The influence of carbon content on the kinetics of phase transformations of undercooled austenite of the Cr-Mn-Mo model alloys

R. Dziurka*, J. Pacyna

Faculty of Metals Engineering and Industrial Computer Science,
AGH University of Science and Technology, Al. Mickiewicza 30, 30-059 Kraków, Poland
* Corresponding author: E-mail address: dziurka@agh.edu.pl

ABSTRACT

Purpose: Present work corresponds to the research on the kinetics of phase transformation of undercooled austenite of three Cr-Mn-Mo models alloys with a different carbon content. The kinetics of phase transformation of undercooled austenite of investigated alloys was presented on CTT diagrams. Also the methodology of a dilatometric samples preparation and the method of the critical points determination were described.

Design/methodology/approach: The austenitizing temperature was assumed, in a standard way, which means higher by 50 °C than Ac_3 temperature for W I and W II alloys and 50 °C higher than Ac_{1f} temperature for W III alloy. The first melt underwent the normalizing annealing and for the second melt the full annealing was proposed. For W III alloy the technology of soft annealing was proposed. The CCT diagrams were made on the grounds of dilatograms recorded for samples cooled with various rates. The microstructure of each dilatometric sample was photographed after its cooling to the room temperature and the sample hardness was measured.

Findings: The most noticeable influence of the increased carbon concentration in the investigated Cr-Mn-Mo alloys is increasing the austenite stability range within the bainitic transformation (but only up to 0.30 %C) and increasing the pearlite fraction. Along with the carbon concentration increase only the M_s temperature systematically decreases.

Research limitations/implications: The investigated alloys are the models alloys. Taking into account their chemical compositions the possibility of improving their properties by means of the heat treatment can be expected. In the first place the kinetics of phase transformations during tempering should be investigated.

Practical implications: Broadening the knowledge on the carbon influence in Cr-Mn-Mo alloys, which will help in designing new alloys with better properties.

Originality/value: The carbon influence on structures and properties of model alloys with Cr-Mn-Mo were undertaken.

Keywords: Metallic alloys; Kinetic phase transformations of undercooled austenite; CCT diagrams; Model alloys

Reference to this paper should be given in the following way:

R. Dziurka, J. Pacyna, The influence of carbon content on the kinetics of phase transformations of undercooled austenite of the Cr-Mn-Mo model alloys, Archives of Materials Science and Engineering 47/2 (2011) 77-84.

MATERIALS

1. Introduction

Carbon is not an alloying element. However, by a definition, it is present in steels. Along with a carbon content increase a strength and hardness are increasing while ductility and weldability of steel decreasing. Low-carbon steels are characterized by a moderate strength and good ductility. A strength and hardness of martensite in steels depends mainly on a carbon content. Alloying elements insignificantly influence the martensite strength. Carbon also causes an increase of the steel hardening capacity. Steels of a higher carbon content in the tempered and as-quenched state have a high strength and crack resistance.

The results of investigations concerning the carbon influence on the steel structure and properties originate from fifties and sixties. They were mainly obtained for 'real' alloys of the determined chemical composition. Opinions formed about carbon influence on steels structure and properties are in large measure based on works of Houdremont [1] and Bain and Paxton [2]. As it is known, these works are of a qualitative character and often do not concern a quantitative carbon influence on structures and properties of various steel grades. Due to this, from several dozen of years, investigations of the influence of various elements on structures and properties of steel carried out with the use of model alloys, it means alloys in which concentration of only one element is variable − have been performed in the University of Science and Technology (AGH).

It was indicated in paper [3], that carbon in the concentration range from 0.40 to 0.59% causes a significant increase of hardenability of model alloys containing app. 2% of manganese and the so-called weak background of the remaining alloying elements. It shifts phase transformation curves on the CCT diagrams to the right (into the direction of longer times) and in the direction of lower temperatures. In the whole concentration range i.e. 0.17-1.19% it causes a hardness increase in as-quenched state and favourably influences hardness changes with tempering temperature, especially low tempering.

Increased carbon concentration, in the range 0.12-1.15%, in austenite of model alloys containing app. 1.3% of chromium and a weak background of other alloying elements, caused first of all a prolongation of time before the start of the ferrite precipitation, whereas time before the start of the pearlitic transformation remained practically the same [4]. Carbon in this concentration range strongly increases hardness in as-quenched state but simultaneously decreases a crack resistance of alloys with chromium (in the whole range of tempering temperatures).

However, in case of model alloys containing app. 1% of silica and a weak background of other alloying elements, the carbon concentration increase in the range from 0.14 to 1.07% increases the austenite stability period within all transformations and simultaneously shifts curves of the start of ferrite, pearlite and bainite precipitations into lower temperatures [5]. In a similar fashion as manganese, also chromium strongly increases hardness in as-quenched state, with an increase of the tempering temperature a hardness decrease of low-carbon steels with silica is visibly smaller than in high-carbon steels.

Investigations carried out on model alloys containing app. 0.4% of vanadium and a strong background of other alloying elements [6] indicated, that the increased carbon concentration (0.31-1.25%) in austenite of these alloys significantly shifts the range of pearlitic and bainitic transformations towards longer times and also lowers the start and finish temperatures of the bainitic transformation.

