UTILIZATION OF NUMERICAL SIMULATION FOR STEEL HARDNESS DETERMINATION

Adam KEŠNER[1], Rostislav CHOTĚBORSKÝ[1], Miloslav LINDA[2], Monika HROMASOVÁ[2]

[1]Department of Material Science and Manufacturing Technology, Faculty of Engineering, Czech University of Life Sciences Prague, Kamýcká 129, 165 21 Prague – Suchdol, Czech Republic
[2]Department of Electrical Engineering and Automation, Faculty of Engineering, Czech University of Life Sciences Prague, Kamýcká 129, 165 21 Prague – Suchdol, Czech Republic

Abstract
Agricultural tools must meet the requirements for durability and abrasion wear resistance. Steel hardness is one of the most important mechanical properties of agricultural tools. Low cost production of agricultural tools is nowadays a necessary factor in maintaining the competitiveness of producers. I is one of reasons, why numerical simulation is used to design of the heat treatment of steel for agricultural tools. Mathematical models allow cost reductions and time consumption if is it compared to the practical experiment. The hardness of 51CrV4 steel was determined in this work. Numerical inverse methods were used to simulation of steel hardness. The results of the model were verified by an experiment. The results show good relationships between measured hardness and numerical simulation.

Key words: *hardness; agriculture tools; heat treatment; steel.*

INTRODUCTION

Agricultural tools must meet the high customer requirements for abrasion wear resistance, hardness and toughness (Rose, Sutherland, Parker, Lobley, Winter, Morris, Twining, Ffoulkes, Amano, Dicks 2016; Votava 2014; Nalbant, Tufan Palali 2011). These requirements are obtained by setting various parameters of the heat treatment of steels for agricultural tools (Fernandes, Prabhu 2008; Lee, Mishra, Palmer 2016; Shaeri, Saghafian, Shabestari 2012). Heat treatment parameters are determined by experience in many companies (Votava 2014; Rose, Sutherland, Parker, Lobley, Winter, Morris, Twining, Ffoulkes, Amano, Dicks 2016). Numerical models of heat treatment of steel can reduce production cost if it is compare with experimental heat treatment of steel in experiments (Sinha, Prasad, Mandal, Maity 2007; Babu, Prasanna Kumar 2009; Teixeira, Rincon, Liu 2009).
Numerical simulation must be set with the exact boundary conditions (heat flux, specific heat capacity, thermal conductivity) for accurate heat treatment (Liu, Xu, Liu 2003; Şimşir, Gür 2008). The inovation of boundary and material conditions is described in articles (Kešner, Chotěborský, Linda 2016a, 2016b, 2017).
Microstructure of steel is the most important for steel hardness after its heat treatment (Li, Luo, Yeung, Lau 1997; Zdravecká, Tkáčová, Ondáč 2014). Results of some authors show that abrasion wear resistance is advisable to provide a combination of bainitic and martensitic microstructure (Das Bakshi, Shipway, Bhadeshia 2013a; Ohtsuka 2007; Das Bakshi, Shipway, Bhadeshia 2013b).
The size of the heat flux is variable in time during the heat treatment. For this reason, standard procedures for calculating the course of heat treatment in steel cannot be used. Numerical inversion methods of heat treatment can be used to design heat conduction and the associated calculations of the microstructural phases of individual steel properties such as hardness (Teixeira, Rincon, Liu 2009; T Telejko 2004; T. Telejko 2004).
The aim of this work was to design an algorithm that is able to predict the final steel hardness after its heat treatment and thair verification with experimental data.

MATERIALS AND METHODS

Low alloyed 51CrV4 steel was chosen for the experiment of this work. The tablature chemical composition is shown in Tab. 1.

Tab. 1 Chemical composition of steels 51CrV4 (wt. %)

material	C	Mn	Si	P	S	Cr	Ni	Cu	Al	Mo	V
51CrV4	0.53	0.89	0.26	0.012	0.025	1.02	0.08	0.13	0.028	0.02	0.12

Steels samples were prepared from rod in size 25 mm x 10 mm x 50 mm. The heating temperature 800 °C was used for all samples. The cooling parameters were designed to achieve a combination of bainite and martensite structures for austempering – see Tab. 2. Salt bath of 50 wt.% $NaNO_2$ + 50 wt.% $NaNO_3$ was used for cooling steel samples.

