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DILATOMETRIC AND HARDNESS ANALYSIS OF C45 STEEL TEMPERING WITH DIFFERENT HEATING-UP RATES

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Modelling of technological processes of heat treatment or welding, involving multiple heat source transitions, requires considering the phenomenon of tempering. In work have been presented results of dilatometric research of hardened C45 steel subjected to tempering. The analysis of the influence of heating rate at the kinetic determined from dilatometric curves has been made. There have also been estimated quantities of transformation expansions and thermal expansion coefficients of hardening and tempering structures (austenite, ferrite, pearlite, martensite and sorbite). The analysis of tempering time influence on the hardness of tempered steel has been made. Functions associating hardness with tempering time (rate of heating-up) in technological processes based on short-timed action of a heat source (eg. laser treatment) have been suggested.

Key words: dilatometric analysis, hardness, tempering, heat treatment, mechanical properties

Dilatrometrijska i analiza tvrdoće čelika C45 popuštanog uz različite brzine zagrijavanja. Modeliranje tehnološkog procesa toplinske obrade ili zagrijavanja, uključivo višedjelne izvore prijelaza topline, zahtijeva razmatranje fenomena toplinske obrade popuštanje. U radu su prezentirani rezultati popuštanja tvrdoće zakaljenog čelika C45. Analiza utjecaja brzine zagrijavanja na kinetiku procesa je determinirana dilatometrijskim krivuljama. Procijenjeni su kvantitativni transformacijski izrazi i koeficijent toplinskog širenja kaljenih i propuštenih struktura (austenit, perlit, mertenzit, sorbit). Napravljena je analiza utjecaja trajanja popuštanja na tvrdoću popuštenog čelika. Preporučena je funkcija koja udružuje tvrdoću i trajanje propuštanja (brzina zagrijavanja) u tehnološkom procesu temeljena na kratkotrajnom djelovanju izvora topline (npr. tretman laserom).

Ključne riječi: dilatometrijska analiza, tvrdoća, popuštanje, toplinska obrada, mehanička svojstva

INTRODUCTION

In technological processes of heat treatment and welding, depending on steel genre and process parameters, can occur quenching structures, including martensite. In case of process connected with multiple laser beam transitions or welding electrode making next welds cause tempering of already hardened areas. Most frequently, initial heating-up of heat-treated material above M_S temperature of the beginning of martensitic transformation during cooling, is used in order to prevent creation of austenite during to prevent creation of austenite during technolo-gical process. In other case it is essential to take into consideration tempering. In the case of welding processes in order to obtain appropriate final structure, temper bead application is used [1]. In order to project final structure of the material after the process or to calculate strain and stress state in heat-treated object it is essential to have the knowledge in kinetics of phase changes tempering. 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 before and after the tempering [2-7]. While in modelling of stress states during tempering, the influence of phase changes is frequently omitted [8]. In the case of heat treatment the time of heating-up amounts to several dozen minutes, while annealing can last even hours. 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 tempearture 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

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transformations in steel both during austenitisation [13-16], as well as during heating-up from hardened stage (of tempering) [17,18].

TEMPERING IN STEELS

In conventional heat treatment process in steels with the carbon content up to 0,2 wt.% tempering begins already in the environment temperature moving coal atoms [19]. After that segregation from temperature 80 ^{0}C occurs liberating of carbides – it proceeds most intensively in the temperature range between 150 – 200 ^{0}C, ends mainly at 250 ^{0}C, but sometimes at 400 ^{0}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 α and carbide ε is called low-tempered martensite.

Between 100 and 350 ^{0}C any retained austenite begins to decompose. It has been suggested that this happens by transformation into bainitic ferrite and cementite [19]. Above 350 ^{0}C martensite decomposes liberating cement grains creating the phase called sorbite or troostite. 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 ^{0}C. Above 600 ^{0}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.

EXPERIMENTAL WORK

The chemical composition of researched steel is shown in Table 1.