Time, temperature, transformation (TTT) diagrams are the best tool which allows to perform the analysis of phase transformations of undercooled austenite. There are two main types of the TTT diagrams. The first, which is obtained during isothermal holding at various temperatures is called the TTT diagram. The second, determining the transformation kinetics of undercooled austenite at continuous cooling is called the CCT diagram (continuous cooling transformation).

From the practical point of view more important are the CCT diagrams. Information contained in such diagrams have been appreciated for a long time. Already in 1961 F. Wever and A. Rose created the atlas of the CCT diagrams for various steel grades [7]. Similar atlas prepared J. Jech in 1979 [8]. Their diagrams were of strictly practical meaning since they described kinetics of transformations of undercooled austenite of the well known and often used steel grades.

In addition, there are other important diagrams, the CHT (continuous, heating from as-quenched state, transformation). There are many publications in which are presented the importance information's from these diagrams [9-15].

During the last 20 years several new steel grades were developed in the University of Science and Technology (AGH) [9-11, 16-18]. For each new steel the original CHT or CCT diagram was made. Due to these diagrams it was possible to determine, simply and accurately, the possibility of modifying properties of steels by the heat treatment as well as the influence of individual alloying additions on the kinetics of transformation of undercooled austenite.

Designing of the chemical composition of new steels of a priori expected properties requires a lot of experience and the broad data base concerning influences of individual elements on the transformation kinetics of undercooled austenite. In order to supplement those data concerning the carbon influence on structures and properties of model alloys with manganese, silica, chromium and vanadium [3-6], endeavours of the quantitative determination of the carbon influence on structure and properties of model chromium-manganese-molybdenum alloys were undertaken – within the framework of the presented study.

2. Experimental procedure

The chemical composition of the new alloys was designed in the Laboratory of Phase Transformations, Department of Physical and Powder Metallurgy, AGH University of Science and Technology.

The microstructure of the investigated material was examined by the light microscope Axiovert 200 MAT.

The hardness measurements were performed with the Vickers HPO250 apparatus.

The dilatometric measurements were performed with the optic dilatometer LS 4 as well with the DT 1000 dilatometer.

3. Material for investigations

Three model alloys, which were melted and cast in the Institute of Ferrous Metallurgy in Gliwice then reforged in INTECH-MET in Gliwice and supplied as rods of a rectangular cross-section of dimensions: 35x20 mm, constituted the material for investigations. Chemical compositions of these steels are given in Table 1, while photographs of their microstructures in as-delivered condition (soft annealing after forging at 650 °C for 10 hours) are presented in Figure 1.

As it is seen in Figure 1a, W I (0.05% C) alloy in as-delivered condition had the structure consisting mainly of ferrite and fine precipitates of cementite. Hardness of this alloy in as-delivered condition was 139 HV30. Whereas W II (0.30% C) alloy (Fig. 1b) was characterized by a microstructure consisting of bainite and pearlite, which carbides were partially coagulated. Its hardness, in this state, equalled 310 HV30. A microstructure of W III (0.99% C) alloy in as-delivered condition (Fig. 1c) was characteristic for hypereutectoid steel, in addition to which carbides – both in pearlite and hypereutectoid ones (forming network) were partially coagulated. Hardness in this state was 239 HV30.

It is required, in the investigation of the phase transformation kinetics of undercooled austenite, to have the material in a state near the equilibrium one. Therefore before the beginning of examinations it is necessary to apply an adequate heat treatment i.e. normalizing annealing, full or soft. Performing each of these annealing requires at first the determination of critical temperatures for as-delivered condition. These temperatures were determined dilatometrically and equal for the alloy:

W I, Ac_{1s}= 775 °C, Ac_{1f}= 820 °C, Ac_3= 890 °C,

W II, Ac_{1s}= 745 °C, Ac_{1f}= 780 °C, Ac_3= 810°C,

W III, Ac_{1s}= 745 °C, Ac_{1f}= 780 °C.

The chemical composition of the investigated steel and the determined critical temperatures allowed to propose the proper annealing technology for these alloys (Fig. 2).

The austenitizing temperature was assumed, in a standard way, according to [16,17], which means higher by 50 °C than Ac_3 temperature for W I and W II alloys and 50 °C higher than Ac_{1f} temperature for W III alloy.

The first melt underwent the normalizing annealing (Fig. 2a), which means that it was austenitized for 60 minutes and then cooled together with the furnace. For the second melt the full annealing was proposed (Fig. 2b). It is based on the steel heating to temperatures being 30-50 °C above Ac_3 and a further slow cooling. It is aimed at obtaining the structure near the equilibrium state, at the improvement of the steel treatment ability as well as at the removal of inner stresses. For W III alloy the technology of soft annealing was proposed (Fig. 2c). This annealing consists of heating the investigated steel only slightly above Ac_{1f}, holding it at this temperature and then slow cooling to 500 °C (in this case) followed by further cooling together with the furnace. The applied soft annealing was characterized by a very slow cooling due to the expected high hardenability of the new steel being the result of high content of carbon, Mn, Mo and Cr.

