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CONTRIBUTION TO THE THERMAL PROPERTIES OF SELECTED STEELS

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The paper deals with the influence of structural changes on heat transport phenomena of steels samples. Three samples of 10GN2MFA steel were thermally treated at quenching temperatures equal to 900 °C, 1 000 °C and 1 100 °C, and temperature of the tempering was 670 °C. Both thermal diffusivity and thermal conductivity increase with the quenching temperature. Specific heat capacity of steel samples after thermal treatment does not change significantly. Further three different high manganese steels were measured. Maximal content of Mn and C was 27 and 0,5 mass percent. From results of thermophysical properties after ageing, one can see the increase of thermal diffusivity up to 20 percent, thermal conductivity up to 15 percent, decrease of specific heat capacity is not significant. All measured values of thermophysical properties are in good agreement with literary data (before ageing).

Key words: steel alloy, low carbon steel, thermal treatment, thermal diffusivity and conductivity, specific heat capacity

INTRODUCTION

The 10GN2MFA steel is extensively used at the manufacture of large power units of nuclear power stations. This steel is characterized by high strength and plasticity due to optimal alloying of the solid solution and to high deep-hardening properties [1, 2] It consists of following elements in mass percent. 0,10 of C, 0,84 of Mn, 0,27 of Si, 0,011 of P, 0,008 of S, 0,06 of Cu, 1,90 of Ni, 0,23 of Cr, 0,48 of Mo, 0,03 of V.

The submitted model in [3] describes a counter diffusion of carbon towards to the interface and of oxygen towards to the volume of metal during levitation of drop and does justice to all features of decarburization. The results demonstrate the decisive influence of concentration of carbon and oxygen at the interface on decarburization.

High manganese TRIPLEX steels have a higher strength, plasticity, toughness and show excellent hydrogen response [4], but corrosion resistance can be lower. In the paper [5] corrosion properties of X70MnAl28-9 TRIPLEX steel were tested after hot rolling and subsequent ageing at 500 °C for 6, 30 and 60 min. and at 600 °C for the same times. The contribution [6] deals with the use of artificial neural networks for prediction of steel atmospheric corrosion. Atmospheric corrosion of metal materials exposed under atmospheric conditions depends on various factors such as local temperature, relative humidity, amount of precipitation, pH of rainfall, concentration of main pollutants and exposition time.

The purpose of the work [7] is to investigate the influence of different tempering temperatures on the hydrogen delayed fracture susceptibility of ultra-high-strength quenched steel.

The precipitation of the secondary carbides in high-speed steel of AISI M2 type modified with titanium diboride was investigated for both the as-cast and the heat-treated states. Production of nanomaterials by forming with extreme plastic deformation ECAP (Equal-Channel Angular Pressing) is a way of preparing nano-structures of engineering materials [8]. Development of a nanostructure in steel AISI 309 (EN X15CrNiSi20.20) with the technology of ECAP, and a new method for determination of the grain size are analyzed here.

Austenitic manganese steels belong to materials used in automotive industry.

Thermal ageing of high Mn steels is special heat treatment which use annealing at the temperature close to 600 °*C* to rise diffusion ability of C in austenitic matrix, thus to creation of very fine K-carbides [9].

The aim of the paper is to find relation between structure of chosen steels and their thermal properties. Calculated data were statistically tested. Structural changes induced in both types of steels by different thermal treatment were reflected on thermal parameters - specific heat capacity, the thermal diffusivity and the thermal conductivity.

THEORETICAL BACKGROUND

The cooling of objects is often described by a law, derived from Newton´s law, which states that the temperature difference of a cooling body with respect to the surroundings decreases exponentially with time [10].

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Lumped capacity model (LCM) is special case of Newton's cooling law. In this method the internal temperature changes can be neglected, thus temperature of sample T is function only of a time t [11].

A heat given to a sample can be found in the form $Q = c_p \cdot \Delta T$, where c_p is the specific heat capacity of a sample and ΔT is the temperature increase during a heat transfer.

