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# THE KINETICS OF PHASE TRANSFORMATIONS DURING TEMPERING OF TOOL STEELS WITH DIFFERENT CARBON CONTENT

## KINETYKA PRZEMIAN FAZOWYCH PRZY ODPUSZCZANIU W STALACH NARZĘDZIOWYCH O RÓŻNEJ ZAWARTOŚCI WĘGLA

The main purpose of this study was the description of phase transformation kinetics during continuous heating from the as-quenched state (tempering) of newly designed tool steels for mill rolls with different carbon content. Dilatometry was used to determine the characteristic temperatures of phase transformations occurring in the investigated steels during he4ating from the as-quenched condition. The paper contains interpretations of dilatometric curves and describes the influence of heating rate on the temperature range of occurrence of a particular transformation¿ The effect of carbon content on transformation strains was also studied.

Celem niniejszej pracy był opis kinetyki przemian fazowych przy nagrzewaniu ciągłym ze stanu zahartowanego (odpuszczaniu) nowo zaprojektowanych stali narzędziowych na walce hutnicze o różnej zawartości węgla. Na podstawie badań dylatometrycznych wyznaczono zakresy występowania poszczególnych przemian fazowych podczas nagrzewania ze stanu zahartowanego. Zamieszczono interpretację dylatogramów oraz opisano wpływ szybkości nagrzewania do odpuszczania na temperaturowe zakresy występowania poszczególnych przemian. Ponadto opisano wpływ zawartości węgla na efekty dylatacyjne towarzyszące poszczególnym przemianom.

## 1. Introduction

The most important properties of tool steels are: bending strength, hardness and wear resistance at working temperatures as well as resistance to rapid, cyclic changes in temperature (thermal fatigue). The above properties are archived by the proper selection of of chemical composition and heat treatment conditions [1-3].

By changing the microstructure through heat treatment it is possible to obtain a required combination of high hardnes and mechanical strength and good ductility. As the phase transformations occuring during tempering are controlled by diffusion, for a steel with a given chemical composition the major role in obtaining of required properties is played by the tempering parameters, such as temperature and time [4-8].

The undertaken research will assist in better understanding the tempering process and provide guidance on tempering cycles to be applied for high dimension rolls which expeience different heating rates along the cross-section leading to a wide variation in mechanical strength and fracture toughness.

## 2. Experimental procedure

The research was conducted on two Cr-Mo-V steels designet at the AGH UST by the Phase Transformations Research Group. Their chemical composition are given in Table 1. The 50 kg ingots (120 mm diameter), produced under laboratory conditions, were forged into bars having cross-section of 20x35 mm. The bars where subsequently annealed and machined to size required for dilatometric specimens.

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TABLE 1

Chemical composition of investigated steels

| Grade | C | Mn | Si | P | S | Cr | Mo | V | Al | Fe |
|---|---|---|---|---|---|---|---|---|---|---|
| 35MnCrMoV8–6–4–1 | 0.37 | 1.93 | 0.35 | 0.014 | 0.03 | 1.60 | 0.43 | 0.12 | 0.04 | bal. |
| 120MnCrMoV8–6–4–2 | 1.22 | 1.93 | 0.19 | 0.018 | 0.02 | 1.52 | 0.36 | 0.17 | 0.04 | bal. |

The dilatometric tests were performed using the *Adamel* DT1000 highy-speed dilatometer. Speciments 2 mm in diameter and 12 mm high, were austenitized for 20 minutes, quenched and heated to 700°C at a rate ranging between 0.05 and 35°C/s. Dilatometric curves ($\Delta l/l_o$ vs. T) were acquired at the heating up stage and differentiated, in order to facilitate determination of the start and finish temperatures of phase transformations.

