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The kinetics of phase transformations during the tempering of HS6-5-2 steel

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ABSTRACT

Purpose: This work contains a detailed description of the kinetics of phase transformations during tempering of hardened HS6-5-2 high-speed steel. Moreover, the microstructure development in tested samples, reflecting the extend of the phase transformations during tempering, was discussed too.

Design/methodology/approach: CHT diagram, illustrating the kinetics of phase transformations during continuous heating (tempering) from as-quenched state of investigated steel, was elaborated using a DT 1000 dilatometer of a French company Adamel. The influence of the heating rate on the retained austenite transformation as well as the results of threefold tempering at 560ºC were also determined.

Findings: Heating of the investigated steel from the as-quenched state resulted in the occurrence of 4 primary transformations: precipitation of ε carbide, M_3C precipitation, transformation of retained austenite and precipitation of alloy carbides of MC and M_2C type. It was shown that in the quenched high-speed steels a part of retained austenite is already transformed during heating for tempering, but its significant part is transformed only during cooling after tempering as well as during consecutive heatings for temperings. Examination of the microstructure of investigated steel, mainly focused on microstructural development relating to the advancement of transformations during continuous tempering, showed an adequacy of the microstructural changes to CHT diagrams.

Research limitations/implications: The new CHT diagram of investigated steel was determined.

Practical implications: The obtained CHT diagram may be used to design new technologies of tempering of this steel.

Originality/value: The new CHT diagram.

Keywords: Tool materials; Tempering; CHT – diagram; Retained austenite

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MATERIALS

1. Introduction

During heating from the quenched state (tempering) of unalloyed, medium and high carbon steels, an occurrence of three principal transformations can be observed: precipitation of ε carbide, transformation of retained austenite into lower bainite and precipitation of cementite [1,2]. In the steels containing the elements which evoke the secondary hardness effect (V, W, Mo) there is the fourth stage of tempering, i.e. precipitation of alloy carbides of MC and M_2C type, nucleating independently [1-3].

During the first transformation in the range of temperatures 100-200°C, the ε ($Fe_{2.4}C$) carbides of compact hexagonal structure are precipitated. Precipitating ε carbide of high dispersion results in decreasing the martensite tetragonality and strong strength erring of steel. Nevertheless, the fall of carbon content in martensite results in its softening and, consequently, the strength of steel tempered in this range decreases slightly [1,2,4-6].

Second transformation proceeding during tempering in the temperature range of 200-320°C is a transformation of retained austenite. This process results in the origin of a heterogeneous mixture consisting of oversaturated ferrite and iron carbide, called lower bainite. It should be observed that this transformation occurs only in steels containing C>0.3% because the amount of austenite which remained in the steel after quenching depends precisely on the carbon content [7].

Cementite is formed during the third transformation occurring during tempering in the temperature range of 200-420°C. Iron transient carbides (ε) are dissolved and it enables the steel matrix to recover whereas the precipitating cementite, according to Blicharski [8], nucleates independently on grain boundaries of the former austenite and on some particles of transient carbides (in situ nucleation) and, according to Pacyna and Pawłowski [9], also on the boundaries of the newly formed cellular structure.

Above 400°C, diffusion of alloying elements such as V, Mo and W becomes occur as takes place. Cementite, unstable in these conditions, dissolves and the carbides of alloy elements nucleate independently or in situ i.e. cementite transforms gradually in a carbide of another type. The carbides of MC and M_2C type, precipitated during tempering, which nucleate independently and which are tiny and coherent with the matrix, increase hardness and strength properties [3,10-12]. High-speed steels are described in literature [10,12-20].

The first diagrams of kinetics of phase transformations at tempering (called CHT diagrams – Continuous Heating Transformations) of HS18-0-1 and HS6-5-2 high-speed steels were published in ref. [11]. According to the investigations [11,21] the CHT diagrams contribute to interfering in the degree of advancement of successive transformations during tempering (e.g. by means of the change of heating rate, temperature and time of soaking) and respectively, to achieving advantageous properties, in particular high fracture toughness.

