the diagram presented in Fig. 5, much greater ferritic and pearlitic area and significantly smaller bainitic region, which, however, is shifted more towards shorter times, i.e. to higher the cooling rates. Another interesting fact is that in the CCT diagram of the authors [24,25], the line representing the beginning of



a) austenitization temperature 830°C

b) austenitization temperature 850°C

c) austenitization temperature 870°C

d) austenitization temperature 900°C

e) austenitization temperature 930°C

Fig. 2. The original austenitic grain etched in the samples quenched from different austenitization temperatures

the martensitic transformation slightly rises with the decreasing cooling rate, which is not quite common – see the works [16,23].

For the comparison we constructed for analogical conditions of heating and cooling as in the case of dilatometric tests a CCT diagram of the investigated steel also with the use of the calculation software QTSteel – see Fig. 7, in which the individual structural phases are marked as F – ferrite, P – pearlite, B – bainite and M – martensite.

By comparison of the experimentally determined CCT diagram (see Fig. 5) with the corresponding diagram obtained by calculation (see Fig. 7) it is possible to find some differences in the position and shape of the ferritic nose and in the size of the

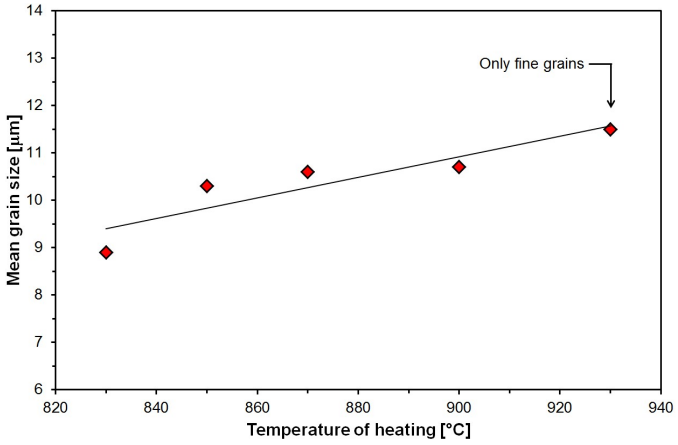


Fig. 3. The influence of the heating temperature on the mean size of austenitic grain

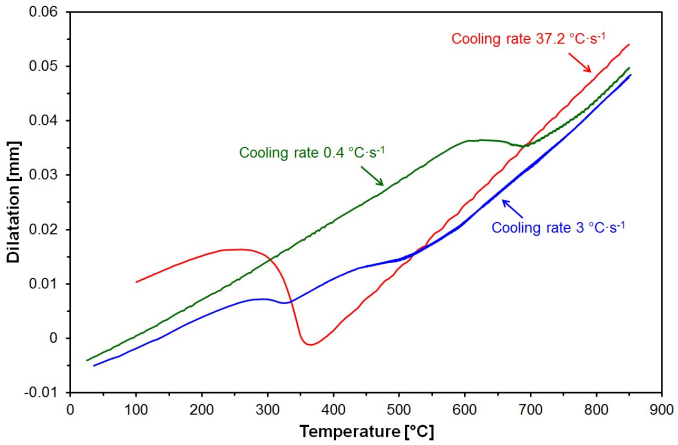


Fig. 4. Influence of the selected cooling rates on the shape of dilatation curves