## 3. Results and discussion

### 3.1. Microstructure of steels in the as-quenched condition

After quenching from 870°C the microstructure of the 35MnCrVMo8–6–4–1 steel consists of marten-site and retained austenite (about 5.6%), located between laths of martensite (Fig. 1). On the other hand, after quenching from 900°C the microstructure of the 120MnCrMoV8–6–4–2 steel consists of partially twinned martensite, retained austenite (about 36.8%) and un-dissolved $M_3C$ type carbides (Fig. 2). The retained austenite appears as islands and thin layers between laths of martensite. Since for the 120MnCrMoV8–6–4–2 steel $A_{cm}=960$°C, the manganese and chromium containing alloyed cementite remains in the microstructure after quenching from 900°C. Such carbides were, however, found to have negligible effect on tempering [9].
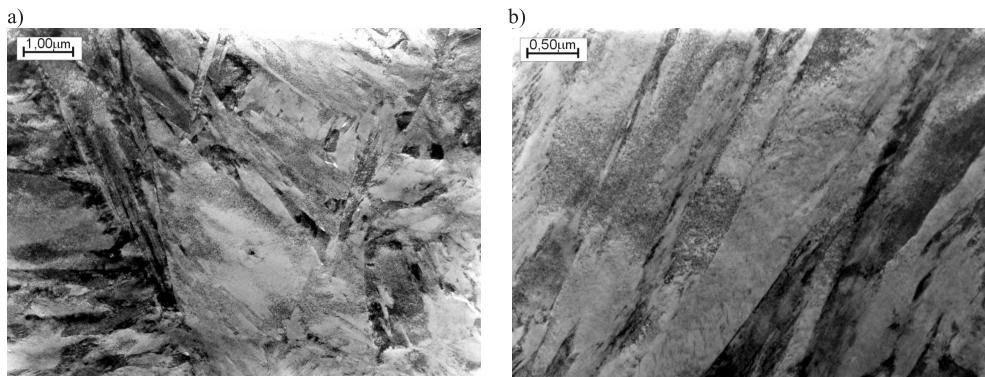


Fig. 1. TEM micrographs of the 35MnCrMoV8-6-4-1 steel quenched from 870°C
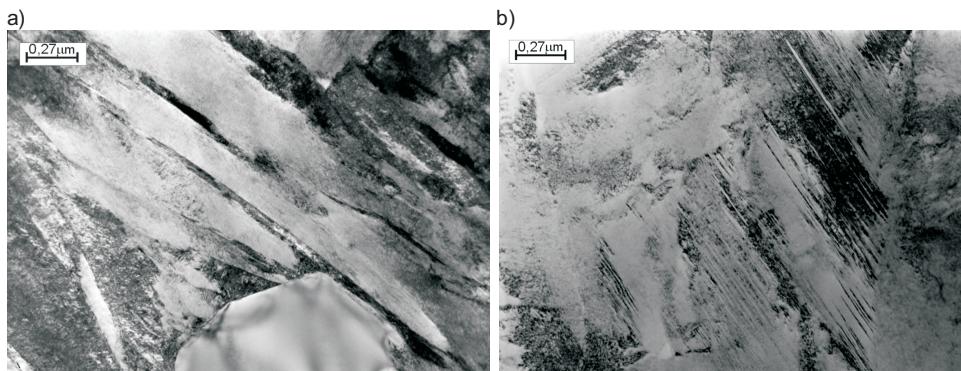