2. Test material

The research was conducted on the HS6-5-2 high speed steel with the chemical composition given in Table 1.

Table 1.
Chemical composition of the investigated steel

Grade	mass %						
	C	Mn	Si	Cr	Mo	W	V
HS6-5-2	0.85	0.30	0.31	4.14	4.61	6.55	1.94

3. Experimental procedure

CHT diagram, illustrating the kinetics of phase transformations during continuous heating (tempering) from as-quenched state of investigated steel, was elaborated using a DT 1000 dilatometer of a French company Adamel. Samples with a diameter of 2 mm and a height of 12 mm, after quenching from 1240°C (austenitizing time of 150 s), were heated to 700°C with a heating rate in the range of 0.05 to 35°C/s. Digitally recorded dilatograms (engineering strain elongation $\Delta l/l_o$ in relation to the temperature T) for heated samples were differentiated, what facilitated determination of the start and end temperatures of consecutive transformations and help to build the CHT diagram for the investigated steel (in the Time-Temperature-Transformation system for continuous heating from quenched state).

Moreover, the heating dilatograms enabled M_S temperature of retained austenite of the tested steel to by read out which were the base to construct the diagrams of dependences of M_S temperature of retained austenite on the heating rate of tempering. Multiple tempering was carried out to illustrate the stability of retained austenite in the investigated steel. It consisted in consecutive heatings with the same rate 0.05°C/s up to 560°C, holding for 1 h and then cooling the sample with 1°C/s.

Hardened samples (∅2x12 mm) were heated with a rate of 0.05°C/s to the temperatures of 210, 410, 560 and 790°C. The microstructure of these samples were examined by a light microscope Axiovert 200 MAT and scanning electron microscope Stereoscan 120. Similarly, heat treated samples, with a diameter of 3 mm and a height of 10 mm, were used for TEM investigations using JEM 200CX microscope.

The measurements of hardness were performed with the Vickers HPO250 apparatus.

4. Research results and discussion

Fig. 1 shows a dilatogram of a sample (quenched from 900°C) heated with a rate of 0.05°C/s, along with a corresponding differential curve showing a method of an interpretation of dilatograms, basing on which a CHT diagram was created. As it can be observed, this steel reveals at first the shrinkage connected with the precipitation of ε carbide. This shrinkage starts at the temperature of ε_s and ends at the temperature of ε_f. The positive dilatation effect, connected with the transformation of retained austenite, is very clear. It is visible in the range of temperatures RA_s - RA_f. Cementite precipitates in the range of temperatures $(M_3C)_s$ - $(M_3C)_f$, independently nucleating carbides of MC type precipitate from the temperature MC_s to MC_f and the temperature $(M_2C)_s$ process of precipitation of M_2C carbides starts. The alloy carbides which precipitate in the process of tempering of the HS6-5-2 steel comprise mainly the carbides of tungsten, vanadium and molybdenum.

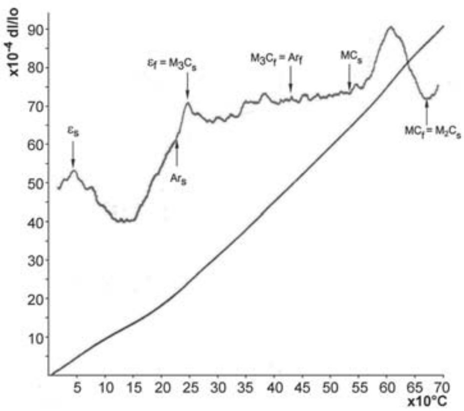

Fig. 1. Dilatogram of heating with the rate 0.05°/s of a sample previously hardened from 1240°C with the corresponding differentiation curve