Table 1 **Chemical composition of C45 steel substrates wt. % (max.)**

C	Mn	Si	P	S	Al	Cr	Ni	Mo	Cu
0,44	0,660	0,250	0,015	0,024	0,017	0,011	0,10	0,025	0,24

Dilatometric experiments were carried out in thermal cycle simulator Smitweld TCS1405 (Figure 1). The influence of the speed of heating-up on the temperature of the beginning and the end of tempering has been researched for the speed of heating from 0,1 to 100 ^{0}C/s. Samples for tempering research have been heated-up to 1100 ^{0}C, then cooled with the velocity 200 ^{0}C/s. Martensitic structure of hardened sample is presented in Figure 2. 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 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 cycle with the heating-up with the velocity V_H = 10 ^{0}C/s during tempering has been presented in Figure 3. 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 ^{0}C) do not affect significantly

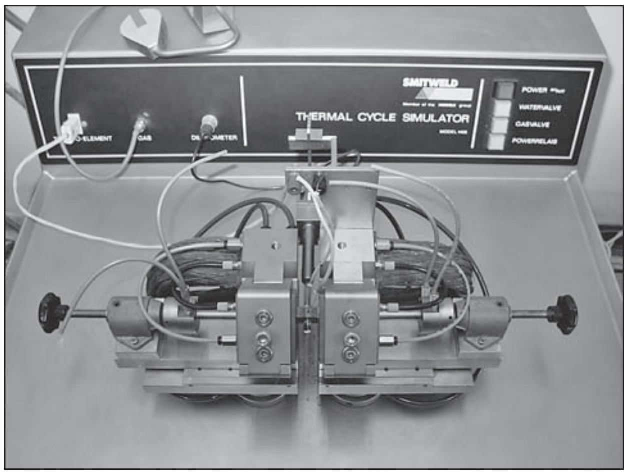

Figure 1 Thermal Cycle Simulator Smitweld 1405

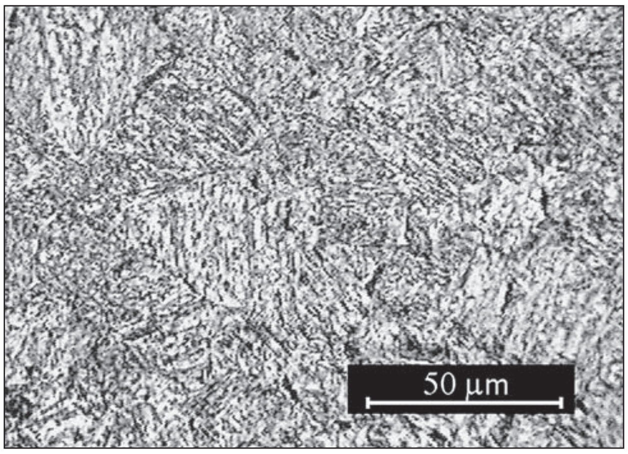

Figure 2 Martensitic structure of a hardened sample

Table 2 **Average temperature values T_s and T_f**

V_H / ^{0}C/s	0,1	0,5	1	2	5	10
T_s / ^{0}C	290	300	310	315	320	325
T_f / ^{0}C	420	430	435	440	450	465
V_H / ^{0}C/s	20	30	40	50	60	100
T_s / ^{0}C	335	340	345	350	355	370
T_f / ^{0}C	470	475	480	485	490	500

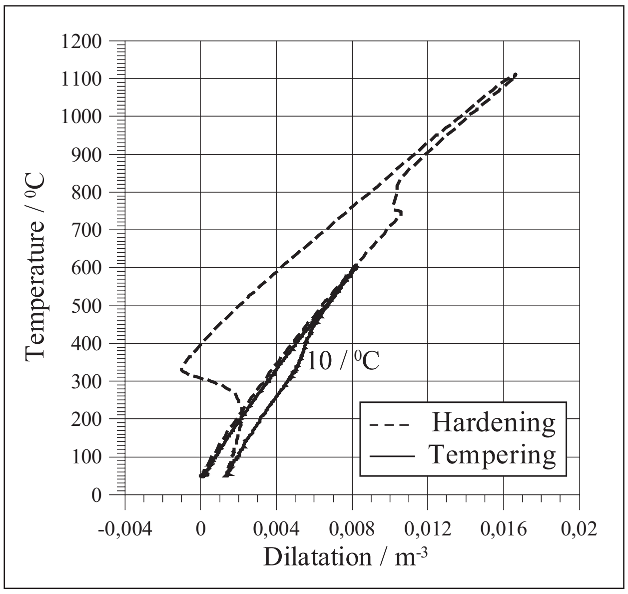

Figure 3 Dilatometric curves for hardening-tempering cycle

the shape of dilatometric curve. Distinct changes on dilatometric graphs have been observed in the temperature range 290 - 500 ^{0}C, during forming of sorbite.

The dependence of temperature T_s on the heating rate $V(H)$ (Figure 4) has been determined by approximation of dilatometric measure-ments by Hoerl regression model using program CurveExpert [20]:

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

where: a = 306,16454, b = 1,0007254, c = 0,025137007, correlation coefficient is 0,997, while standard error 2,137.