Fig. 2. TEM micrographs of the 120MnCrMoV8-6-4-1 steel quenched from 900°C

## 3.2. Kinetics of phase transformations during continuous heating from the as-quenched condition

Figure 3 presents dilatometric curves recorded at various heating rates for the 35MnCrVMo8–6–4–1 steel. It is evident from the curves that during the first stage of tempering the precipitation of non-equilibrium $\varepsilon$ carbide [10] ($Fe_{2.4}C$ having hexagonal structure) suppresses the specimen expansion as the temperature grows between $\varepsilon_s$ and $\varepsilon_f$. In the lower carbon steel (35MnCrVMo8–6–4–1) the dimensional response (contraction) to the precipitation of $\varepsilon$ carbides is very small. An increase of the heating rate from 0.05 to 35°C/s results in shifting the range of $\varepsilon$ precipitation from 100÷220°C to 120÷310°C, respectively. At higher temperatures the $\varepsilon$ carbide decomposes and cementite forms which also hinder the rate of specimen expansion. As the $\varepsilon$ and $M_3C$ precipitation ranges overlap it was assumed that $\varepsilon_f$ corresponds to the onset of cementite precipitation $(M_3C)s$ in order to facilitate interpretation of the recorded dilatometric curves. The formation of cementite terminates at $(M_3C)_f$ which temperature rises from 440 to 550°C as the heating rate increases from 0.05 to 35 °C/s, respectively.
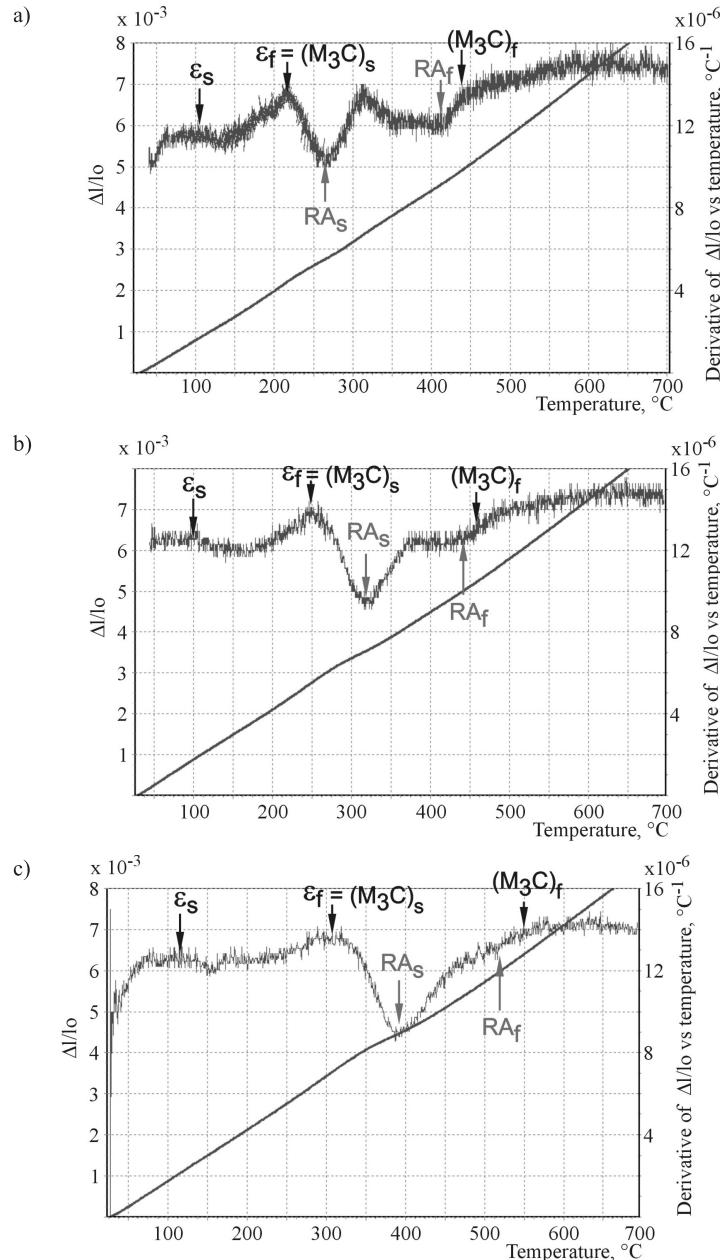


Fig. 3. Dilatometric curves recorded for the 35MnCrMoV8-6-4-1 steel at: a) 0.05°C/s, b) 1°C/s c) 35°C/s

The transformation of retained austenite to tempered martensite, which occur between $RA_s$ and $RA_f$, is accompanied by an accelerated specimen expansion. It is also seen that along with the increase of the heating rate the contraction caused by the precipitation of $M_3C$ increases, while the expansion due to the transformation of retained austenite decreases.