For a heat flow from a sample to an environment with temperature T_∞ Newton´s cooling law can be written in the form

$$dQ/dt = -h\cdot S\cdot (T-T_\infty), \quad (1)$$

where Q is the heat given to a sample, h is the total heat transfer coefficient of a sample, S is the total heat flow area, T_∞ is the environment temperature.

For the lumped capacitance method solution of surface temperature T can be found from differential equation

$$m\cdot c_p\cdot (dT/dt) = -h\cdot S\cdot (T-T_\infty), \tag{2}$$

and it is in the form

$$T = dT_{max}\cdot \exp(-t/\tau)+T_\infty, \tag{3}$$

where dT_{max} is maximal temperature difference between the sample and environment, τ is relaxation time.

Relaxation time can be described by the equation

$$\tau = (\rho\cdot c_p\cdot L)/(2\cdot h), \tag{4}$$

where ρ is density of the sample and L is sample thickness.

Lumped capacitance model is valid when the value of the Biot number is smaller than 0,1. In this case heat transfer by conduction can be neglected and heat transfer consists mainly of convective and partly radiative heat transfer.

EXPERIMENTAL PROCEDURE

For our measurements we have used experimental arrangement which is presented in [12].

The measured samples in our case have a mass approximately of about (10 x 10 x 2) mm^3 and must be finely ground. Matt black spray-paint is applied on all sides of the samples in order to ensure they have the same emissivity.

All samples were measured ten times and uncertainties (99 % confidence interval P_{99}) were calculated for every material.

Before measurements of selected steels, thermal properties of Cu, as a crucial test of the measuring system based on *LCM,* was tested.

As expected, an extremely low value of Biot number ($3,7\cdot 10^{-5}$) was obtained which supports the validity of LCM in these cases according to equation (6). The measured results are compared with those in the tables. Table 1 shows statistical parameters of measured data evaluation for Cu sample. The presented data show that used apparatus is proper for determination of c_p, thermal diffusivity α and thermal conductivity k in metals.

Thermal properties of steel 10GN2MFA before thermal treatment are documented in Table 2. Experimental results description we start with measurements of the steel 10GN2MFA. Thermophysical properties of material were compared with those for steels in which amount of Ni is 0 percent or 20 percent [13].

Table 1 **Selected thermal parameters of the Cu sample with uncertainties P_{99} and table values**

Copper	Arithmetic mean	P_{99}	Tables
$<c_p>$ / $J\cdot kg^{-1}\cdot K^{-1}$	367,3 ± 9,3	379,4-405,2	380
$<\alpha>$ / $mm^2\cdot s^{-1}$	117,96 ± 0,3	117,6-123,6	118,3
$<k>$ / $W\cdot m^{-1}\cdot K^{-1}$	399,30 ± 0,8	396,6-401,9	401

Table 2 **Thermal properties of steel 10GN2MFA before thermal treatment**

$<c_p>$ / $J\cdot kg^{-1}\cdot K^{-1}$	$<k>$ / $W\cdot m^{-1}\cdot K^{-1}$	$<\alpha>$ / $mm^2\cdot s^{-1}$
412,9 ± 0,6	36,5 ± 0,34	12,7 ± 0,4
P_{99} / $J\cdot kg^{-1}\cdot K^{-1}$	P_{99} / $mm^2\cdot s^{-1}$	P_{99} / $mm^2\cdot s^{-1}$
410,8 - 414,9	35,4 - 37,6	12,3 - 13,1

From presented results together with values of confidence interval P_{99} it is apparent relatively good precision of measured thermal parameters and as well as agreement with table values. Biot number is for all investigated materials much more lower than 0,1 and so the *LCM* is valid.

In the next step the influence of quenching on thermal parameters of 10GN2MFA steel was tested.

It is well known that the quenching increases the grain size. A polycrystalline material contains a large number of grain boundaries, which represent a high-energy area due to inefficient packing of atoms [14].