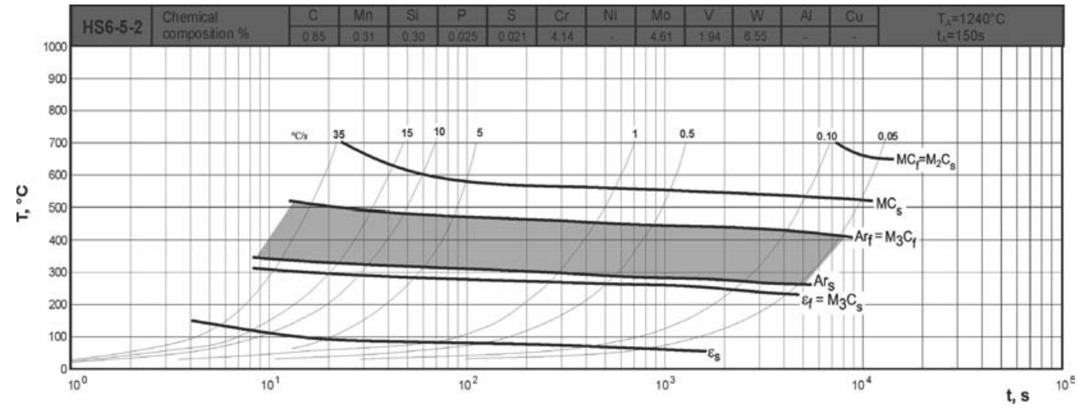

Fig. 2. CHT diagram of the investigated steel

Fig. 2 shows a new CHT diagram for the HS6-5-2 steel. The diagram contains the ranges of precipitation of ε carbide, transformations of retained austenite, precipitation of cementite and alloy carbides of MC and M_2C type.

The dilatation effect from the transformation of retained austenite during cooling (Fig. 3) is higher than during heating (cf. Fig. 1) which proves that only after tempering a larger amount of austenite is transformed.

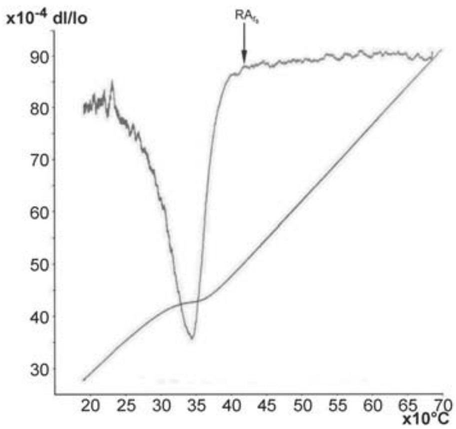

Fig. 3. Dilatogram of cooling of the HS6-5-2 steel sample with of cooling rate of 1°C/s, previously quenched from 1240°C and heated up to 700°C with of heating rate of 0.05°C/s, together with the corresponding differential curve with the marked temperature of the beginning of retained austenite transformation during cooling RAr_s

The diagram of dependences of RAc_s and RAr_s temperatures on the heating to 700°C for the HS6-5-2 steel is presented on Fig. 4. As it can be observed, the temperature of the beginning of transformation of retained austenite (RAc_s) increases with the rise of heating rate from 0.05°C/s to 35°C/s. However, at the rates over 15°C/s this parameter does not affect so strongly the RAc_s temperature as it happens for lower heating rates.

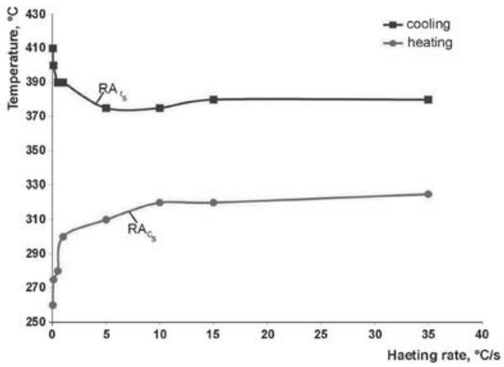

Fig. 4. The effect of heating rate up to 700°C after quenching from 1240°C on the temperature of beginning of transformation of retained austenite at heating (RAc_s) and at the next cooling with 1°C/s (RAr_s) for the HS6-5-2 steel

Multiple tempering was performed to investigate the stability of retained austenite in the tested steel. Fig. 5 shows 3 dilatograms of consecutive temperings of the HS6-5-2 steel. As it can be noticed, the second and third tempering, according to the generally accepted procedure of heat treatment for these steels can be justified from the point of view of transformation of retained austenite because minimum dilatation effects can be observed on dilatation curves, originating most probably from the transformation of the phase.