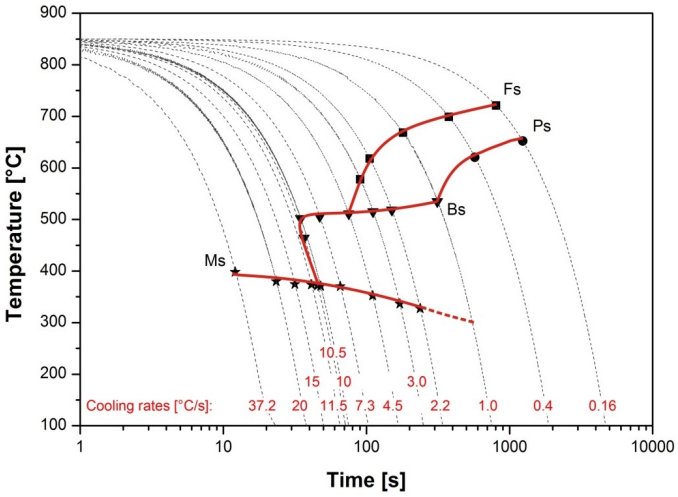


Fig. 5. CCT diagram plotted on the basis of dilatometric tests

bainitic area. Furthermore, the diagram constructed by calculation in the program QTSteel does not reflect the temperature drop at the beginning of the martensitic transformation with the decreasing cooling rate and the pink curve representing the area of martensite ends already at the cooling rate of 11.5°C · s^{-1}.

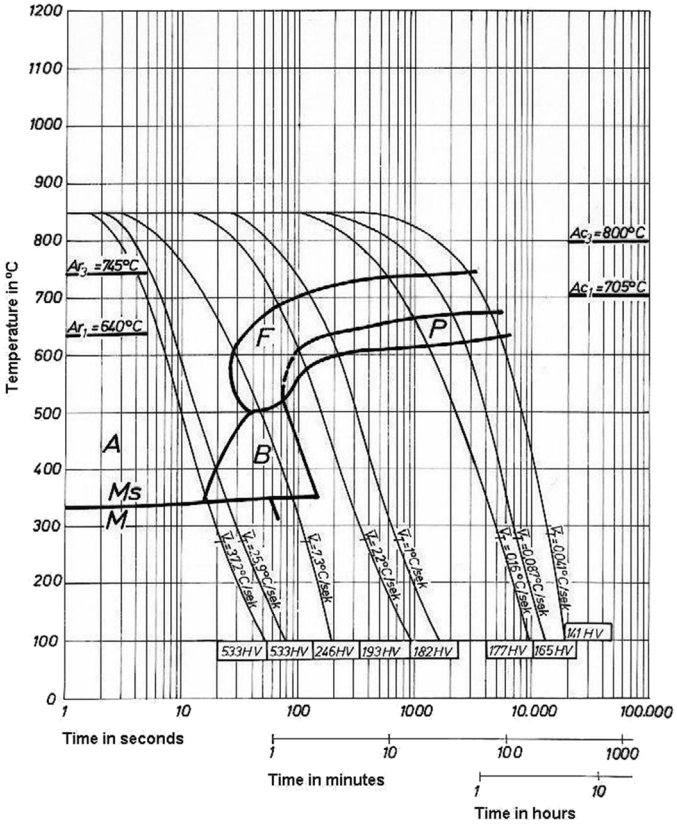


Fig. 6. CCT diagram of the steel 27MnCrB5 according to the works [24,25]

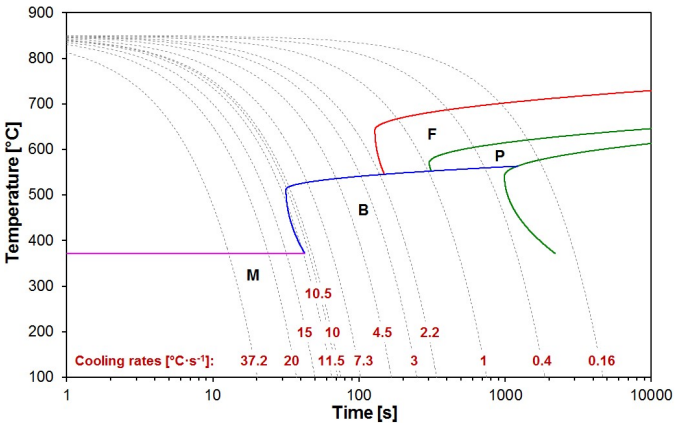
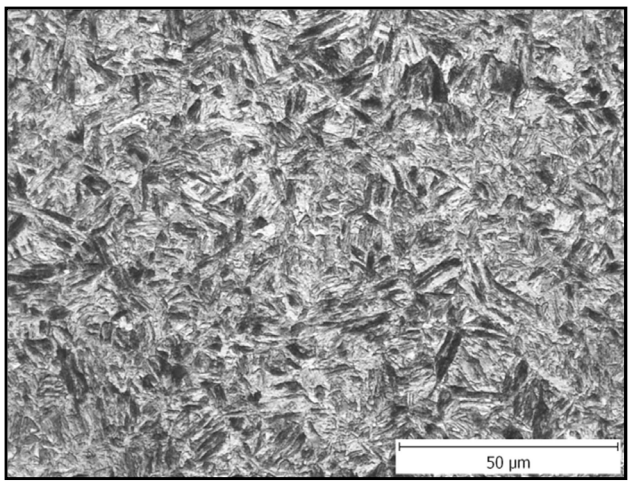