Tab. 2 Cooling parameters for austempering

	cooling 1			cooling 2			cooling 3		
sample	temp.	medium	time [s]	temp.	medium	time [s]	temp.	medium	time [s]
V1	300	salt bath	40	300	air	1000	20	air	to 20°C
V2	300	salt bath	40	20	water	to 20°C	X	X	X
V3	400	salt bath	40	400	air	1200	20	air	to 20°C
V4	400	salt bath	40	20	water	to 20°C	X	X	X

The algorithm was compiled for numerical simulation of final hardness in ElmerFem software. The entire cooling process has been included in the algorithm. The processing diagram of the algorithm procedure is shown in Fig. 1. The size of the model object was taken from experimental samples (25 mm x10 mm). The mesh was created with interest points in the center of the object 12.5 x 5 mm and close to surface 22 mm x 5 mm. The input parameters of the numerical simulation are the same as for experimental – see Tab. 2. The material constants of thermal capacity and thermal conductivity was taken from literature (Kešner, Chotěborský, Linda 2017).
Solution of numerical simulation was carried out in step Δt, when every step has been created in file **.vtu*, where the change of temperature was stored in the individual parts of the object. Thus it was created in „M“ files, it showing the number of steps of the simulation.

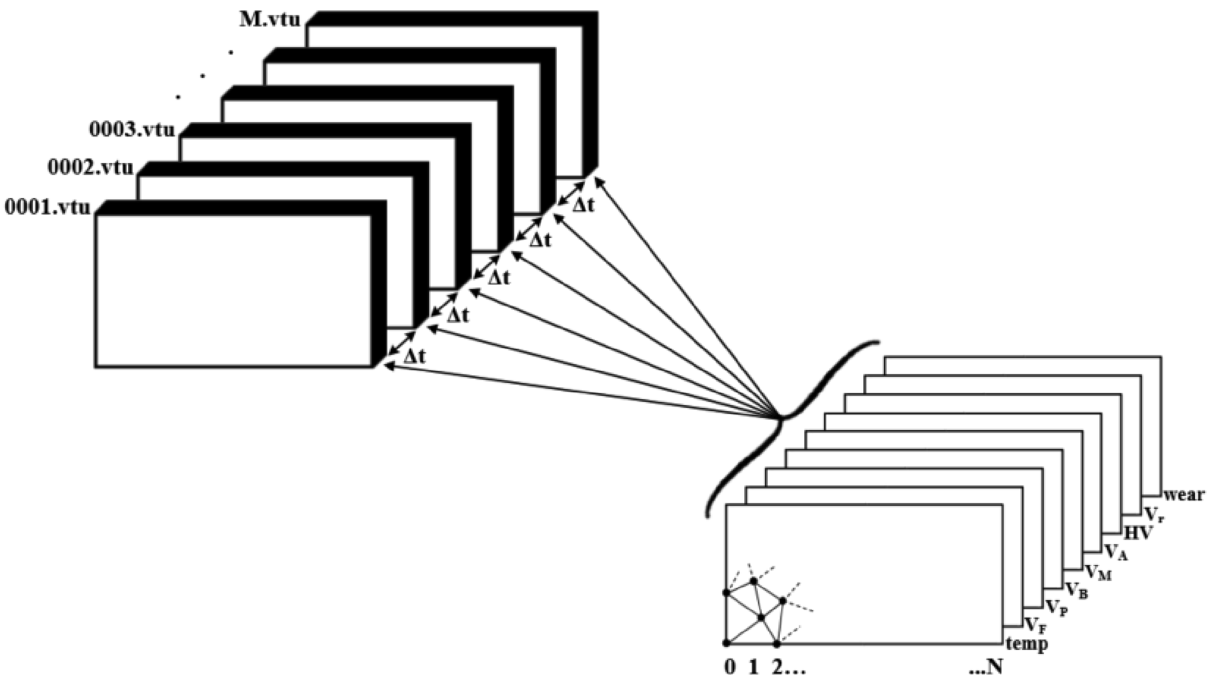

Fig. 1 Flow chart for determinate volume of phase and hardness

Volume of ferrite *Vf*, perlite *Vp*, bainite *Vb* and martensite *Vm*, hardness $HV_{0.3}$ / kgf mm^{-2} and cooling rate *VR* were calculated according to the cooling curve at each calculation step. The conditions for the formation of the individual phases were taken from the TTT diagram and were included in the algorithm calculation. The volume fraction of each phase was calculated at each timestep (equations 1 to 5). Vickers hardness was calculated according to the volume fraction of the phases (equation 6) and the chemical composition of the steel which was found in the material database (Chotěborský, Linda 2015).

