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## TEMPCORE PROCESS ANALYSIS BASED ON THE KINETICS OF PHASE TRANSFORMATIONS

### ANALIZA PROCESU TEMPCORE W OPARCIU O KINETYKĘ PRZEMIAN FAZOWYCH

The description of the phase transformation kinetics of undercooled austenite in the form of the CCT (Continuous Cooling Transformation) diagram as well as the phase transformation kinetics during tempering in the form of the CHT (Continuous Heating Transformation) diagram of the plain carbon steel, B500SP, intended for production of reinforcing bars by means of the Tempcore technology, is presented in the hereby paper. Changes in the microstructure of the bar cross-section (of a diameter of 8 mm) were described and the mechanical properties were determined in the static tensile test.

It was found that the hardenability of the steel under testing is sufficient in respect of its application in the production of reinforcing bars using of the Tempcore technology. It will allow to obtain, in the bar near-surface, martensite (eventually also bainite), which will be tempered due to the heat from the bar core activity. Parameters of the Tempcore process should be selected in such a way as not to heat (temper) martensite - formed directly below the surface – to temperatures higher than 300°C, in order to prevent an advancement of the cementite precipitation, which would significantly lower strength and hardness of martensite.

W pracy zaprezentowano opis kinetyki przemian fazowych przechłodzonego austenitu w postaci wykresu CCT oraz opis kinetyki przemian fazowych przy odpuszczaniu w postaci wykresu CHT stali niestopowej B500SP przeznaczonej do produkcji prętów zbrojeniowych wykonywanych według technologii Tempcore. W odniesieniu do wyżej wymienionych wyników opisano zmiany w mikrostrukturze na przekroju pręta o średnicy 8 mm oraz określono własności mechaniczne w statycznej próbie rozciągania.

Stwierdzono, że hartowność badanej stali w odniesieniu do jej przeznaczenia na pręty do zbrojenia betonu wykonanych wg technologii Tempcore jest wystarczająca, tj. pozwoli na uzyskanie w ich warstwie przypowierzchniowej martenzytu (ewentualnie i bainitu), który ulegnie odpuszczaniu w wyniku działania ciepła z rdzenia pręta. Parametry procesu Tempcore powinno się dobierać tak, aby powstały bezpośrednio pod powierzchnią martenzyt nie nagrzewał się (odpuszczał) do temperatur wyższych niż 300°C, aby nie został zaawansowany proces wydzielania cementytu w wyniku czego, wytrzymałość i twardość martenzytu obniżałaby się znacząco.

### 1. Introduction

Optimal properties of the reinforcing bars are obtained with the application of the Tempcore technology. The process consists of three stages. The first stage constitutes fast water-cooling of a hot-rolled product. Effectiveness of the cooling installation should be high enough to achieve the cooling rate of the bar surface higher than the critical speed of martensite formation. At the end of this operation the bar has an austenitic core surrounded by a layer of the martensite-austenite mixture. Obtaining the martensitic layer of the required thickness is the purpose of this stage of the process. In the second stage the bars leave the water-cooling zone and move towards the air-cooling one. Heat from

the hot core propagates in the surface direction causing self-tempering of the martensite layer. The tempering process ensures the proper ductility of material, simultaneously preserving its high yield strength. The third stage occurs during a free cooling of bars on the cooler and consists of the austenite transformation into ferrite and perlite in the bar core. Morphology of structural components depends on the steel chemical composition, bar diameter, time and effectiveness of cooling [1÷6].

Improvement of strength parameters as well as other metallurgical and mechanical properties of bars rolled in the Tempcore technology allows to decrease reinforcing bars diameters and their total weight - yielding measurable financial savings to investors.

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Designing of the Tempcore technology requires knowledge of the kinetics of phase transformation in plain carbon steels of a low carbon content [1,2]. Knowledge of the phase transformation kinetics during tempering provides additional possibilities of changes in the heat treatment technology [7-9].

The aim of the present work is to describe the kinetics of phase transformation of under cooled austenite in the form of the CCT diagram and the kinetics of phase transformation at tempering from as-quenched state in the form of the CHT diagram of B500SP steel intended for reinforcing bars produced according to the Tempcore technology.