The proposed annealing technologies brought the expected results. The photographs of microstructures of these steels – after the performed annealing – are presented in Figure 3.

As can be seen, this microstructure is characterized by a better homogeneity than that in as-delivered condition (Fig. 1) and is nearer to the equilibrium state for these alloys.
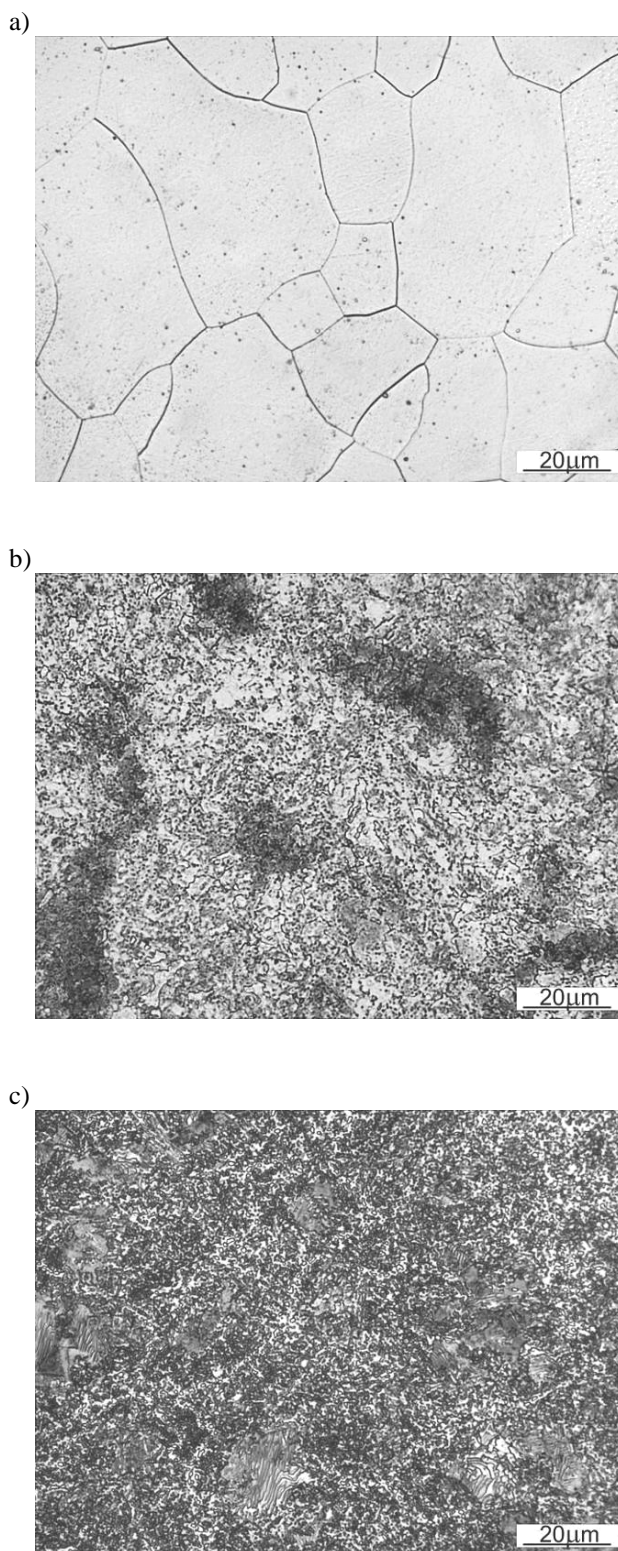
a)

b)

c)

Fig. 1. Microstructure of the investigated alloys: a) W I, b) W II, c) W III in as-delivered condition. Etched by 2% nital