Fig. 6 shows the change of hardness of tested samples, depending on the heating temperature after quenching. As it can be seen, a hardness after quenching is 870HV30. The heating after quenching to temperature 560°C doesn't caused vehemently increase of hardness, like for example in HS18-0-1 [13], what may be the reason for precipitations of MC carbides is only initiate. The highest hardness was shown by the sample quenched, while the lowest belonged to the sample heated up to 790°C, when the coherence of precipitations of MC carbides was broken and the advanced precipitation of M_2C occurred.

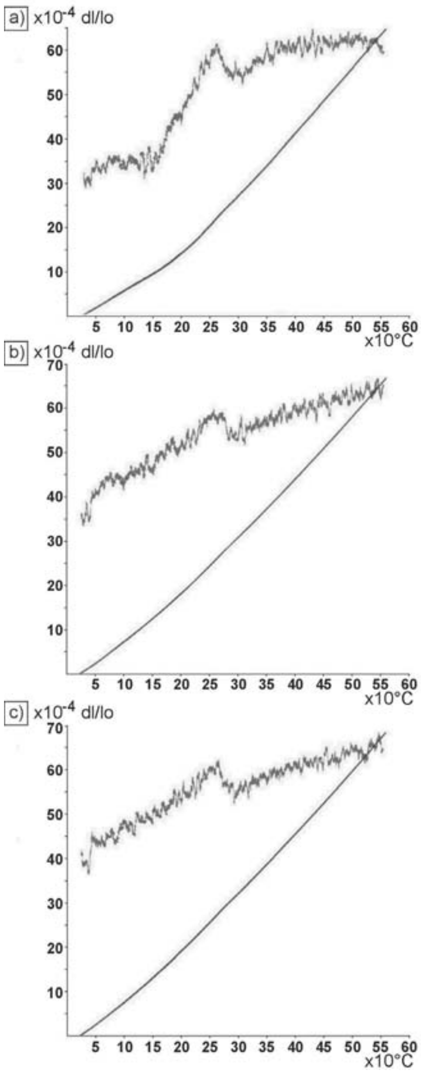

Fig. 5. Dilatograms of heating with the 0.05°C/s velocity up to 560°C for the HS6-5-2 steel: a) from the quenched state, b) second tempering, c) third tempering

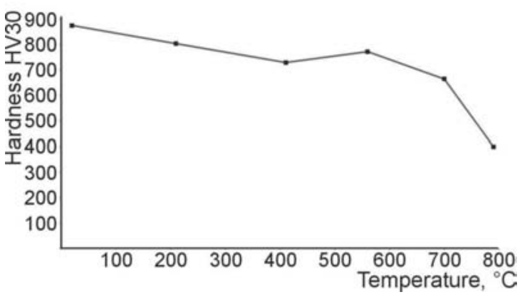

Fig. 6. Dependence of hardness of samples made from the tested steel on heating temperature after quenching

The microstructure of tested steel in the as-quenched state shows Fig. 7. In this condition (sample quenched from 1240°C), the microstructure consists of martensite (partly twinned), retained austenite and M_6C carbides.

a)

b)

c)

