

# Influence of heating rate on sorbitic transformation temperature of tempering C45 steel

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## Abstract

In this paper the analysis of speed heating influence on sorbitic transformation temperature of tempering C45 steel is presented. On the basis of dilatometric research, functions associating heating time with initial and final temperature of sorbitic transformation have been determined as well as the size structural ( $\gamma$ ) and thermal ( $\alpha$ ) expansion coefficients of quenching and tempering structures have been estimated.

**Keywords:** heat treatment, laser treatment, tempering, phase transformation

## 1. Introduction

In heat treatment processes tempering lasts depending on the size of the object from several dozen minutes to do a dozen or so hours, or even longer. In laser heat treatment processes next transitions of laser cause multiple phase changes. Areas already surfaced undergo tempering, in addition to which the process is dynamic. Thermal cycles in laser processes are distinguished by high speed of heating-up in comparison to thermal tempering and slight hold time in maximum temperature.

In laser heat treatment processes, depending on steel genre and process parameters, can occur quenching structures, including martensite. In case of process connected with multiple laser beam transition cause tempering of already hardened areas.

In order to forecast final structure of material after process ending or calculate strains and stress states in surfaced object it is necessary to take into account tempering phenomenon and a knowledge of its phase changes kinetics.

A lot of works have been dedicated to examine the phenomenon of tempering. In most of them carried out experiments concern comparative metallographic analysis and mechanical properties (mostly hardness and impact strength) before and after the tempering [1-6]. While in modelling of stress states during tempering, the influence of phase changes is frequently omitted [7].

In the case of heat treatment the time of heating-up amounts to several dozen minutes, while annealing can last even hours [8]. The result is homogenous tempering structure. For such technological conditions, detailed analysis of changes in microstructure in steel C45 and Ni3.5CrMoV has been presented in work [9]. In welding processes and laser treatment occurs dynamic temperature change, while time of peak temperature during tempering lasts from several to hundreds of seconds. Short austenisation time, as well as of tempering lead to heterogeneous structure. Work [10] examines the microstructure and hardness after multiple welding cycles, while in work [11] have been presented results of metallographic research, microhardness and

impact strength of welds tempered by conventional method. The authors [12] carried out analysis of tempering kinetics of welded elements basing on results of microhardness measurements. There is lack of works describing quantitatively the connection between strains and temperature during welding and laser processes. The speed of heating-up can significantly affect kinetics of heating-up transformations in steel both during austenitisation [13-16], as well as during heating-up from hardened stage (of tempering) [17,18].

## 2. Tempering in steels

The tempering of steel are generally categorized as follows [19-21]. In steels with coal content up to 0.2 wt.% tempering begins already in the environment temperature moving coal atoms. After that segregation from temperature 80°C occurs liberating of carbides – it proceeds most intensively in the temperature range between 150 - 200°C, ends mainly at 200°C, but sometimes at 250°C. As a result of reducing the amount of coal, tetragonality of martensite is decreasing. Created in the first phase of tempering structure, consisting of supersaturated solid solution  $\alpha$  and carbide  $\epsilon$  is called low-tempered martensite [19].

Between 200 and 350°C any retained austenite begins to decompose. It has been suggested that this happens by transformation into bainitic ferrite and cementite [19] and causes a volume increase when carbon concentration in austenite is small [21]. Above 350°C martensite decomposes liberating cement grains creating the phase called sorbite or troostite. In plain carbon steels cementite particles begin coarsen in the temperature range 350°C - 400°C, but addition of chromium, silicon, molybdenum or tungsten delays the coarsening to the range 500°C - 550°C [20]. Then the growth of grains occurs and coagulation of cementite particles, spheroidizing, i.e. forming tiny spherical particles of cementite in ferrite matrix.

Tempering process ends in the temperature range 600 - 700°C. Above 600°C still proceeds coagulation of cementite and spheroidizing of ferrite – formation of divorced pearlite, i.e.

globular cementite in ferrite matrix of low hardness. This stage is called recrystallization.