Table 1.
The chemical composition (wt. %) of the investigated alloys

	C	Mn	Si	P	S	Cr	Ni	Mo	V	Cu
W I	0.05	1.58	0.13	0.009	0.009	1.90	0.01	0.28	0.17	0.022
W II	0.30	1.43	0.14	0.014	0.007	1.78	0.02	0.25	0.19	0.021
W III	0.99	1.51	0.13	0.009	0.012	1.88	0.01	0.27	0.17	0.021
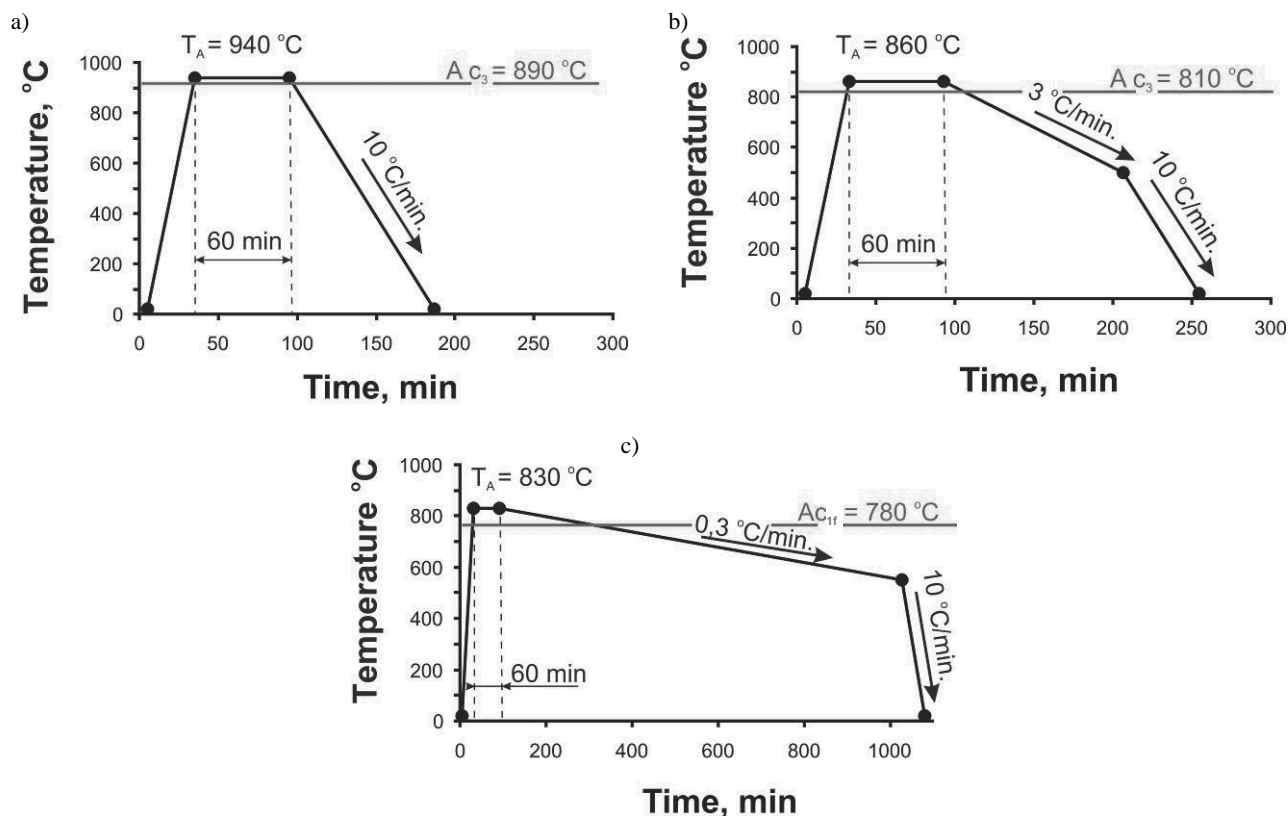
Fig. 2. Schemes of the developed annealing technologies of the investigated alloys: a) W I, b) W II, c) W III, from as-delivered condition

4. Research results and discussion

The CCT diagrams were made on the grounds of dilatograms recorded for samples cooled with various rates. The microstructure of each dilatometric sample was photographed after its cooling to the room temperature and the sample hardness was measured. The CCT diagram for W I alloy is presented in Figure 4. The CCT diagrams for W II and W III alloys are presented in Figures 5 and 6, respectively. Additionally chosen microstructure of the investigated alloys after dilatometric test are shown in Figure 7.

Dashed lines in the CCT diagrams are marking the cooling curves for the worked out annealing technologies shown in Fig. 2. Additionally in Figure 4, which presents the CCT diagram for W I alloy, the dashed line marks the cooling curves for water quenching of this alloy.

The CCT diagrams (Figs. 4-6) are characterized by a distinct division of the diffusive transformation range from the intermediate (bainitic) transformation range.