$$VR = \left(\frac{0.8-C}{0.8}\right)^{-1} + \left(\frac{0.8-C}{0.8}\right)^{-1} \tag{1}$$

$$Vf = \sum_{i=1}^{n} -Kf \times Nf \times t^{Nf-1} \times e^{-Kf \times t^{Nf}} \times (1 - VR) \tag{2}$$

$$Vp = \sum_{i=1}^{n} -Kp \times Np \times t^{Np-1} \times e^{-Kp \times t^{Np}} \times (1 - Vf) \tag{3}$$

$$Vb = \sum_{i=1}^{n} -Kb \times Nb \times t^{Nb-1} \times e^{-Kb \times t^{Nb}} \times (1 - Vf - Vp) \tag{4}$$

$$Vm = 1 - e^{-\beta \times (Tm_{start} - T)} \times (1 - Vf - Vp - Vb) \tag{5}$$

$$HV = V_P \times HV_P + V_B \times HV_B + V_M \times HV_M \tag{6}$$

where *Kf, Kp, Kb* – overall rate constant of feritic, pearlitic and bainitic transformation that generally depends on temperature (-), *Nf, Np, Nb* – Avrami's exponent for feritic, pearlitic and bainitic transformation that depends on temperature (-)

Parameters *Ni* and *Ki* were taken from the work (Kešner, Chotěborský, Linda 2016a) for algorithm calculation. The average cooling rate t_{8-5} (between 800 °C and 500 °C) was determined from simulation. The log VR is included as soon as the sample temperature drops below 500 °C in the hardness equation. Vickers hardness was measured and analyzed from the sample surface to its center with a distance of 0.2 mm.

RESULTS AND DISCUSSION

The accuracy of hardness results depends on the correct estimation of the volume fraction of the individual microstructure phases. The results of hardness determination are shown in Fig. 2. Statistical analysis of measured and simulated hardness was determined of the F-test for significance level α=0.05. Results showed a minimal significant difference between simulated and measured hardness.

The hardness results were fitted with a linear trend. Samples V1, V3 and V4 showed the same direction of linear trend. Differences in the direction of the linear trend were found for sample V2. The simulation of hardness shows small differences in hardness. Experimental hardness results show a decreasing tendency of hardness from the surface of the sample to its core. This deviation may be due to an inaccurate estimate of the volume fravtion of the microstructure phases in the sample cross-section area. Experimental and simulation estimated hardnesses show a slight increase of hardness from the core to surface of the sample in sample V3. However linear trends show the same direction, it is assumed that the hardness increases towards the core of the sample. This may be due to the formation of a different microstructure in the sample cross-section area.

The smallest difference between experimental and simulated hardness (4 HV) was found in sample V3. The biggest hardness difference (38 HV) was found at the core of sample V2.