In a similar way has been determined the dependence of temperature T_f on the heating rate $V(H)$ (Figure 4) using Harris regression model:

$$T_f(V_H) = \frac{1}{a + bV_H^C} \tag{2}$$

where: a = 0,00258774, b = -0,00028544502, c = 0,15680145, correlation coefficient 0,999, standard error 1,259.

The CHT (Continuous Heating Transfor-mations) diagram is presented in Figure 5.

On the basis of dilatometric measurements and results of works [21] have been determined thermal expansion coefficients and transformation expansions values which are shown in Table. 3.

Results of hardness measurement of samples after tempering have been presented in Table 4. Together with the decrease of tempering time (increase of heating-up rate with constant cooling velocity 10 ^{0}C/s in thermal cycles) diminishes hardness.

For carried out researches, the dependence of hardness on rate of heating-up has been approximated with function (Figure 6):

$$HV_{30}(V_H) = aV_H^4 + bV_H^3 + cV_H^2 + dV_H + e \tag{3}$$

where: a = -2,4578808x10^{-6}, b = 0,00054318, c = -0,030563, d = 2,0558168, e = 342,63333, correlation coefficient 0,999, standard error 1,608.

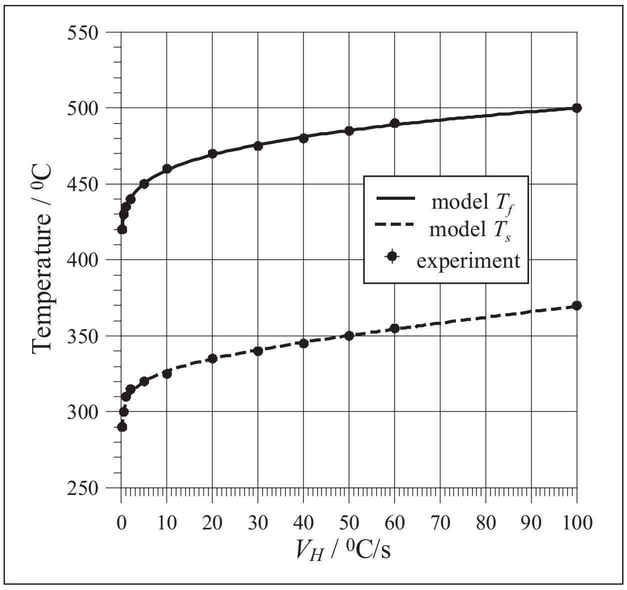

Figure 4 Comparison of $T_s(V_H)$ and $T_f(V_H)$ models and research results

Table 3 **Structural (γ) and thermal (α) expansion coefficients for phase of C45 steel.**

	α / 1/°C		
Austenite	2,178·10^{-5}	$\gamma_{F,P,S\rightarrow A}$	1,986·→10^{-3}
Ferrite	1,534·10^{-5}	$\gamma_{B\rightarrow A}$	1,440·10^{-3}
Pearlite	1,534·→10^{-5}	$\gamma_{A\rightarrow F,P}$	3,055·10^{-3}
Bainite	1,171·→10^{-5}	$\gamma_{A\rightarrow B}$	4,0·10^{-3}
Martensite	1,36·→10^{-5}	$\gamma_{A\rightarrow M}$	6,85·→10^{-3}
Sorbite	1,534·→10^{-5}	$\gamma_{M\rightarrow S}$	1,0·10^{-3}

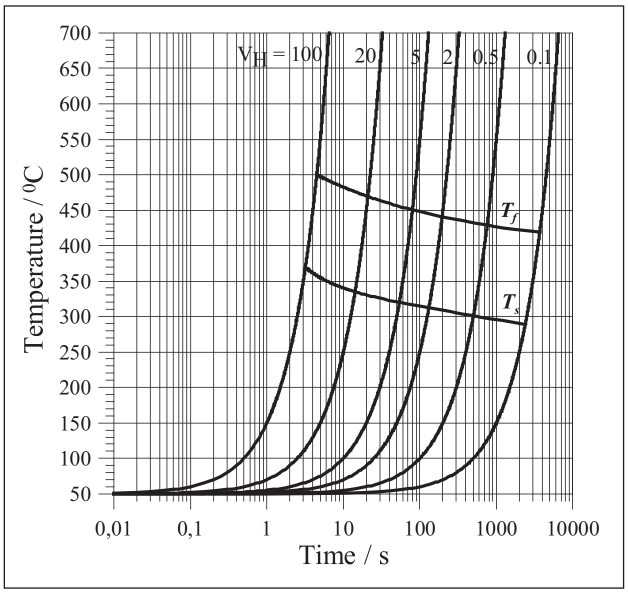

Figure 5 CHT diagram of C45 steel

Table 4 **Average hardness values for different rates of heating-up (tempering times)**