Lower overall energy is obtained in the material if the amount of grain boundary area is reduced by grain growth. Grain growth involves the movement of grain boundaries, permitting growth of larger grains at the expense of smaller grains. It can be concluded that the driving force for grain growth is reduction in grain boundary area. High temperatures or low-activation energies increase the size of the grains. As a result, the strength of metallic material will decrease with the increasing grain size. On the other hand bigger grain boundaries facilitate heat transport through the sample. Obtained results are presented in the Tables 3, 4. Increased value of grain size causes rising of the thermal diffusivity, as well as the thermal conductivity. Specific heat capacity c_p is practically not changed. Biot number is in all cases much more lower than limit 0,1 and so LCM is valid.

In the last part of this contribution, thermophysical properties of three high manganese steels labelled as 1,

Table 3 **Grain size of quenched samples**

Sample	Quenching Temperature / °C	Grain size / μm
1	900	10
2	1 000	25
3	1 100	90

Table 4 **Average values of α and *k* for 10GN2MFA samples**

Sample treatment	$<\alpha>$ / $mm^2 \cdot s^{-1}$	$<k>$ / $W \cdot m^{-1} \cdot K^{-1}$
Non-treated	10,57 ± 0,2	36,86 ± 1,1
Quenching 1	15,49 ± 0,8	54,94 ± 1,9
Quenching 2	17,38 ± 0,6	61,43 ± 1,8
Quenching 3	18,97 ± 0,6	67,92 ± 1,8

Table 5 **TRIPLEX chemical composition / mas. %**

Sample	C	Al	Mn
1	0,179	2,313	26,75
2	0,484	2,283	27,31
3	0,374	2,205	27,36
Sample	Ni	Si	Fe
1	0,01	0,98	69,768
2	0,91	1,05	67,963
3	0,03	0,05	69,981

Parameters of annealing are 560 °C/5 min.

2, 3 before and after annealing were measured. Composition of used materials is shown in Table 5.

From measured values of thermophysical properties of materials labeled as 1, 2 and 3 in non-aged state is clear, that they are in relatively good agreement with table values and statistical evaluation of confidence interval P_{99} shows relatively high precision of measured data [15].

In Tables 6 and 7 is seen the influence of sample ageing on heat transport parameters. Ageing don't sufficiently influences α, c_p and k for sample 2. The change of α and k for sample 3 is approximately 10 %, change of c_p is negligible. Main changes of α and k was observed for the sample 1 and it is approximately 20 %. In sample 1, minimum carbides could precipitate after aging, because carbon content was too low there (see Table 6) to be able to form fine K-carbides of a higher portion in comparison with the other aged samples as it was also presented in paper [16].

Table 6 **Average values of the diffusivity, specific heat capacity and thermal conductivity before and after annealing**

Sample	$<\alpha>$ /$mm^2 \cdot s^{-1}$	$<c_p>$ /$J \cdot kg^{-1} \cdot K^{-1}$	$<k>$ /$W \cdot m^{-1} \cdot K^{-1}$
Sample 1	15,2 ± 1,1	481,9 ± 25,3	50,6 ± 3,2
Sample 1 aged	18,7 ± 0,9	458,1 ± 27,3	60,1 ± 4,4
Sample 2	17,5 ± 0,8	477,0 ± 19,6	57,4±3,4
Sample 2 aged	18,7 ± 0,9	465,3 ± 25,6	61,5 ± 4,3
Sample 3	15,7 ± 0,7	480,3 ± 26,8	55,4 ± 3,9
Sample 3 aged	17,5 ± 0,6	445,2 ± 27,0	60,1 ± 4,1

Table 7 **The confidence interval P_{99} of *α, c_p,* and *k* for samples 1,2,3 in un-aged and aged of high manganese steels**

Sample	$P_{99}<\alpha>$ /$mm^2 \cdot s^{-1}$	$P_{99}<c_p>$ /$J \cdot kg^{-1} \cdot K^{-1}$	$P_{99}<k>$ /$W \cdot m^{-1} \cdot K^{-1}$
Sample 1	15,2 - 16,3	481,9 -487,7	50,6 - 54,8
Sample 1 aged	18,7 - 19,3	458,1 -487,6	60,1 - 61,9
Sample 2	17,8 - 19,4	477,0 -516,8	57,4 - 60,4
Sample 2 aged	18,7 - 18,8	465,3 -472,5	61,5 - 62,0
Sample 3	15,8 - 17,3	480,3 -492,3	55,5 - 61,0
Sample 3 aged	17,5 - 18,8	445,2 -467,5	60,1 - 61,6

CONCLUSIONS

Relatively very precise method for experimental determination of α, c_p and k for materials with different thermal transport properties caused by structure modification was presented.