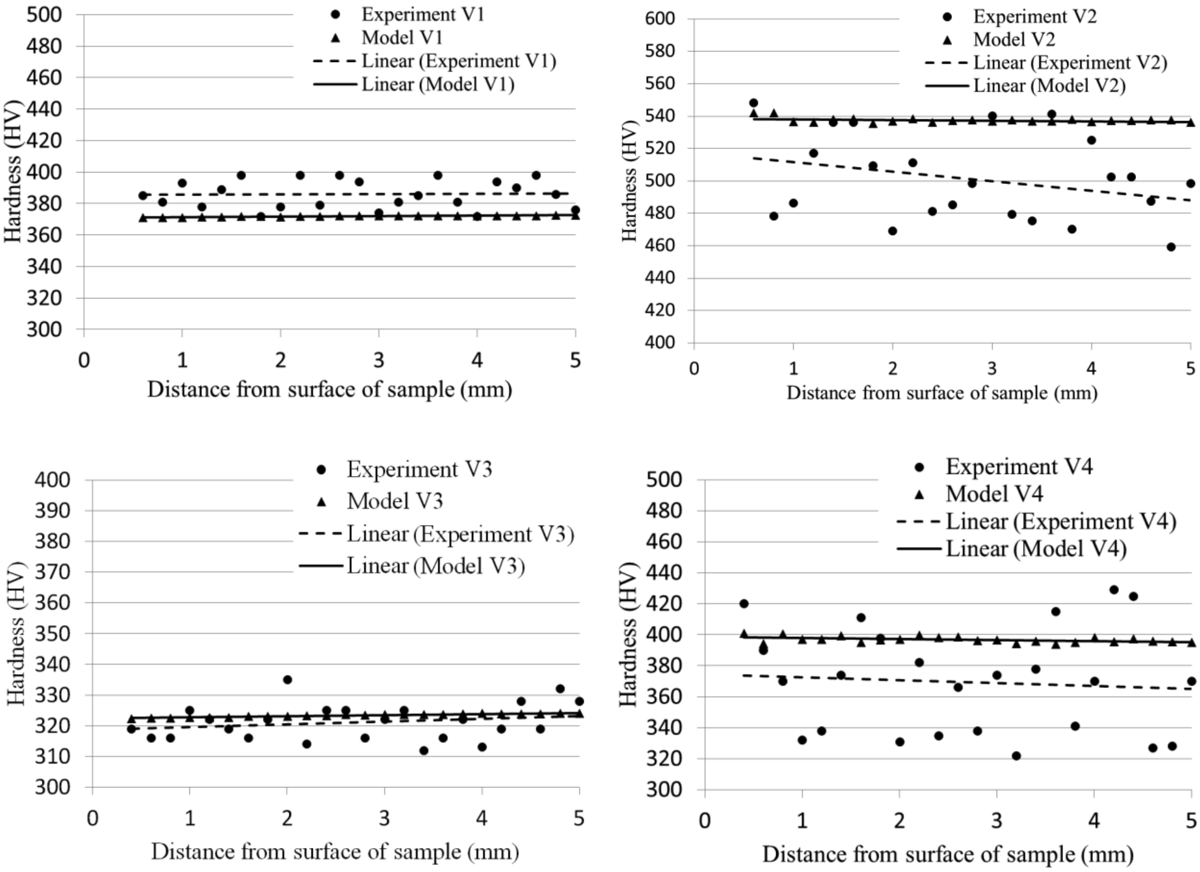

Fig. 2 Comparison of the experimentally measured and mathematically calculated hardness for 51CrV4 steel

A lot of authors (Votava, Kumbár, Polcar 2016; Narayanaswamy, Hodgson, Beladi 2016; LIU, SONG, CAO, CHEN, MENG 2016) describe experimental data of abrasion resistance and hardness in their works only as a supplement. Hardness is an important mechanical properties for agricultural tools (Herian, Aniołek, Cieśla, Skotnicki 2014; Jankauskas, Katinas, Skirkus, Alekneviciene 2014; Das Bakshi, Shipway, Bhadeshia 2013a). Hardness should be considered in the design of agricultural tools. (Chotěborský, Linda 2015) are concerned with the design of microstructure and hardness for a specific agricultural tools and assembly. Their procedure is identical as the procedure which is described in this work. The results of the model hardness and measured results show good agreement for steel of agricultural tool. For this reason, it can be concluded that the procedure described in these works can be used to design a heat treatment of an agricultural instrument where hardness is required.

CONCLUSIONS

A simulation was designed to estimate the hardness after heat treatment for low alloyed steel 51CrV4. The experiment was done to verify the results of a mathematical model of simulation. Microstructure is important for the correct estimation of hardness after heat treatment. The statistical test showed an agreement between model hardness and experimental hardness. The highest difference of hardness was found to be 38 HV between experimental hardness and simulated hardness. The procedure described in this paper can be used to estimate hardness after heat treatment.

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Corresponding author:
Ing. Adam Kešner, Department of Material Science and Manufacturing Technology, Faculty of Engineering, Czech University of Life Sciences Prague, Kamýcká 129, Praha 6, Prague, 16521, Czech Republic, phone: +420 22438 3271, e-mail: kesner@tf.czu.cz