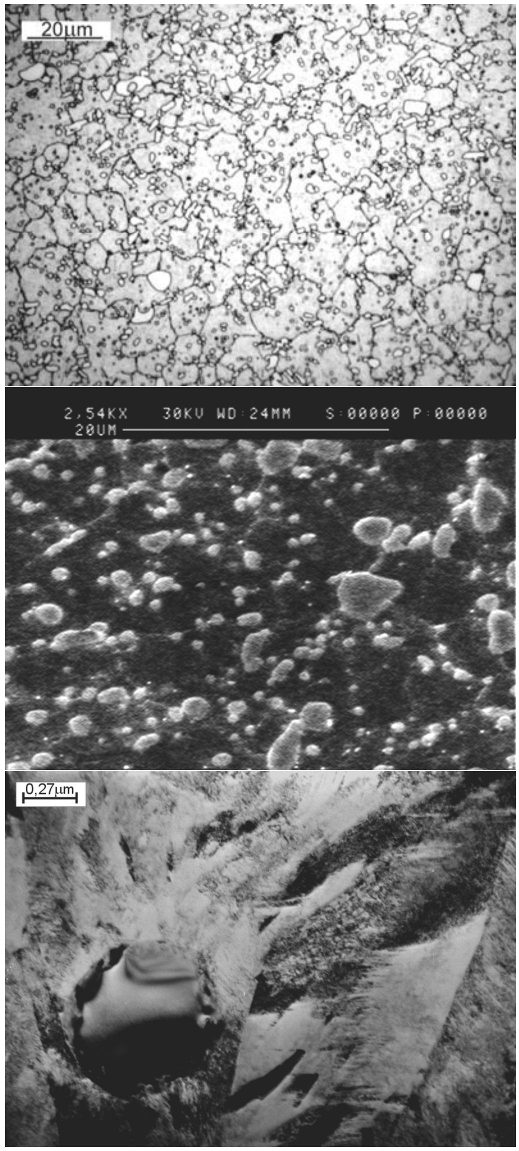

Fig. 7. Microstructure of tested steel in the as-quenched condition a) light microscope, b) scanning microscope, after nital etching, c) TEM

Figures 8-11 show the microstructures of the samples quenched from 1240°C, and then heated with a heating rate of 0.05°C/s (see Fig. 2) to 210, 410, 560 and 790°C respectively. These are specific temperatures, at which, for a given heating rate (0.05°C/s) the following phenomena were noticed: the end of precipitation of ε carbide (before the beginning of transformation of retained austenite), the end of cementite precipitation, the beginning of precipitation of MC alloy carbides and the end of precipitation of carbides of M_2C type. The presented microphotographs indicate a differentiated rate of advancement of transformations during tempering depending on the temperature up which the quenched samples of the tested steel were heated. During heating up to 790°C the morphology of primary carbides is not changed which is visible on microphotographs made with the optical microscope and the electron scanning one. Heating to 210°C caused the precipitation ε carbide which could be observed on microphotographs made with the transmission electron microscope. Besides, heating to this temperature does not cause changes in the structure high-speed steel. Such changes were caused by heating up to 410°C. These changes are clearly seen, especially on the scanning microscope microphotographs (clear relief coming from martensite). Also the TEM microphotographs show clear martensite strips with cementite precipitations. Heating to 560°C initiated the disintegration and transformation of cementite info alloy elements of MC type, difficult to be identified. Dispersive precipitations seen after such tempering in the TEM microstructure are most probably these carbides. Heating to 790°C caused the transformation of martensite into ferrite and precipitation of carbides which can be seen well both on TEM microphotographs and scanning microscope ones. The carbides revealed on the microphotographs of samples of the tested steel after such tempering, observed in TEM, are of M_2C type.

5. Conclusions

Heating of the investigated steel from the as-quenched state resulted in the occurrence of for primary transformations: precipitation of ε carbide, M_3C precipitation, transformation of retained austenite and precipitation of alloy carbides of MC and M_2C type.

It was shown that in the quenched high-speed steels a part of retained austenite is already transformed during heating for tempering, but its significant part is transformed only during cooling after tempering as well as during consecutive heatings for temperings. It is worth noting that the change of heating rate during tempering has a strong effect upon the temperatures of the beginning of transformation of retained austenite RA_{Cs} and RAr_s. Because of this, the evaluation of these temperatures must be carried out at strictly determined heating rate. In this steel, stabilization of retained austenite is higher than in HS18-0-1 [13].