Values of thermal parameters for samples 10GN-2MFA are in agreement with table values and confidence intervals support relatively high measurements precision.

Changes of the structure of 10GN2MFA caused by quenching at 900 – 1 100 °C increase the grain size from 10 to 90 micrometers and also values of α and k. Changes of c_p values are within the measuring inaccuracy. The influence of the grain size on α and k is clearly demonstrated. The statistical analysis of experimental data was performed.

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REFERENCES

[1] M. B. Roshchin, V. B. Sapiro, S. I. Markov. Effect of austenitization conditions on the plasticity of 10GN2MFA steel in repeated heating, Metal Science and Heat Treatment, 24 (1982) 9, 607-612.

[2] V. N. Zemzin and R. Z. Shron, Heat Treatment and Properties of Welded Joints, Leningrad, Russia, 1978.

[3] M. Raclavský, J. Hancl, Z. Jančíková. Dynamic model of decarburization, Metallic materials, 31 (1993) 5, 407-418.

[4] E. Mazancová, I. Schindler, P. Kozelský. Some mechanical and corrosion aspects of chosen TWIP alloy, Metallurgical Journal, 63 (2010) 6, 127-130.

[5] S. Lasek, E. Mazancová. Influence of thermal treatment of on structure and corrosion properties of high manganese triplex steels, Metalurgija, 52 (2013) 4, 441-444.

[6] Z. Jančíková, O. Zimný, P. Koštial, Prediction of metal corrosion by neural networks, Metalurgija, 52 (2013) 3, 379-381.

[7] A. Kuduzović, M. C. Poletti, C. Sommitsch, M. Dománková, S. Mitsche, R. Kienreich. Investigations into the delayed fracture susceptibility of 34CrNiMo6 steel, and the opportunities for its application in ultra-high-strength bolts and fasteners, Materials Science and Engineering: A, 590 (2014), 66-73.

[8] J. Valíček, R. Čep, K. Rokosz, C. Lukianowicz, D. Kozák, M. Zeleňák, P. Koštial, S. Hloch, M. Harničárová, P. Hlaváček, B. Haluzíková. New way to take control of a structural grain size in the formation of nanomaterials by extrusion, Materialwissenschaft und Werkstofftechnik, 43 (2012) 5, 405-411.

[9] E. Mazancová, New material types for automotive industry - physical engineering properties of high strength material alloyed with manganese and of hydride metal alloys for hydrogen storage (in Czech), Ostrava, Czech Republic, 2007.

[10] U. Besson. The History of the Cooling Law: When the Search for Simplicity can be an Obstacle, Science and Education, 21 (2012) 8, 1085-1110.

[11] P. Koštial, I. Ružiak, Z. Jonšta, I. Kopal, R. Hrehuš, J. Kršková. Experimental method for complex thermomechanical material analysis, International Journal of Thermophysics, 31 (2010) 3, 630-636.

[12] P. Koštial, I. Ružiak, Z. Jančíková, Patent NO 303269 CS

[13] D. R. Askeland, P. P. Fulay, W. J. Wright, The science and engineering of materials, Cengage Learning, Hampshire, UK, 2011.

[14] http://www.engineersedge.com/properties_of_metals.html

[15] http://www.steelmills.com/Manganese_Steel.html

[16] E. Mazancová, I. Ružiak, I. Schindler, Influence of rolling conditions and aging process on mechanical properties of high manganese steels, Archives of Civil and Mechanical Engineering, 12 (2012) 2, 142-147.

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