## 3. Experimental research

The chemical composition of researched steel is shown in Table 1. Dilatometric experiments were carried out in thermal cycle simulator Smitweld TCS1405. The influence of the rate of heating-up on the temperature of the beginning and the end of sorbitic transformation has been researched for the rate of heating from 0.1 to 100°C/s.

Samples for tempering research have been heated-up to 1100°C, then cooled with the rate of cooling 200°C/s. Martensitic structure of hardened sample is presented in Fig. 1. The average value of hardness of hardened area was  $HV_{30} = 714$ . For each speed of heating have been made at least 3 dilatometric researches

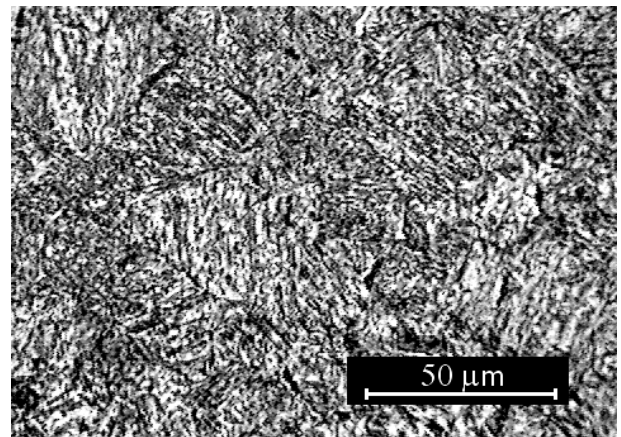


Fig. 1. Martensitic structure of a hardened sample

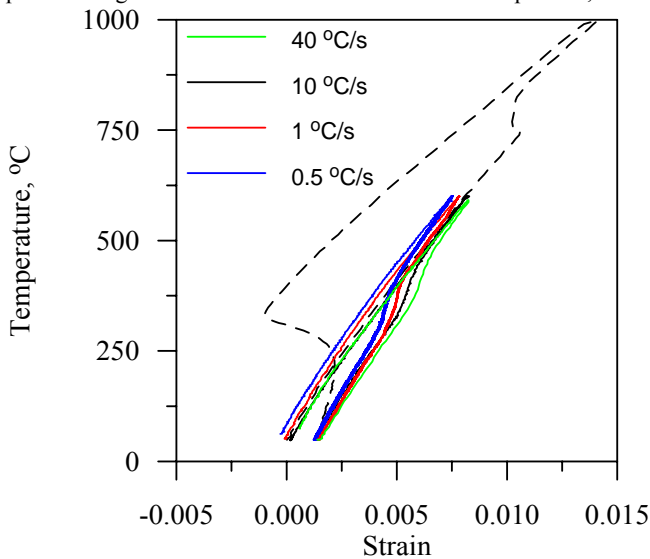


Fig. 2. Dilatometric curves for hardening-tempering cycles.

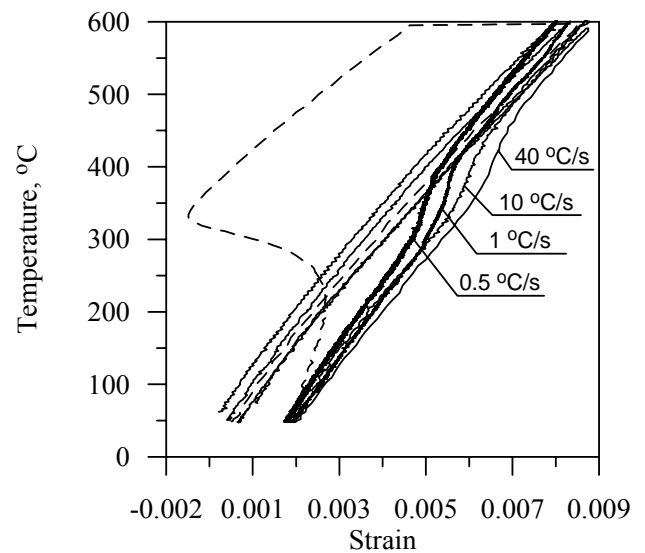


Table 1.  
Chemical composition of C45 steel.