## 2. Experimental procedure

Dilatometric experiments were performed by means of the DT 1000 dilatometer made by Adamel, the French Company. Tests were made on samples of a size:  $\text{Ø}2 \times 12$  mm. Critical points as well as the CCT diagrams (of the kinetics of phase transformation of under cooled austenite) and the CHT diagrams (of the kinetics of phase transformation at continuous heating from as-quenched state) were determined.

Experiments started from the determination of critical (temperatures) points of the steel being tested. The sample was heated to a temperature of 1100 °C with a rate of 0.05 °C/s.

Prior to the main tests the material was normalised annealed at 910 °C for 30 minutes, and cooled in the air. At the selection of the annealing temperature the rule, that this temperature must be 50 °C above the determined Ac3 temperature, was applied.

In order to make the CCT diagram of the kinetics of phase transformation of undercooled austenite the samples were heated to a temperature of 910 °C with a rate of 5 °C/s, hold for 20 minutes and then cooled with various rates ( $200 \div 1$  °C/s) to a temperature of 20 °C. Numerically recorded dilatograms were differentiated to provide more precise readings of characteristic temperatures.

In order to make the CHT diagram of the kinetics of phase transformations at continuous heating from as-quenched state, the previously quenched samples ( $T_A = 910$  °C,  $t_A = 20$  min, quenching in water) were heated with the following rates: 0.05; 0.1; 0.5; 1; 5; 10; 15; 35 °C/s to a temperature of 700 °C, while changes in the samples elongation in dependence of the temperature were recorded. In this case, numerically recorded dilatograms were also differentiated for a more precise reading of characteristic temperatures.

Metallographic examinations were made using the light microscope Axiovert 200 MAT of the Carl Zeiss Company.

Hardness was tested by HPO 250 apparatus applying the Vickers method.

The static tensile test was done by means of the MTS810 machine, using three bars of a diameter 8 mm.

## 3. Results and discussion

The CCT diagram of the steel under testing is presented in Figure 1. Metallographic documentation for this diagram is shown in Figure 2. This is the CCT diagram characteristic for plain carbon steels (of low hardenability) with the range of diffusive transformations shifted visibly to the left (in the direction of shorter times). It seems surprising, that regardless of the applied cooling rates, the microstructure of bainite was not found. None dilatometric effects related to this transformation were observed in the cooling curves. Since the bainitic transformation could be initiated directly after diffusive changes, separation of dilatometric effects related to this change would be impossible. However, since during microscopic observations it was difficult to indicate typically bainitic zones, the bainitic range was not drawn into the CCT diagram. Confirmation of the bainite presence would require performing additional tests by means of the transmission electron microscopy.