For W I alloy the intermediate (bainitic) transformation range is characteristic, since it occurs in a wide range of the applied cooling rates. On that account the investigated steel, which is represented by W I alloy, can be counted as the bainitic steel. Whereas in the CCT diagrams for W II and W III alloys a significant shifting in the direction of longer times of the intermediate transformation start is seen as well as the pearlite appearance, which in W III alloy is the dominating component. Thus, the increased carbon content in Cr-Mn-Mo steels does not influence so explicitly the austenite stability as it could be expected on the basis of previous studies [3-8, 16-18]. These literature data indicated that an increase of the carbon content causes an increase of the steel hardenability and that carbon influences more intensely hardenability of manganese steels [3] than of silicon [5] or chromium steels [4]. It was also known, from these data, that the increased carbon concentration strongly prolonged times before the bainite transformation start and the ferrite precipitation start [3-8, 16-18]. However, the investigations presented in this paper indicate that this influence is more complex, especially in case of the ferrite precipitation.
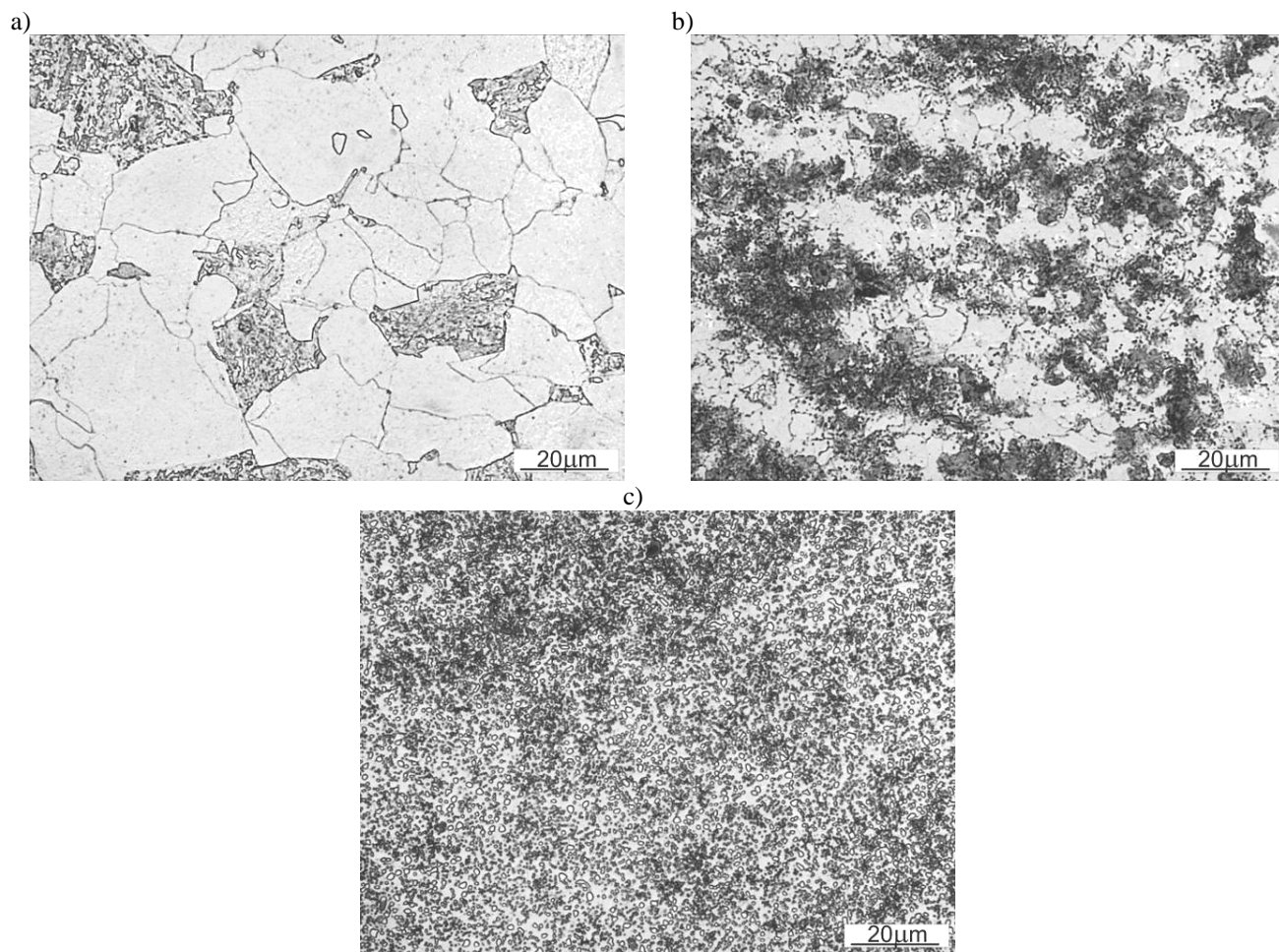
Fig. 3. Microstructure of the investigated steels: a) W I, b) W II, c) W III after annealing – acc. Fig. 2. Etched by 2% nital
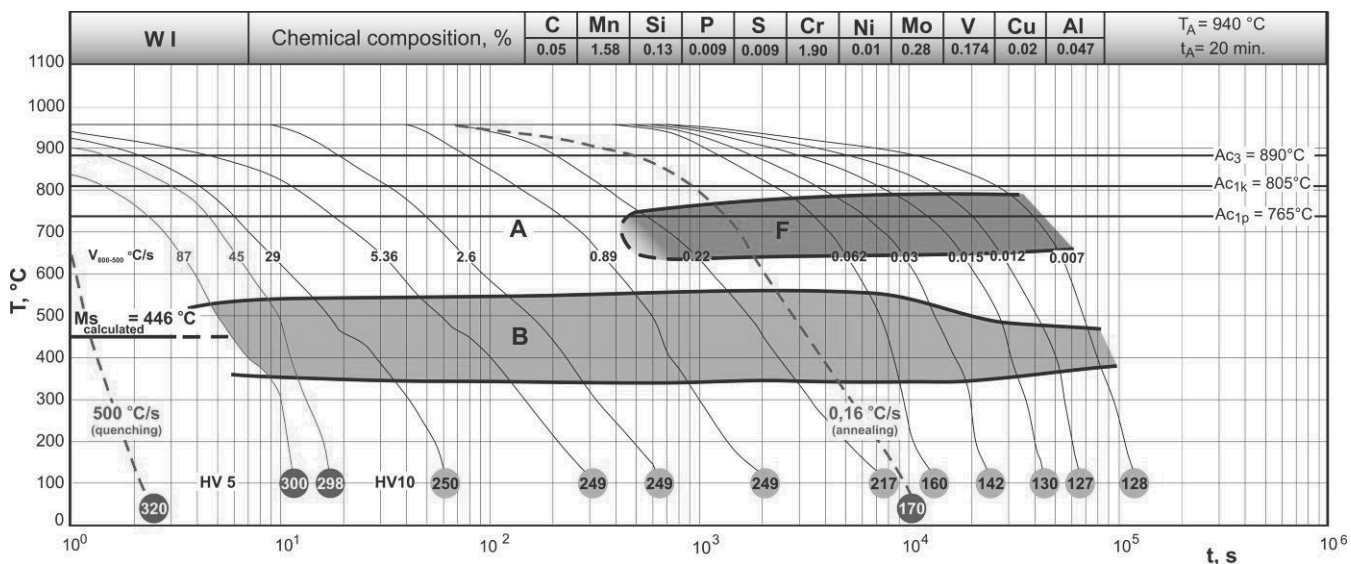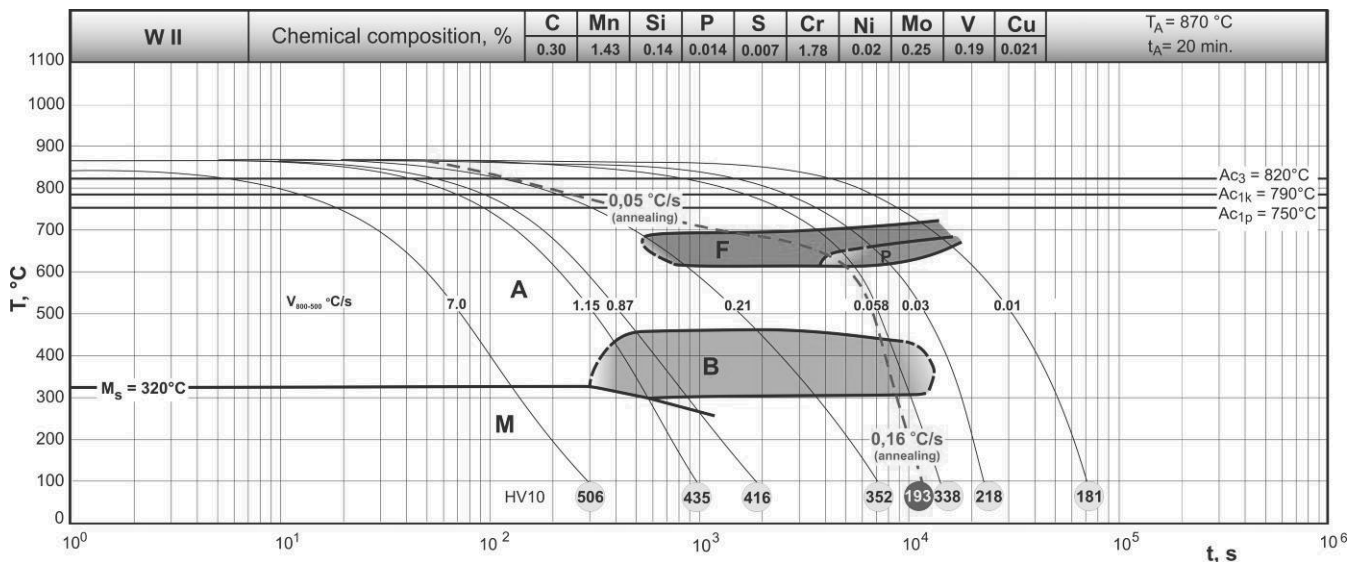