Elements content %									
C	Mn	Si	P	S	Al	Cr	Ni	Mo	Cu
0.440	0.660	0,250	0,015	0,024	0,017	0,110	0,100	0,025	0,240

Table 2.  
Average temperature values  $T_s$  and  $T_f$

$V_H$ [ $^{\circ}\text{C}/\text{s}$ ]	0.1	0.2	0.5	1	2	5	10	20	30	40	50	60	100
$T_s$ [ $^{\circ}\text{C}$ ]	290	290	300	310	315	320	325	335	340	345	350	355	370
$T_f$ [ $^{\circ}\text{C}$ ]	420	420	430	435	440	450	465	470	475	480	485	490	500

which allowed to determine temperature average values  $T_s$  of the beginning and  $T_f$  of the end of tempering process. Average values have been presented in Table 2. Dilatometric graph for hardening-tempering cycles with the heating-up with the rate  $V_H = 10^{\circ}\text{C}/\text{s}$  has been presented in Fig. 2.

From the analysis of dilatometric graphs, we can draw a conclusion that the first stage of tempering – the segregation of coal atoms and liberating carbides (to  $290^{\circ}\text{C}$ ) do not affect significantly the shape of dilatometric curve. Distinct changes on dilatometric graphs have been observed in the temperature range  $290 - 500^{\circ}\text{C}$ , during forming of sorbite.

The dependence of temperature  $T_s$  on the heating rate can be approximated by Hoerl model [23] (Fig. 3):

$$T_s(V_H) = ab^{V_H}(V_H)^c \quad (1)$$

where:  $a = 306.16454$ ,  $b = 1.0007254$ ,  $c = 0.025137007$ , correlation coefficient is 0.997, while standard error 2.137.

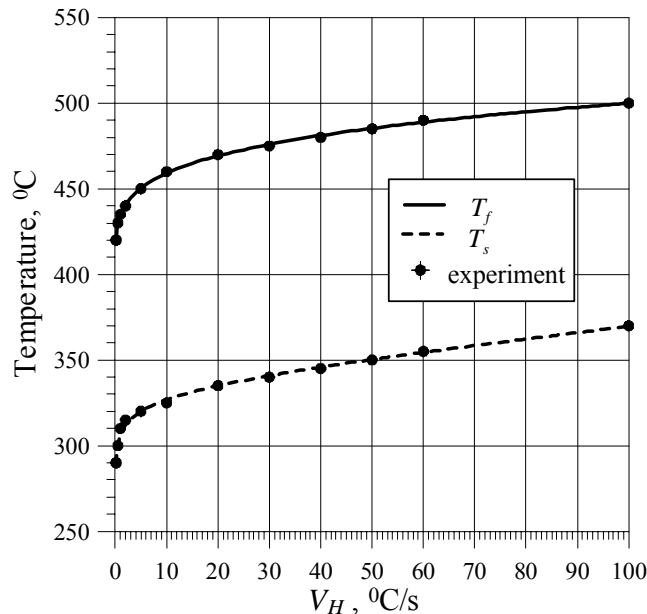


Fig. 3. Comparison of functions  $T_s(V_H)$  and  $T_f(V_H)$ , and the experimental results.

The dependence of temperature  $T_f$  on the heating rate can be approximated by Harris model [23] (Fig. 3):

$$T_f(V_H) = \frac{1}{a + b(V_H)^c} \quad (2)$$

where:  $a = 0.0025877464$ ,  $b = -0.00028544502$ ,  $c = 0.15680145$ , correlation coefficient is 0.999 and standard error 1.259.