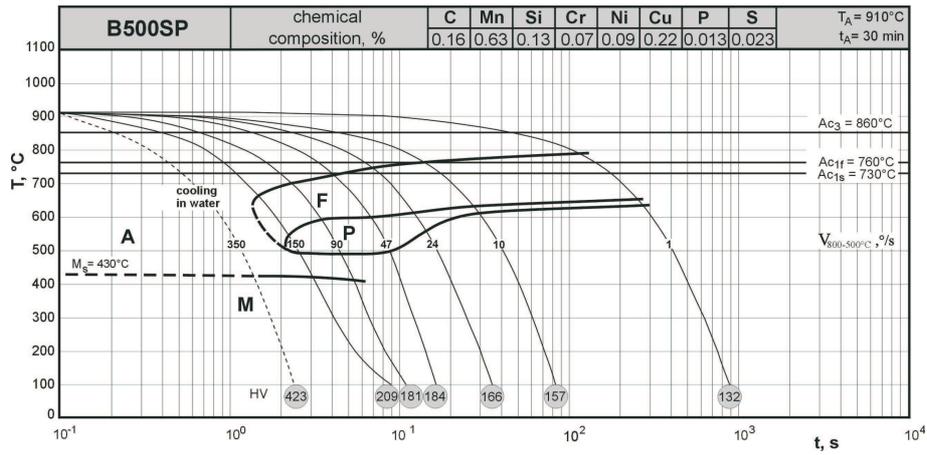


Fig. 1. CCT diagram of investigated steel

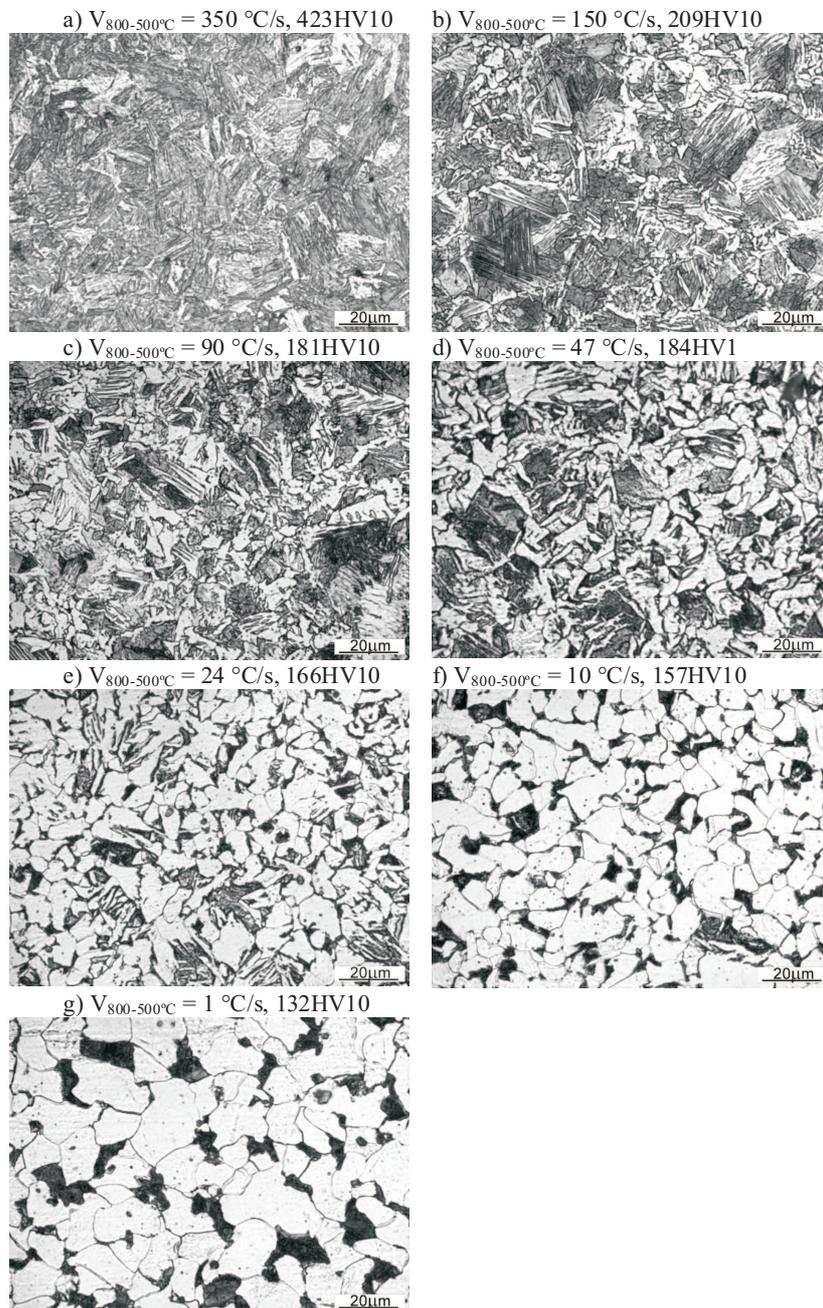


Fig. 2. Microstructures and hardness corresponding to CCT diagram. Etched with 2% nital

Chemical composition of the investigated steel

C	Mn	Si	P	S	Cr	Ni	Cu
0.16	0.63	0.13	0.013	0.023	0.07	0.09	0.22

The lack of the bainitic transformation in the tested steel can be caused by an insignificant participation of alloy elements in its chemical composition (Table 1). In order to obtain the bainitic transformation range in plain carbon steels the contents of manganese (one of the main components of such steels), which favours the bainitic transformation (strongly decreases  $B_s$  temperature and prolongs the time proceeding its formation), should be higher [10]. Another element of a similar activity is chromium. The CCT diagrams with marked ranges of the bainitic transformation can be found in several works (e.g. [1,2]) concerning steel of a carbon content similar to the steel under testing and of much higher content of manganese and chromium.