Figure 4 presents a dilatometric curve recorded at 0.05°C/s for the 35MnCrMoV8–6–4–1 steel quenched from 870°C and sub-zero treated for 1 hour in liquid nitrogen (–196°C). The difference in dimensional changes visible in Figures 3a and 4 results from the application of subquenching in liquid nitrogen, which markedly decreases the volume fraction of retained austenite. Hence the expansion brought about by the transformation of retained austenite is lower in the sub-quenched specimen (Fig. 4) compared with its quenched only counterpart (Fig. 3a). This observation indicates that the transformation of retained austenite to tempered martensite occurs within the range of cementite precipitation, i.e. between $(M_3C)_s$ and $(M_3C)_f$.
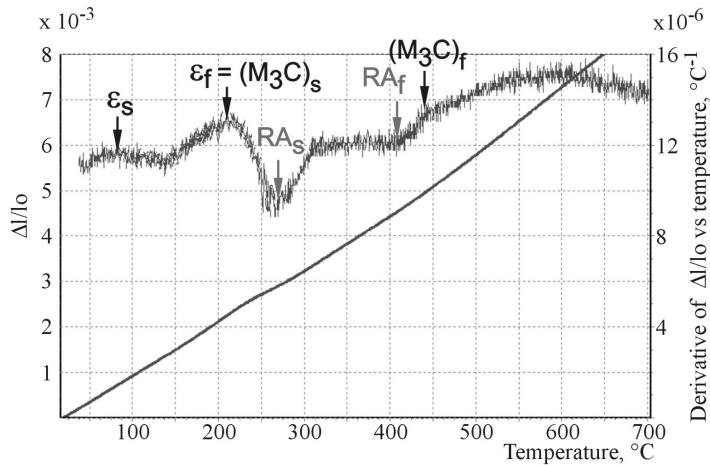


Fig. 4. Dilatometric curves recorded for the subquenched 35MnCrMoV8-6-4-1 steel at 0.05°/s