Fig. 4. The CCT diagram of W I alloy

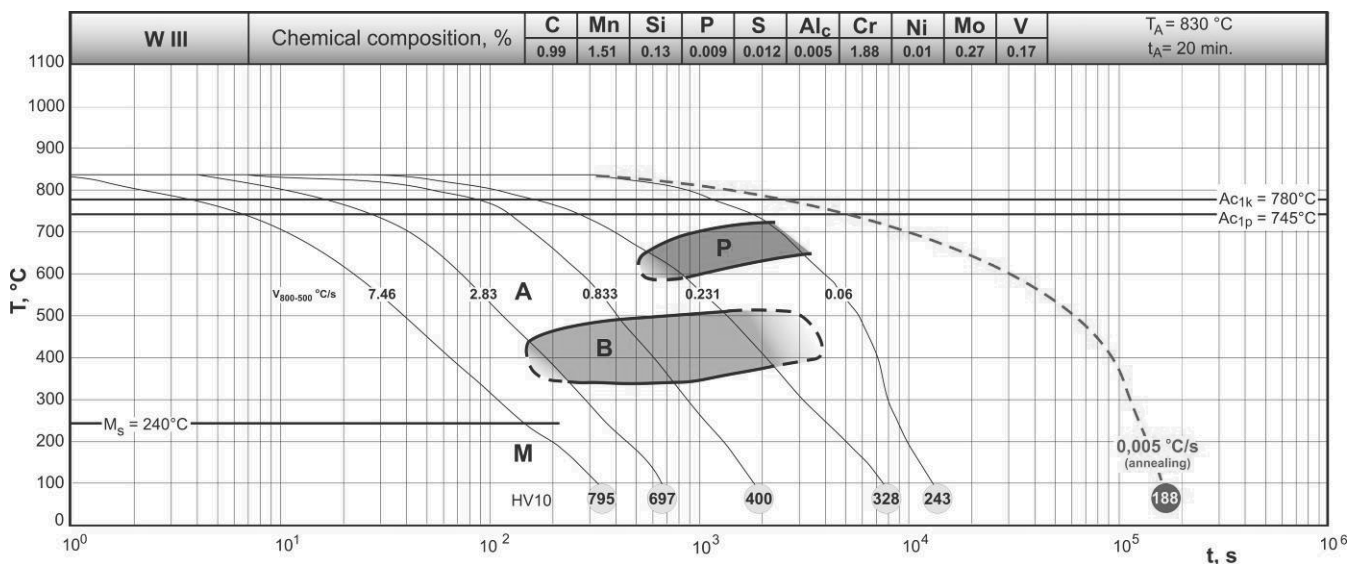Fig. 5. The CCT diagram of W II alloy


Fig. 6. The CCT diagram of W III alloy

In case of W I alloy, in spite of the cooling rate being 87 °C/s, it is not possible to find out the point, which can correspond to a temperature of the martensitic transformation start M_s. Therefore it was decided to apply the Steven and Haynes equation [19] to determine this temperature. The calculated M_s temperature for W I alloy equals 446 °C. However, since this equation is valid for the carbon content 0.1-0.55%, the obtained result can be burdened with a certain error. Obtaining homogenous martensite structure on samples used in the dilatometer DT1000 was only possible after their quenching in water (dashed curve in Figure 4).

The analysis of the obtained CCT diagrams of the tested alloys indicates that an increased carbon concentration caused lowering of critical temperatures and − in accordance with the reference data − lowered the M_s temperature. In case of these alloys an increased carbon concentration only weakly influences the B_s temperature. Likewise, the shifting of diffusive transformations into longer times (hardenability increase) is negligible.

An increased carbon concentration in austenite of the investigated alloys the most noticeably influences the intermediate transformation range. Although, as it was previously mentioned, it does not strongly influence the B_s temperature yet it distinctly prolongs time before it starts (but only up to 0.30 %C).
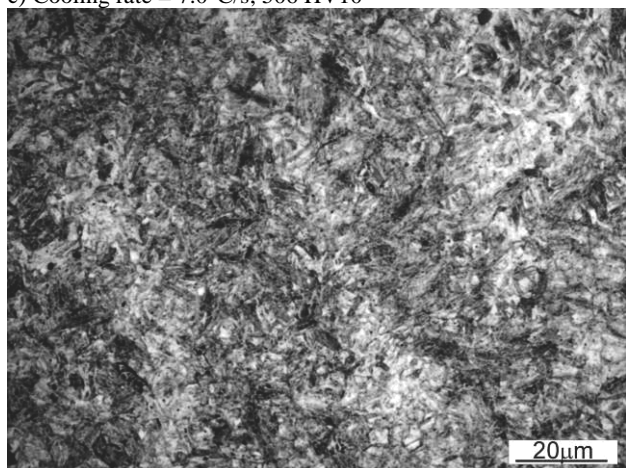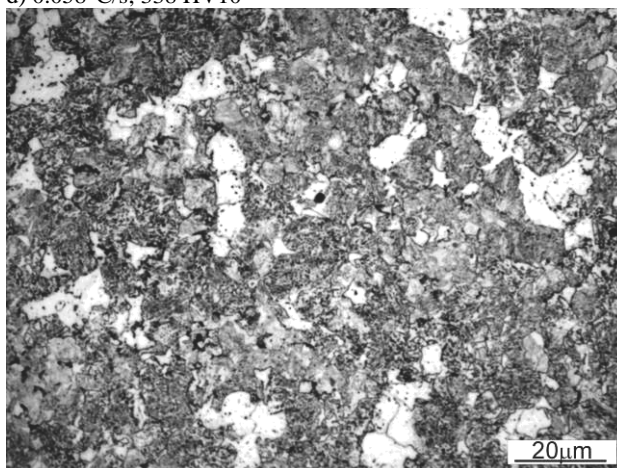
a) Cooling rate = 29 °C/s; 250 HV10
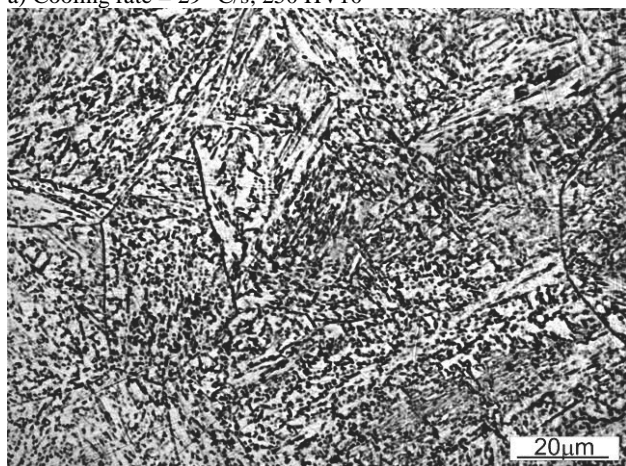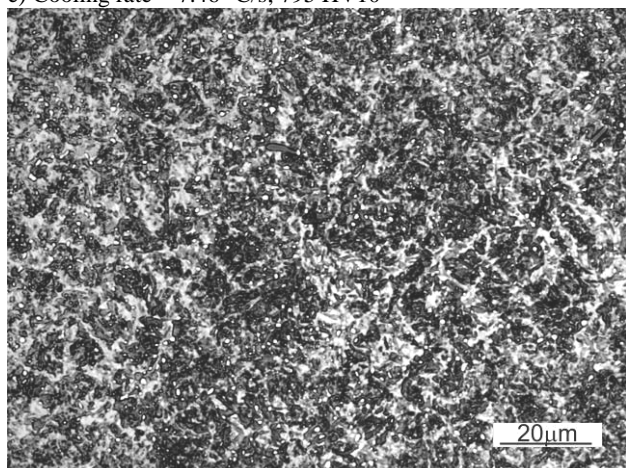
b) Cooling rate = 0.22 °C/s; 217 HV10
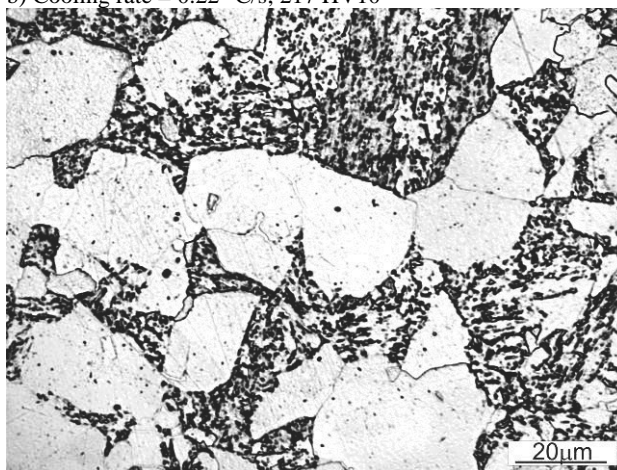
c) Cooling rate = 7.0°C/s; 506 HV10