The martensite microstructure was not obtained in the whole volume at the application of the maximum cooling rate (of the used dilatometer DT1000). Despite the high cooling rate in the temperature range  $800 \div 500$  °C (approximately  $150$  °C/s) ferrite and perlite and small amount of martensite occurs in the microstructure (Fig. 2b), which indicates low hardenability of the steel under testing. Therefore quenching was done outside of the dilatometer, austenitising of samples in the laboratory furnace and cooling in water. Simulation of cooling and calculations of  $M_s$  temperature plotted in the CCT diagram were accomplished by means of the PROstal software. Microstructure of the tested steel, after quenching in water, constitutes martensite (Fig. 2a). However,

ferritic and bainitic zones can be observed too in the microstructure. At such low carbon content (0.16 %) and other alloy elements the hyper quenching of the matrix is not high. In addition, the high  $M_s$  temperature of the steel under testing (approximately  $430$  °C) is the reason that certain self-tempering of martensite could occur during cooling, thus causing that microstructure has features of martensite and bainite. Although the formation of martensite with bainite – during water-cooling – cannot be excluded.

Hardenability of the tested steel in respect of its destination for the reinforcing bars production according to the Tempcore technology is sufficient. It means that it allows for obtaining martensite (eventually also bainite) in the near surface layer of the bar, and that this martensite will be tempered due to a heat from the bar core. In the intermediate zone, in between the surface hardened into martensite and the core, fine acicular ferrite with perlite will be formed, while in the core itself ferrite with perlite will be formed. Such microstructure distribution allows to obtain a high strength at good plastic properties of the steel under testing.

The example of the dilatogram of heating the steel sample (previously quenched from  $910$  °C) with the rate of  $0.1$  C/s is shown in Figure 3, together with the corresponding differential curve, in which the method of dilatograms interpretation is presented. The CHT diagram is based on those dilatograms (Fig. 4).

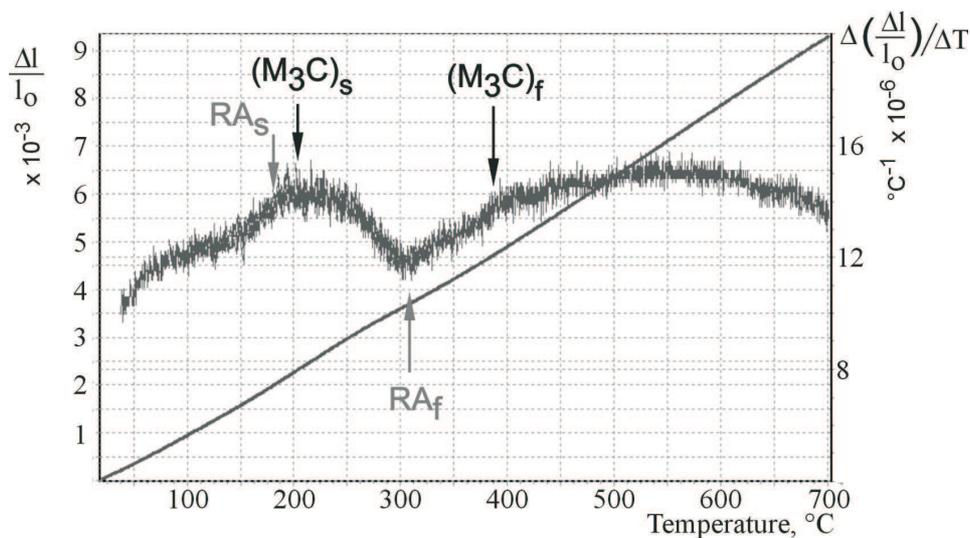


Fig. 3. Dilatometric curve recorded for investigated steel at  $0.1$  °C/s after quenching in water

The steel under testing shows a certain small shrinkage, related – the most probably – to the rearrangement of carbon atoms or clusters or to carbide  $\epsilon$  precipitation, in the first stage of the tempering process. As it was already mentioned, the martensite hyper-quenching is not high in this type of steels (simple chemical composition, low carbon content). Hence such weak dilatation effects during tempering, especially below 200 °C. Due to a high  $M_S$  temperature a self-tempering of martensite can occur already during the quenching process. The weak positive dilatation effect related to the transformation of the retained – after quenching – austenite was recorded in the temperature range  $RA_S \div RA_F$ . This indicates a small amount of the retained austenite. Thus a question arises, whether this effect should be related to the presence of the retained austenite. Analysis of all dilatograms of tempering performed with various heating rates: 0.05 ÷ 35 °C/s – indicates the presence of the retained austenite in the microstructure of the tested steel after tempering. A small amount of the retained austenite as well as the character of the Tempcore process results in the fact that

even an eventual presence of austenite does not have any direct technological meaning.