Examination of the microstructure of investigated steel, mainly focused on microstructural development relating to the advancement of transformations during continuous tempering, showed an adequacy of the microstructural changes to CHT diagrams.

a) b) c) d)

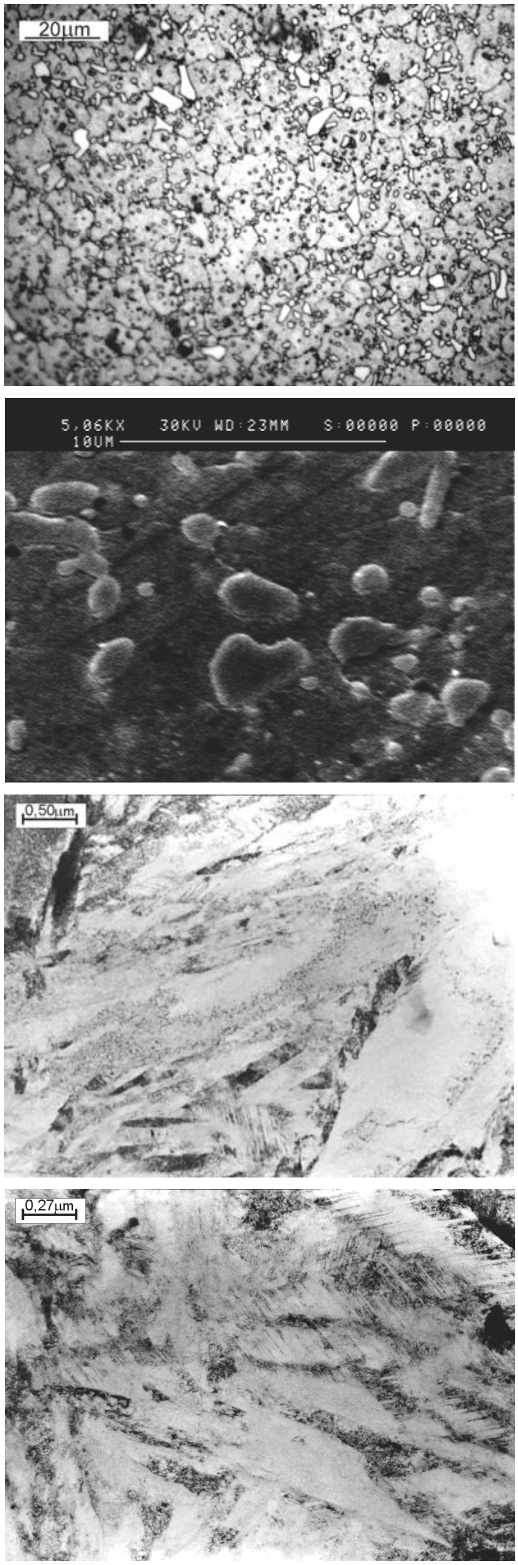

Fig. 8. Microstructures of the investigated steel after hardening from 1240°C and heating with the rate 0.05°C/s up to 210°C: a) light microscope, b) scanning microscope, after nital etching and c,d) TEM