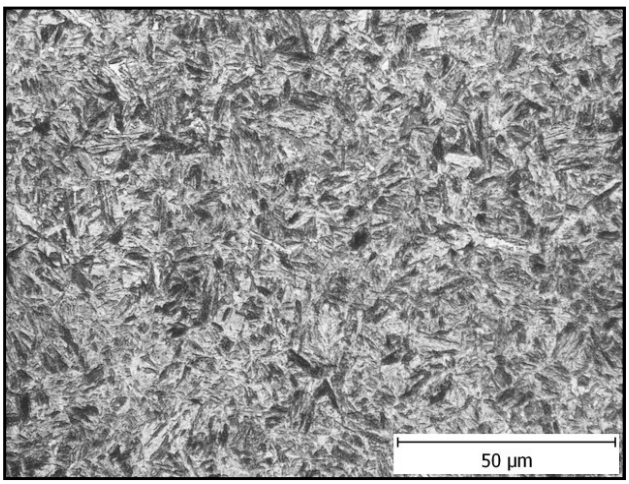
Fig. 7. CCT diagram constructed in the software QTSteel

Certain differences, mainly in the size of individual structural phases, between the CCT diagrams determined by dilatometry and those calculated mathematically are evident also in the works of the authors [16-18]. It is evident already from this comparison that the programs operating on the basis of universal computational models do not always provide a completely accurate information on the final structure of the heat treated steels. From this perspective, the physical methods of testing, comprising also dilatometric analysis, are indispensable.

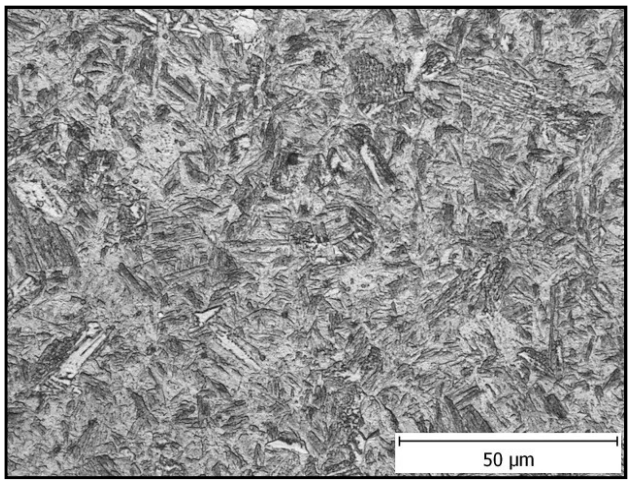
The photo documentation of the microstructure of selected samples tested by dilatometry, which were examined by optical microscopy, is shown in Fig. 8.