Figure 5 presents dilatometric curves recorded for the high carbon 120MnCrMoV8–6–4–2 steel quenched from 900°C. As in the lower carbon steel, the $\varepsilon$ carbide precipitates during the first stage of tempering. An increase in the heating rate delays the carbide formation ($\varepsilon_s$) which starts at ~50°C for 0.05 °C/s and ~120°C for 35 °C/s, and likewise the $\varepsilon_f$ temperature is increased from 200 to 310°C. Experiments conducted using other testing techniques [11,12] confirm precipitation of exclusively $\varepsilon$ carbide during the first stage of tempering, whereas the other transitory iron carbides, such as the orthorhombic $\eta(Fe_2C)$ [5,13-15] and monoclinic $\chi$ ($Fe_5C_2$) [16,17], were not found.
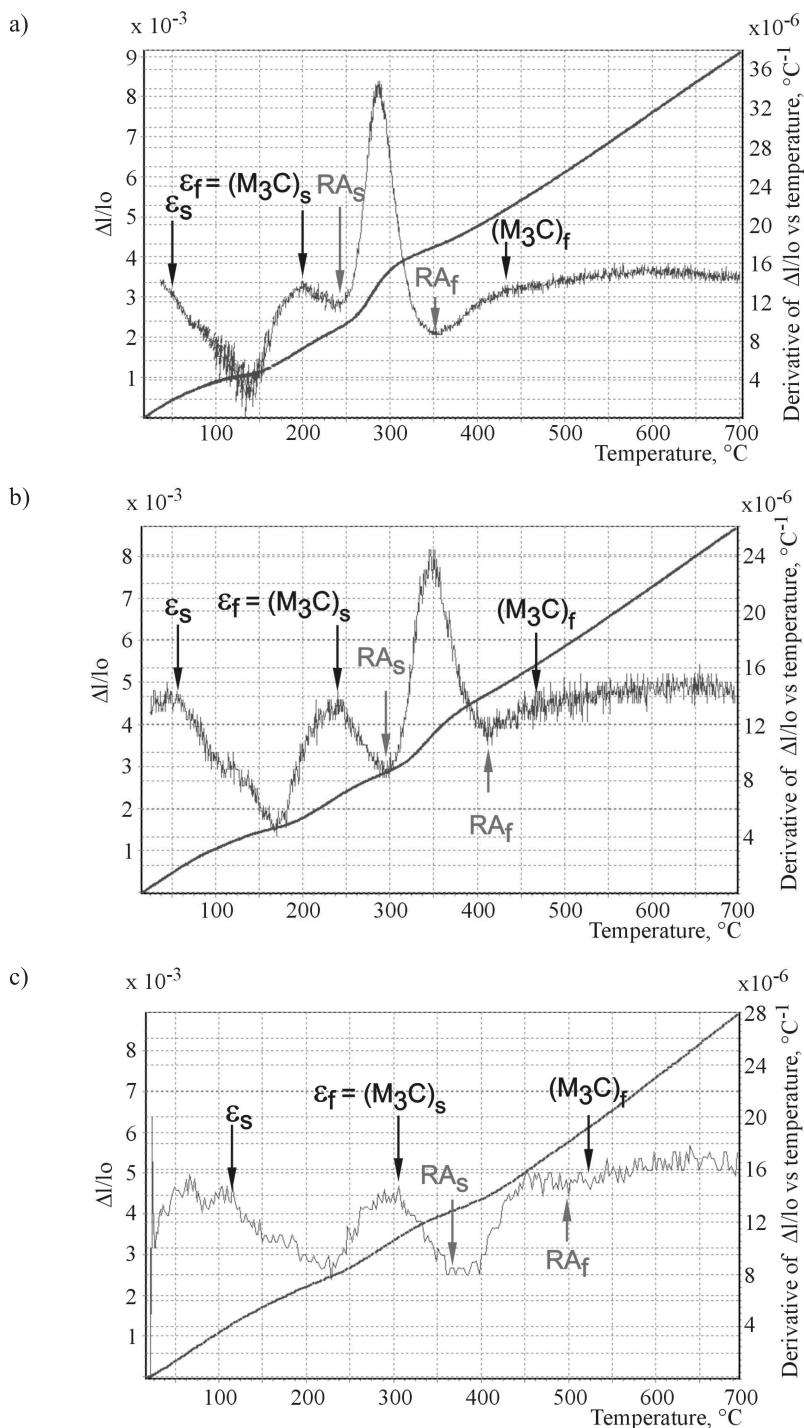
Fig. 5. Dilatometric curves recorded for the 120MnCrMoV8-6-4-2 steel at: a) 0.05°/s, b) 1°C/s, c) 35°C/s

Due to the transformation of retained austenite to tempered martensite an intense expansion is seen. An increase in the heating rate from 0.05 to 35°C/s shifts the $RA_s \div RA_f$ transformation range from 250÷350°C to 360÷500°C and markedly decreases dimensional changes. It is worth to note that the transformation of retained austenite takes place within the cementite precipitation range $(M_3C)s \div (M_3C)_f$.

In order to exclude the effects corresponding to the transformation of retained austenite a dilatometric curve was also recorded for a subquenched 120MnCrMoV8–6–4–2 steel (Fig. 6). As compared to the as-quenched condition (Fig. 5a), the specimen expansion is to a greater degree reduced by the precipitation of $\varepsilon$ and $M_3C$ carbides and smaller expansion is also in-duced by the transformation of retained austenite.
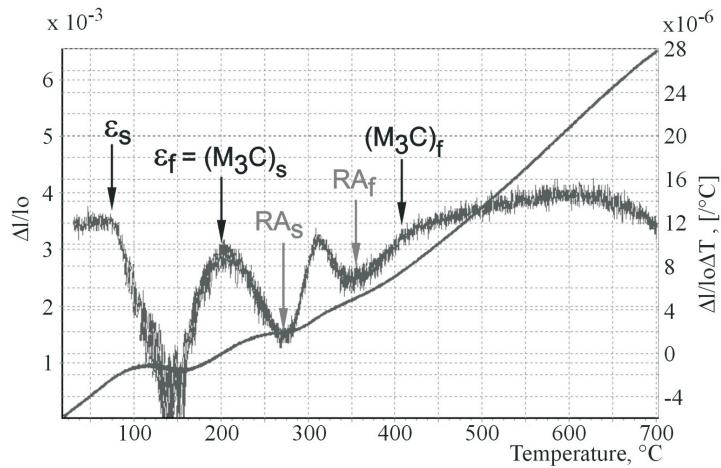
Fig. 6. Dilatometric curve recorded for the subquenched 120MnCrMoV8-6-4-2 steel at 0.05°/s