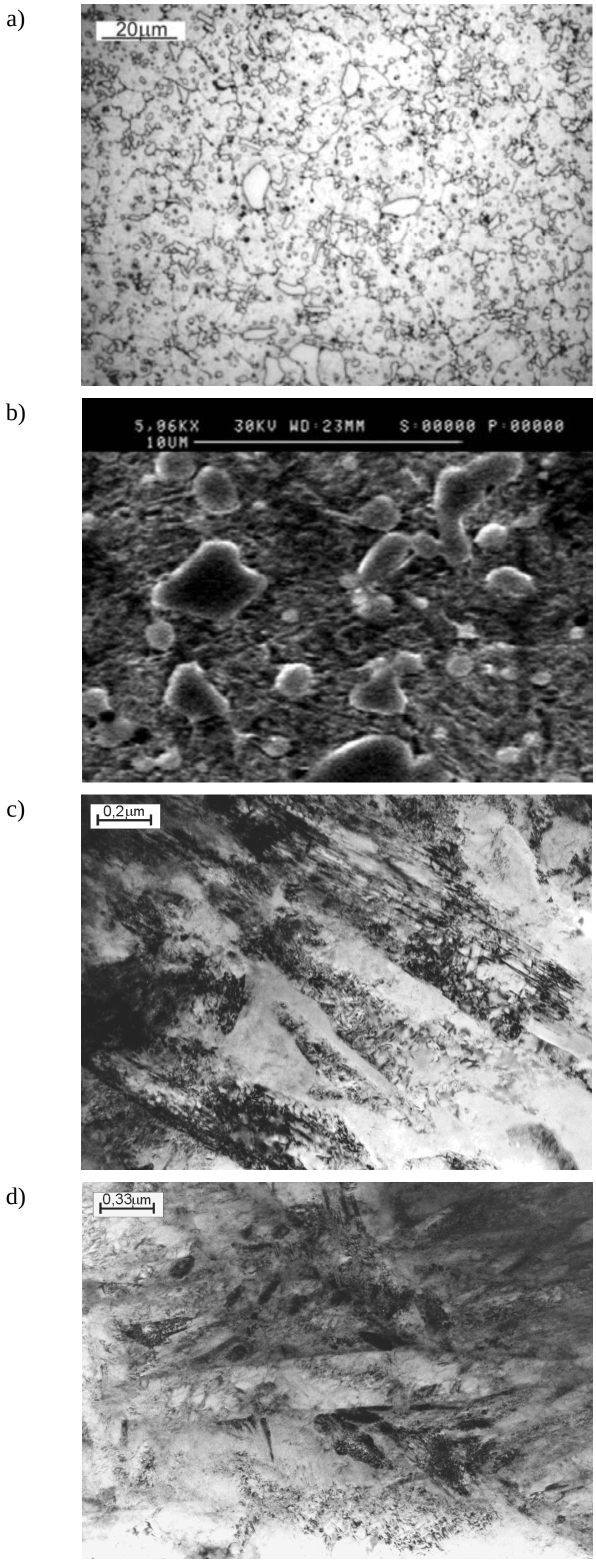

Fig. 9. Microstructures of the investigated steel after hardening from 1240°C and heating with the rate 0.05°C/s up to 410°C: a) light microscope, b) scanning microscope, after nital etching and c,d) TEM