The CHT (Continuous Heating Transformations) diagram is presented in Fig. 4. On the basis of dilatometric measurements and results of works [22] have been determined thermal expansion coefficients and transformation strains (Table 3).

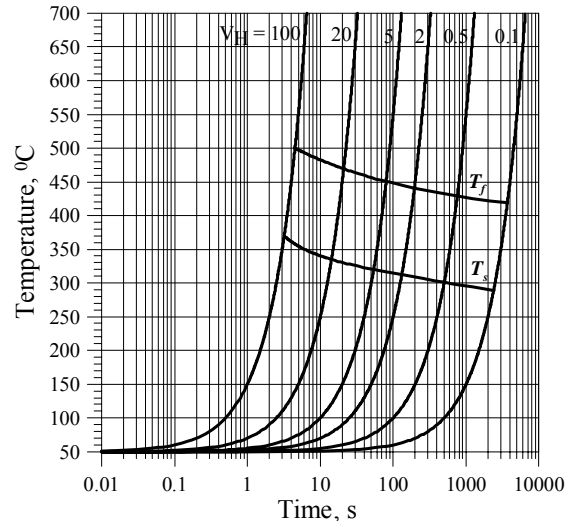


Fig. 4. CHT diagram of C45 steel

Table 3.  
Structural strains ( $\gamma$ ) and thermal expansion coefficients ( $\alpha$ ) for phase of C45 steel.

	$\alpha$ , $1/^{\circ}\text{C}$		
Austenite	$2.178 \cdot 10^{-5}$	$\gamma_{F,P,S \rightarrow A}$	$1.986 \cdot 10^{-3}$
Ferrite	$1.534 \cdot 10^{-5}$	$\gamma_{B \rightarrow A}$	$1.440 \cdot 10^{-3}$
Pearlite	$1.534 \cdot 10^{-5}$	$\gamma_{A \rightarrow F,P}$	$3.055 \cdot 10^{-3}$
Bainite	$1.171 \cdot 10^{-5}$	$\gamma_{A \rightarrow B}$	$4.0 \cdot 10^{-3}$
Martensite	$1.36 \cdot 10^{-5}$	$\gamma_{A \rightarrow M}$	$6.85 \cdot 10^{-3}$
Sorbite	$1.534 \cdot 10^{-5}$	$\gamma_{M \rightarrow S}$	$1.0 \cdot 10^{-3}$

## 4. Conclusions

In work has been made analysis of influence of the heating-up rate on tempering kinetics. On the basis of dilatometric graphs has been proposed the function bounding the rate of heating-up with the temperature of the beginning and the end of tempering phase changes. Quantities of transformation expansions and thermal expansion coefficients of hardening and tempering structures have been estimated. Determined quantities enable to describe the thermomechanical changes (strain and stress) in steel elements in laser treatment processes.