V_H / ^{0}C/s	0,1	0,5	1	2	5	10
time / s	7070	1470	770	420	210	140
HV_{30}	340	343	346	349	353	360
V_H / ^{0}C/s	20	30	40	50	60	100
time / s	105	93,33	87,5	84	81,66	77
HV_{30}	375	389	405	422	441	540

The influence of tempering time t on hardness has been determined by functions (Figure 7):

- for t <= 100 s

$$HV_{30}(t) = a + bt + \frac{c}{t^2} \tag{4}$$

where: a = 375,85089, b = -23065,856, c = 0,1459668, correlation coefficient 0,999, standard error 3,2,

- for t > 100 s

$$HV_{30}(t) = \frac{a}{1 + b\exp(-ct)} \tag{5}$$

where: a = 344,95107, b = -0,0070576689, c = 357598, correlation coefficient 0,992, standard error 2,523.

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 temperature of the beginning and the end of transformation expansions during tempering phase changes. Quantities of transformation

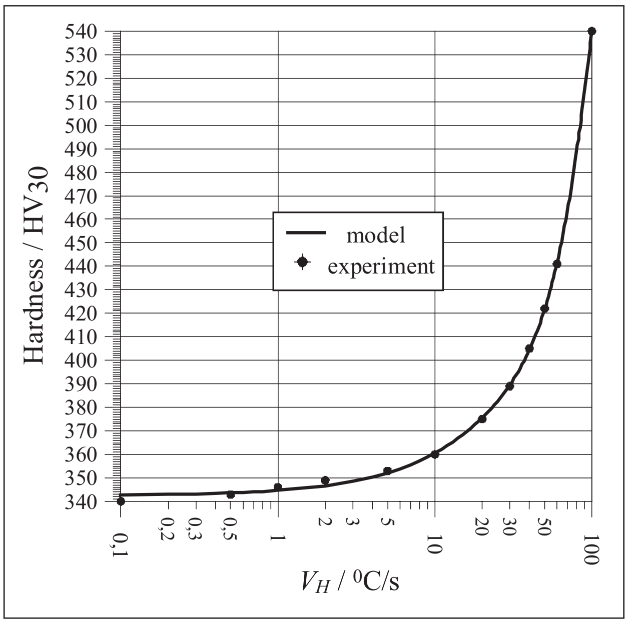

Figure 6 Influnce rate of heating-up of tempering on hardness

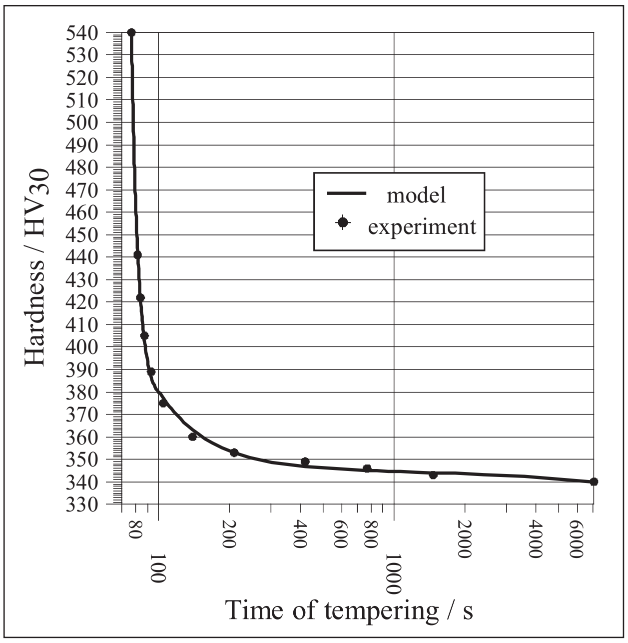

Figure 7 Influnce time of tempering on hardness.

expansions and thermal expansion coefficients of hardening and tempering structures have been estimated.

Functions associating the hardness of steel with time (the rate of heating-up) have been determined.

Suggested functions and determined quantities enable to describe the termomechanical changes (strain and stress) and predict the hardness in steel elements during technological processes based on short-timed action of a heat source (eg. laser treatment, welding).

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