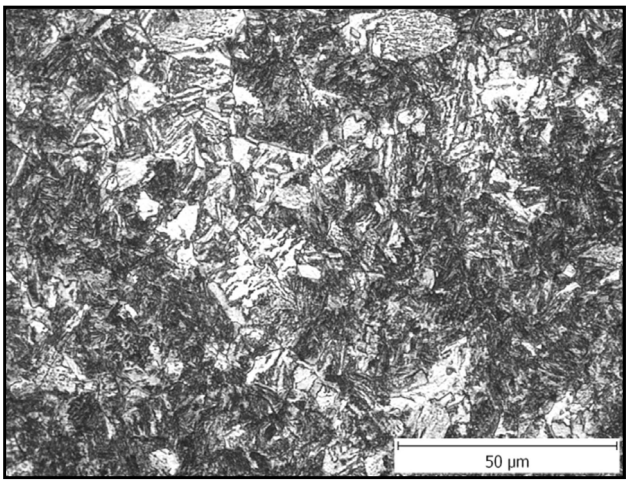
a) cooling rate of 20 °C·s^{-1}



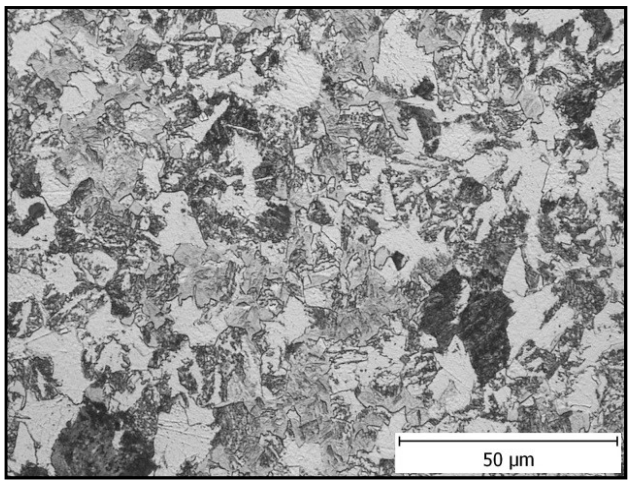
b) cooling rate of 10 °C·s^{-1}



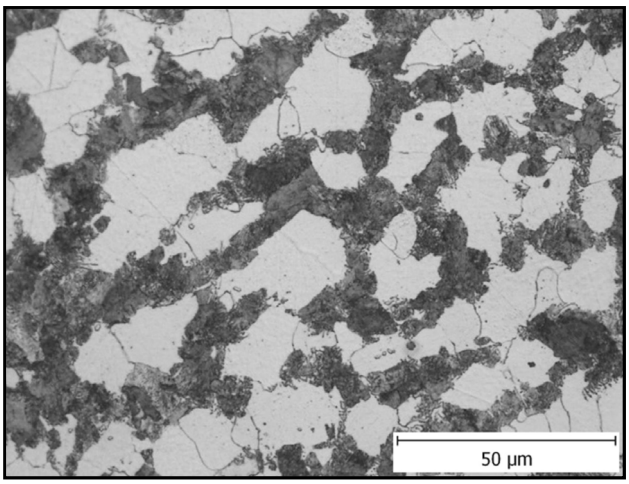
c) cooling rate of 7.3 °C·s^{-1}



d) cooling rate of 3 °C·s^{-1}



e) cooling rate of 1 °C·s^{-1}

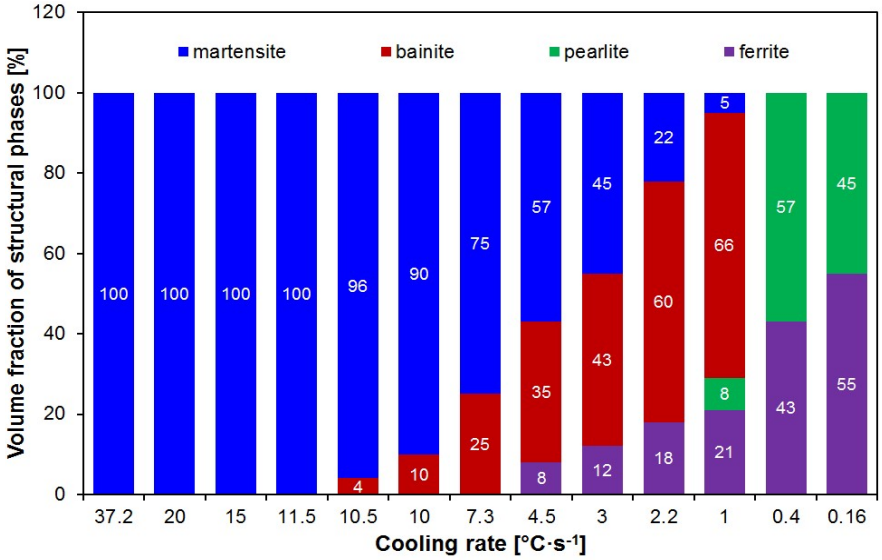


f) cooling rate of 0.16 °C·s^{-1}

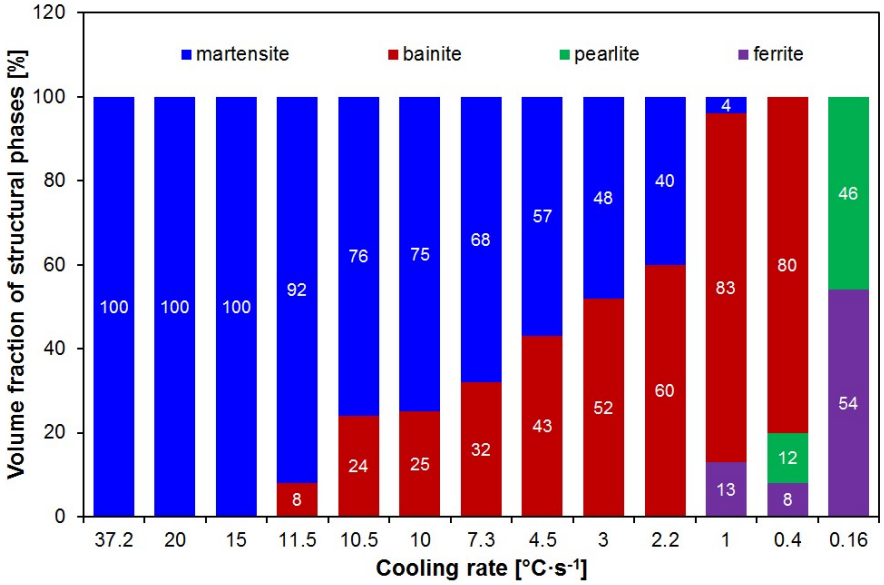
Fig. 8. Microstructure of the samples tested by dilatometry

The microstructure of the samples tested by dilatometry cooled down at the cooling rates of at least 11.5°C·s^{-1} was formed solely by martensite. The cooling rates from 10.5 to 7.3°C·s^{-1} resulted in the formation of martensitic-bainitic structure. The samples cooled at the cooling rates from 4.5 to 1°C·s^{-1} exhibited a microstructure formed by a mixture of hardening phases and ferrite, or in the case of the sample cooled at the cooling rate of 1°C·s^{-1} by a mixture of hardening phases of ferrite and pearlite. The cooling rates from 0.4 and 0.16°C·s^{-1} resulted in a microstructure formed by a mixture of ferrite and pearlite.

The volume fractions of the structural phases represented in individual samples tested by dilatometry, or determined for



a) samples tested by dilatometry



b) QTSteel

Fig. 9. The volume fractions of the structural phases of the samples tested by dilatometry and those determined by calculation in the software QTSteel

analogical cooling rates by calculation program QTSteel are documented by the diagram in Fig. 9.

Similarly as in the case of comparison of the CCT diagrams determined by both used methods, also in the case of the volume fractions of individual structural phases, determined metallographic analysis of the samples tested by dilatometry, or by calculation in the QTSteel calculation program, it is possible to observe the differences. It was found by calculation in the QTSteel program that the bainitic phase is represented in a wider range of cooling rates (from 11.5 to 0.4°C·s^{-1}) which does not correspond to metallographic analyses of the samples tested by dilatometry. In contrast, the ferritic phase was determined by calculating program QTSteel only for the cooling rates from 1 to 0.16°C·s^{-1}, while in the case of the samples tested by dilatometry a ferritic phase was observed in the microstructure in a wider range of cooling rates (from 4.5 to 0.16°C·s^{-1}). The volume fraction of martensite determined by metallographic analyses of the samples tested by dilatometry and by the calculation in the program QTSteel show a very good agreement. The quite interesting fact is, however, that both by mathematical calculation in the software QTSteel and by the dilatometric analysis of the tested samples only very small volume fraction of the martensitic phase was determined even at a comparatively low cooling rate of 1°C·s^{-1}.