## References

- [1] K.J. Bimal, S.M. Nirmalendu, Microstructural evolution during tempering of multiphase steel containing retained austenite, *Mat. Sci. Eng. A263* (1999) 42-55
- [2] M. Gojic, L. Kosec, P. Matkovic, The effect of tempering temperature on mechanical properties and microstructure of low alloy Cr and CrMo steel, *J. Mat. Sci.* 33 (1998) 395-403
- [3] I. Tkalec, C. Azcoitia, S. Crevoiserat, D. Mari, Tempering effects on a martensitic high carbon steel, *Mat. Sci. Eng. A* 387-389 (2004) 352-356
- [4] I. Tkalec I., Mechanical properties and microstructure of a high carbon steel, PhD Thesis No 3089, Ecole Polytechnique Federale de Lausanne, 2004, pp. 75-85
- [5] L.W. Shyan, D.T. Tian, Mechanical and microstructural features of AISI 4340 high-strength alloy steel under quenched and tempered conditions, *J. Mat. Proc. Techn.* 87 (1999) 198-206
- [6] A.K. Lis, Mechanical properties and microstructure of ULCB steels affected by thermomechanical rolling, quenching and tempering, *J. Mat. Proc. Techn.* 106 (2000) 212-218
- [7] V.I. Kostylev, B.Z. Margolin, Determination of residual stress and strain fields caused by cladding and tempering of reactor pressure vessels, *Press. Vess. Pipp.*, 77 (2000) 723-735
- [8] E. Wakai, T. Taguchi, T. Yamamoto, F. Takada Effect of tempering temperature and time on tensile properties of F82H irradiated by neutrons, *J. Nuclear Mater.* 329-333 (2004) 1133-1136
- [9] Shi Wei, Yao Ke-fu, Chen Nan, Wang Hong-peng, Experimental study of microstructure evolution during tempering of quenched steel and its application, *Proceedings of the 14-th IFHTSE Congress, Trans. Mat. Heat Treatment*, 25 (2004) No. 5 736-739
- [10] A.S. Oddy, J.M.J. McDill, Numerical prediction of microstructure and hardness in multicycle simulations, *J. Mat. Eng. Perf.* 1996 (5) No 3 June 365-372
- [11] R.K. Shiue, K.C. Lan, C. Chen C., Toughness and austenite stability of modified 9Cr-1Mo welds after tempering, *Mat. Sci. Eng. A287* (2000) 10-16
- [12] M. Vijayalakshmi, S. Saroja, R. Mythili, V.Y. Paul, V.S. Raghunathan, Mechanism and kinetics of tempering in weldments of 9Cr-1Mo steel, *J. Nucl. Mat.* 279 (2000) 293-300
- [13] W. Piekarska, Numerical analysis of thermomechanical phenomena during laser welding process. The temperature fields, phase transformations and stresses, *Monographes 135, Czestochowa University of Technol.* 2007 (in Polish)
- [14] J.W. Elmer, T.A. Palmer, W. Zhang, B Wood , T. DebRoy, Kinetic modeling of phase transformations occurring in the HAZ of C-Mn welds based on direct observations, *Acta Mater.* 51 (2003) vol. 51, 3333-3349.
- [15] A. Danon, C. Servant, A. Alamo, J.C. Brachet, Heterogeneous austenite grain growth in 9Cr martensitic steels: influence of the heating rate and the austenitization temperature, *Mat. Sci. Eng. A348* (2003) 122-132
- [16] T. Miokovic, J. Schwarzer, V. Schulze, O. Vöhringer, D. Löhe, Description of short time phase transformations during the heating of steels based on high-rate experimental data, *J. Phys. IV France* 120 (2004) 591-598
- [17] J. Pacyna, A. Jędrzejewska –Strach, M. Strach, The effect of manganese and silicon on the kinetics of phase transformation during tempering – Continuous Heating Transformation (CHT) curves, *J. Mat. Proc. Techn.*, 64 (1997) 311-318
- [18] J. Pacyna, P. Bała, T. Skrzypek, The kinetics of phase transformation during continuous heating from quenched state of new high carbon alloy steel, *Metallurgist – Metall. Eng. News*, 2006, No 2, p. 46 - 49 (in Polish)
- [19] L. A. Dobrzański, Bases of sciences about materials and metal science. Engineering materials with bases of material designs. WN-T, Gliwice 2002, pp. 275 – 276 (in Polish)
- [20] H.K.D.H. Bhadeshia, H. Badeshia, R.W.K. Honeycombe, *Steel: microstructure and properties*, Elsevier 2006, 183-208
- [21] M. Jung, S.J. Lee, Y.K. Lee, Microstructural and dilatational changes during tempering and tempering kinetics in martensitic medium-carbon steel, *Metal. Mat. Trans.* 40A (2009) 551-559
- [22] A. Kulawik, Numerical analysis of thermal and mechanical phenomena during hardening process of the 45 steel, PhD Thesis, Czestochowa 2005, p. 68 (in Polish)
- [23] <http://www.curveexpert.net/>