The shrinkage, starting at a temperature  $(M_3C)_S$ , related to the cementite precipitation superimposes on the positive dilatation effect caused by the transformation of the residual austenite. The cementite precipitation ends at a temperature  $(M_3C)_F$ .

Ranges of rearrangement processes of carbon atoms (or clusters) and eventual carbide  $\epsilon$  precipitation (marked as  $\epsilon$ ) as well as ranges of the residual austenite transformation and cementite precipitation are marked in the CHT diagram of the investigated steel (Fig. 4). As can be noticed, temperatures of starting and ending of individual transformations increase with the heating rate increase from 0.05 to 35 °C/s. On the basis of the CHT diagram, it can be stated that parameters of the Tempcore process should be selected in such a way as, to prevent heating (tempering) – to temperatures higher than 200 – 300 °C – of the martensite formed directly below the surface and due to this, to prevent an advancement of the cementite precipitation, which would significantly decrease strength and hardness of martensite.

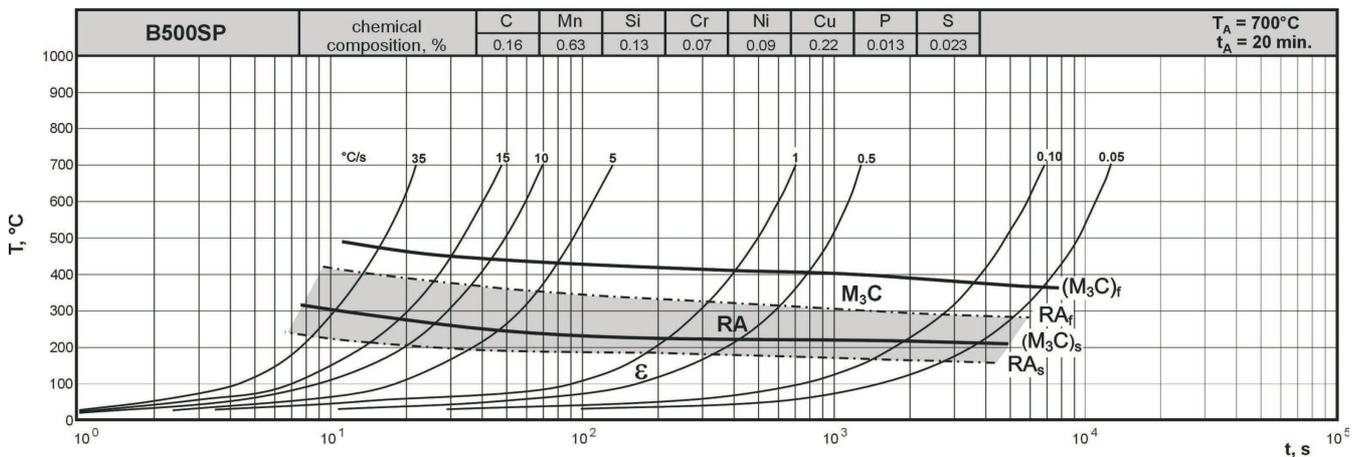


Fig. 4. CHT diagram of investigated steel

Changes in the microstructure and hardness of the bar (of a diameter of 8 mm) produced in the Tempcore technology are shown in Figure 5, as an example. Hardness at a distance of 0.5 mm below the surface equals approximately 280 HV. The microstructure constitutes tempered martensite (cooling rate during quenching higher than 150 °C/s). The thickness of the quenched zone is 1 mm. Hardness of martensite, at the same carbon content as in the investigated steel (approximately 0.16%) equals 420 HV (see Fig. 1). Thus, it means that the surface after quenching was heated by the core heat to a temperature not higher than 300 °C.