d) 0.058°C/s; 338 HV10

e) Cooling rate = 7.46 °C/s; 795 HV10
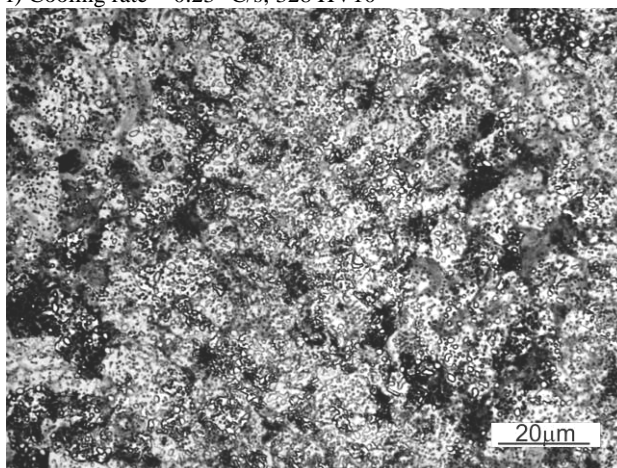
f) Cooling rate = 0.23 °C/s; 328 HV10

Fig. 7. Chosen microstructure of the investigated alloys: a, b) W I, c, d) W II, e, f) W III after dilatometric test. Samples cooled with various rates. Etched by 2% nital

In accordance with the information which can be found in references [1-8, 16-18], an increased carbon concentration significantly influences the alloy hardness, which is seen in the CCT diagrams.

The investigated alloys are the models alloys. Taking into account their chemical compositions the possibility of improving their properties by means of the heat treatment can be expected. In the first place the kinetics of phase transformations during tempering should be investigated. For each new alloy the original CCT (continuous cooling transformation) and CHT (continuous heating from as-quenched state) diagram should be made [9-15, 16-18]. Due to these diagrams it is possible to determine, simply and accurately, the possibility of modifying properties of steels by the heat treatment.

5. Conclusions

The analysis of the results obtained within the framework of this study allows to formulate several conclusions.
1. Since it was not possible to determine, by means of the dilatometric method, the M_s temperature for W I alloy containing 0.05%C, this temperature was calculated on the basis of the equation given in paper [12]. Thus, $M_s = 446\ °C$.
2. Along with the carbon concentration increase only the Ms temperature systematically decreases.
3. The CCT diagrams of the investigated steels are of type IV according to F. Wever and A. Rose classification.
4. High B_s temperature (reaching 500 °C) of the investigated alloys indicates that during their quenching significant amount of the upper bainite can be formed on the cross-section.
5. The most noticeable influence of the increased carbon concentration in the investigated Cr-Mn-Mo alloys is increasing the austenite stability range within the bainitic transformation (but only up to 0.30 %C) and increasing the pearlite fraction.
6. The increased carbon concentration in the investigated alloys increases their hardness.

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