The samples tested by dilatometry were after the metallographic analyses subjected to the tests of the hardness HV30. For analogical conditions of heating and cooling, the hardness HV30 of the investigated steel was calculated also in the program QTSteel. The influence of the cooling rate on the hardness of the samples tested by dilatometry, or on the hardness of

the examined steels determined by calculation in the program QTSteel, is documented in Fig. 10. The hardness predicted by the program QTSteel is in all cases higher than the actual hardness, or the hardness determined on the samples tested by dilatometry.

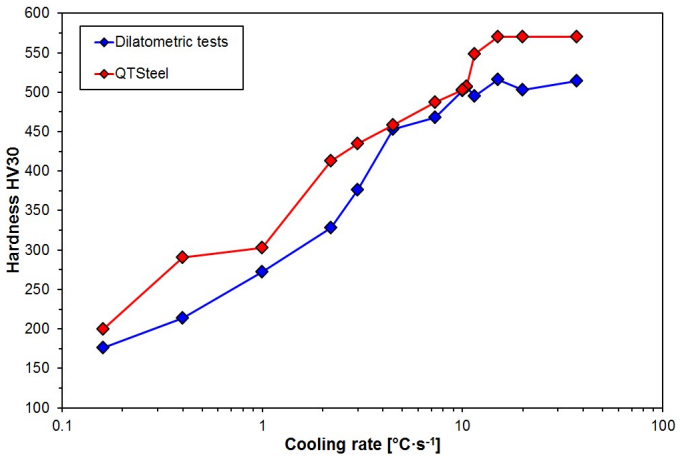


Fig. 10. The influence of the cooling rate on the resulting hardness HV30

4. Conclusions

The selected structure forming processes running in the steel 27MnCrB5 in the phase of its austenitization and cooling at different cooling rates were investigated by the combination of experimental works performed on the plastometer GLEEBLE 3800, of metallographic analyses, hardness measurements and mathematical modelling in the program QTSteel.

The influence of the heating temperature (from 830°C to 930°C) on the size of the austenitic grain with more or less linear evolution of dependence was quantified, with the exception of an abnormal coarsening of some grains after their heating to the temperature of 930°C. This temperature appeared to be completely unsuitable for an austenitization of the investigated steel before its heat treatment since it produces a highly heterogeneous structure.

Using dilatometric tests performed on the plastometer GLEEBLE 3800 and software QTSteel a CCT diagram of the examined steel after cooling from the heating temperature of 850°C at the cooling rates from 0.16 to 37.2°C·s^{-1} was constructed. Agreement of both diagrams determined by two different methods is not quite good. Certain differences can be found particularly in the position and shape of the ferritic nose and in the size of the areas of hardening phases. The CCT diagram drawn by calculation in the program QTSteel provides more information for the pearlite region, but in contrast to dilatometric measurements, it does not reflect the drop in the temperature of the beginning of the martensitic transformation with the decreasing cooling rate.

The dilatometric tests were completed by metallographic analyses and by hardness measurements. What concerns the shares of structural phases determined by metallographic analyses of the samples tested by dilatometry, or determined by calculation in the program QTSteel, a relatively good agreement was achieved only in the case of martensite. For the remaining phases the differences between their shares, determined by both methods for the given cooling rates, were more striking. The hardness values determined by calculation in the program QTSteel were in all cases higher than in the case of analogically cooled samples tested by dilatometry.

The presented results demonstrate the importance of the physical measurements, in this case of the performed dilatometric tests, which with consideration of the meaningful results cannot be fully replaced by universal computer programs.

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