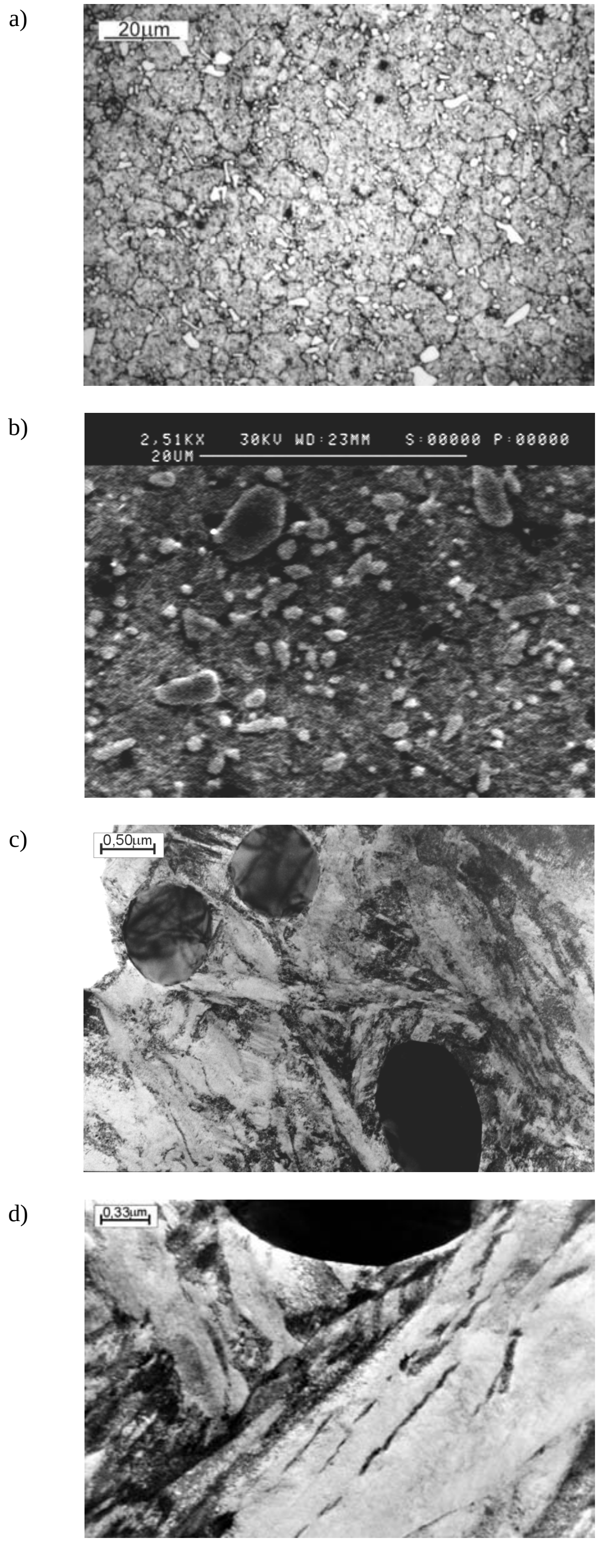

Fig. 10. Microstructures of the investigated steel after hardening from 1240°C and heating with the rate 0.05°C/s up to 560°C: a) light microscope, b) scanning microscope, after nital etching and c,d) TEM

a)

b)

c)

d)

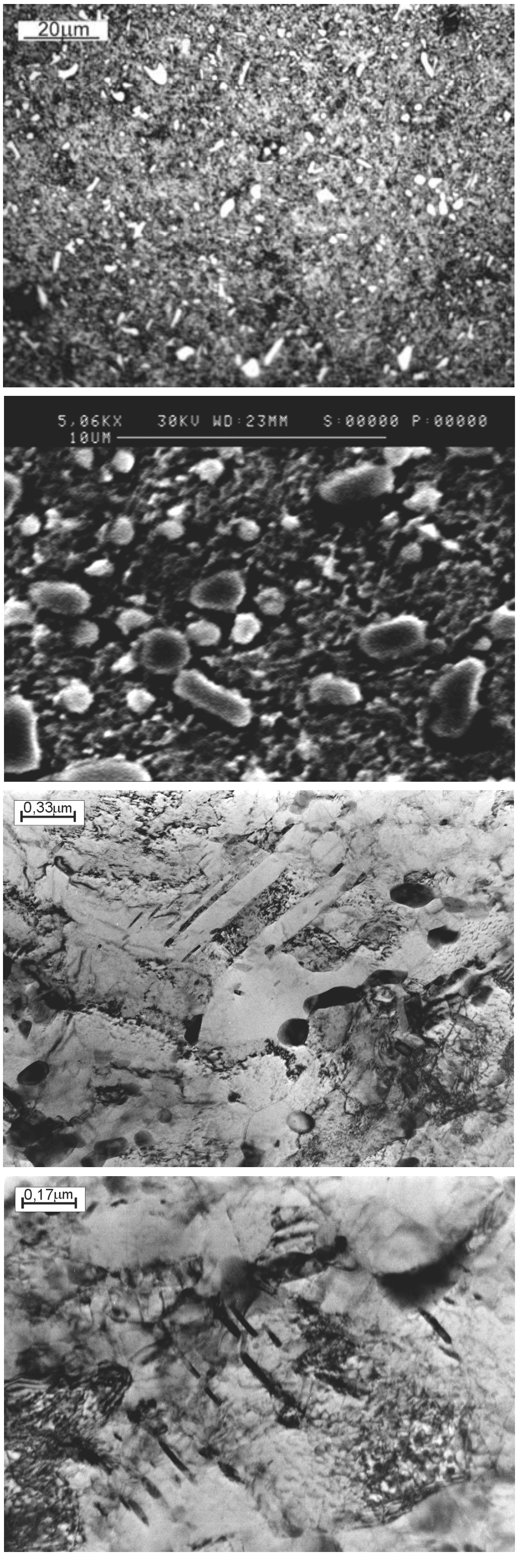

Fig. 11. Microstructures of the investigated steel after hardening from 1240°C and heating with the rate 0.05°C/s up to 790°C: a) light microscope, b) scanning microscope, after nital etching and c,d) TEM

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