By comparing the dilatometric data acquired for the two investigated steels it becomes evident that the carbon content of steel (assuming similar content of other alloying elements) markedly influences the magnitude of dimensional changes brought about by a particular transformation and has a negligible effect on its temperature, except for a decrease of $\varepsilon_s$ observed at low heating rates $(0.05\div1°C/s)$.

The effect of heating rate on hardness of the investigated steels is shown in figures 7 and 8. The marked rise in the Vickers hardness number is observed as the heating rate increases from 0.05 to 0.5°C/s. Beyond 1°C/s hardness stabilises on a certain level as a result of a lesser extent of precipitation and growth of $M_3C$ carbides.
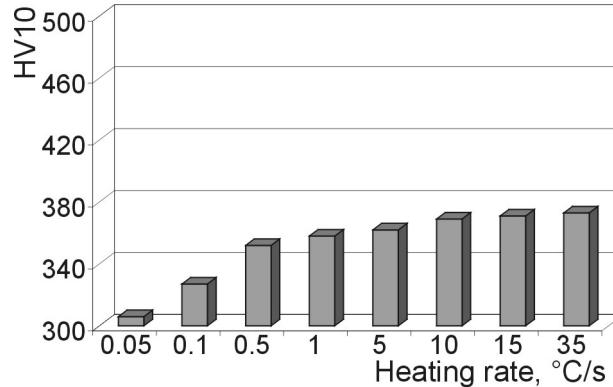


Fig. 7. The effect of heating rate on hardness of the 35MnCrMoV8-6-4-1 steel
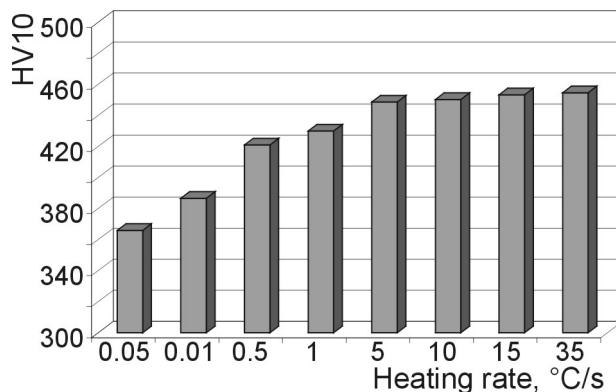
Fig. 8. The effect of heating rate on hardness of the 120MnCrMoV8-6-4-2 steel

## 4. Conclusion

The change in microstructure of the investigated steels during heating from the as-quenched condition results from precipitation of $\varepsilon$ and $M_3C$ carbides, and transformation of retained austenite to tempered martensite. Irrespective of the applied heating rate the precipitation of $\varepsilon$ carbide and cementite cannot be overheated and always occur. An increase in the rate of heating from 0.05 to 35°C/s shifts the ranges of carbides formation ($\varepsilon_s \div \varepsilon_f$, $(M_3C)_s \div (M_3C)_f$) and retained austenite decomposition ($RA_s \div RA_f$) to higher temperatures and reduces the dimen-sional response which accompanies each of these transformations.

Precipitation of MC and $M_2C$ type alloy carbides have not been detected although the investigated steels contain molybdenum and vanadium, and 0.37 or 1.22% carbon.

For a given heating rate the rise in carbon from 0.37 to 1.22% brings about a profound increase in the dimensional change corresponding to a particular transformation and virtually does not affect the transformation start and finish temperatures.

It has also been found that hardness of the tested steels markedly increases as the heating rate is accelerated from 0.05 to 0.5°C/s, and stabilises on a certain level, which depends on the carbon content of steel, at about 1°C/s and beyond.

### Acknowledgements

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