In the intermediate zone the hardness changes from

180 to 250 HV<sub>10</sub>, by 70 units. The layer below the surface decreases its hardness due to a less intensive cooling during quenching (cooling rate range: 150 ÷ 25 °C/s) and a higher tempering temperature (closer to the core). A further hardness drop is additionally caused by an appearance of ferrite and perlite, apart from martensite (and probably also bainite) in the microstructure. It is difficult to indicate explicitly bainitic spaces in the intermediate zone of the tested bars. However, an existence of this structural component cannot be excluded since a low or medium tempered martensite has a microstructure similar to lower bainite.

Further into the depth of the sample ferrite and per-

lite, of a hardness of approximately 170 HV, constitute the microstructure, and then in the core itself there is a majority of ferrite with a small amount of perlite (hardness approximately 160 HV). Hardness differences in the

ferritic-perlitic zones are the result of various cooling intensities in these zones. When cooling is more intensive acicular ferrite and fine-lamellar perlite is formed.

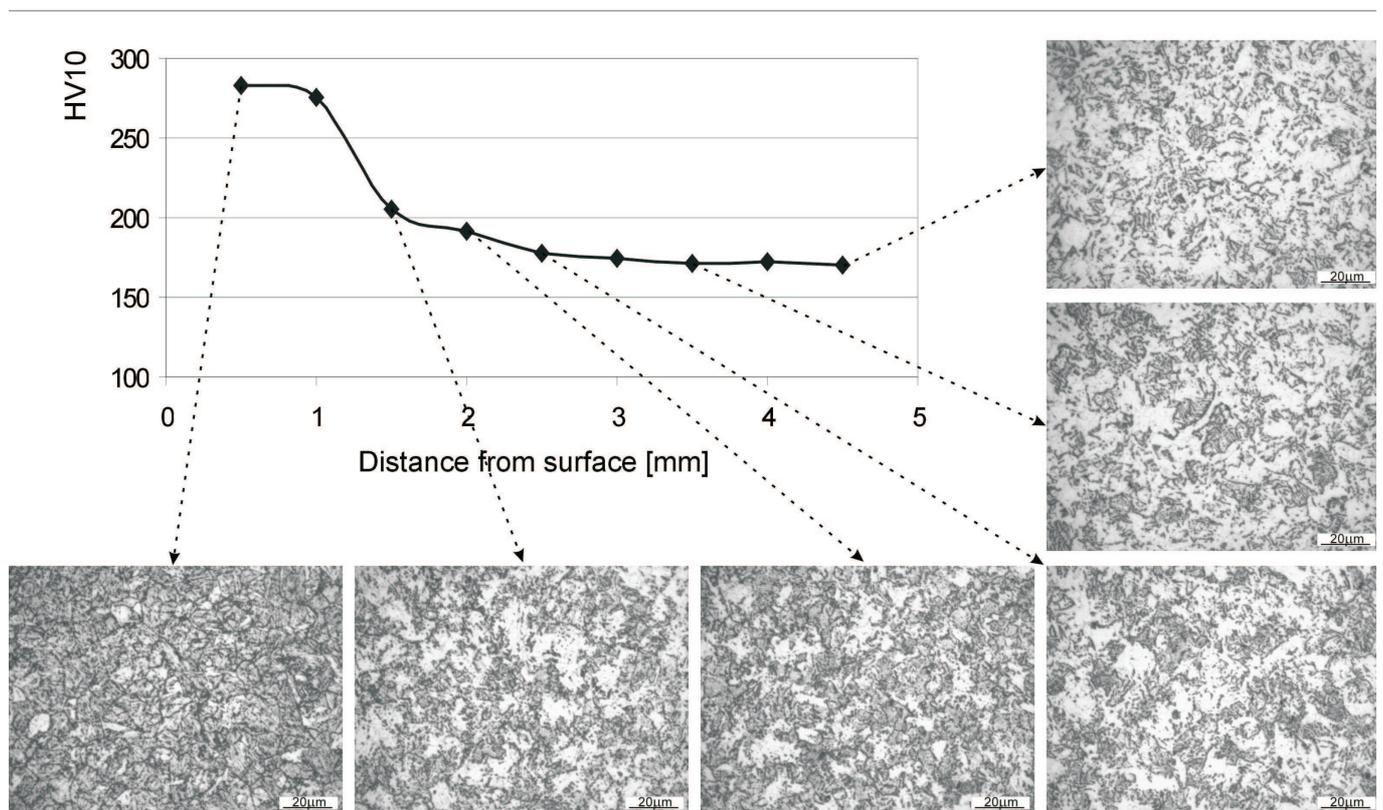


Fig. 5. Changes in hardness and microstructure versus a distance from the bar surface (bar diameter 8 mm)

The graph of stretching the reinforcing bar (of a diameter of 8 mm) produced according to the Tempcore technology is shown in Figure 6. At so low carbon content, being 0.16%, this method of bar treatment allows for obtaining very good strength properties such as  $R_m = 727$  MPa at good plastic properties: reduction of area and elongation being 52.7% and 15.8% – respectively.

Steels of similar carbon content, for which the TEMP-CORE process was not applied, obtain the upper plasticity limit at the level of 235 MPa, tensile strength approximately 360-510 MPa, and elongation approximately 25% (according to PN-EN 10025-2:2005). The tested bar exhibits the correct (recommended by PN-EN ISO 156301,15-1,35) quotient  $R_m/R_e = 1.18$ .

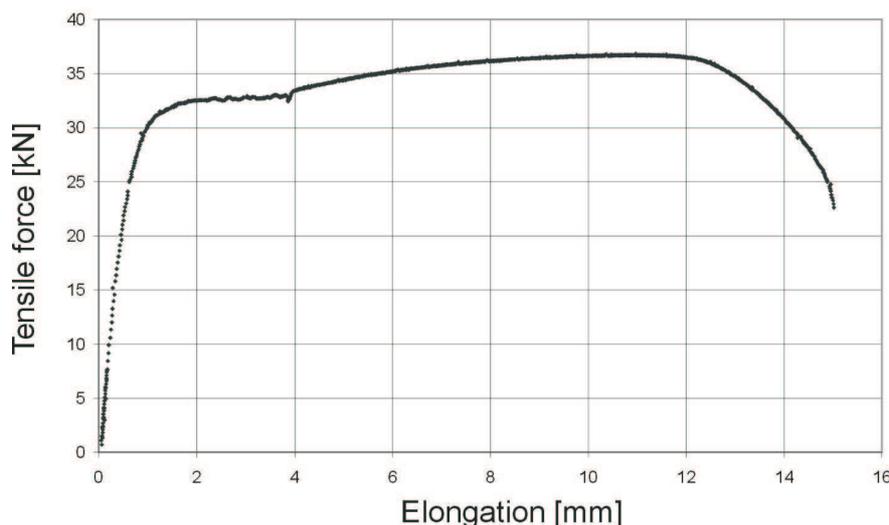


Fig. 6. Graph of stretching the reinforcing bar (of a diameter of 8 mm)

#### 4. Conclusion

The results that are contained in the present paper and their discussion allow for the formulation of the following conclusions:

1. The CCT diagram is characterised by the range of diffusive changes shifted strongly to the left, it means to shorter times (low hardenability). Hardenability of the investigated steel is enough small that during the cooling rate of 150 °C/s ferrite and perlite apart from a small amount of martensite occur in the microstructure.
2. Hardenability of the investigated steel intended for reinforcing bars produced according to the Tempcore technology is sufficient, which means that it will allow to obtain – in the near surface layer of the bar – martensite (eventually also bainite), which will be tempered due to the heat from the bar core.
3. Weak dilatation effects related to the rearrangement of carbon atoms (clusters) or to the precipitation of carbides  $\epsilon$  as well as the transformation of residual austenite and precipitation of cementite were recorded during the continuous heating from as-quenched state.
4. Parameters of the Tempcore process should be selected in such a way as to prevent heating (tempering) to temperatures higher than 300 °C the martensite formed directly below the surface and due to this to prevent the advancement of the cementite precipitation, which would significantly decrease strength and hardness of martensite.
5. When knowing the phase transformation kinetics the correct determination of the Tempcore process parameters (at the production of bars) allows for obtaining very good strength properties.

6. The tested bar exhibits the correct (recommended by PN-EN ISO 15630 1.15-1.35) quotient  $R_m/R_e = 1.18$ .

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