SELECTED PROPERTIES OF HIGH STRENGTH MANGANESE STEELS

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Abstract

Work is aimed at three laboratory manufactured high strength manganese steels after cast, rolling and aging process (at 500 °C after 6, 12, 30 and/or 60 minutes of dwell). Micro-hardnesses (HV0.2) as well as potential k-carbides formation of micro- and/or nano-size and microstructures characters of all treatment modes are mutually compared. Revealed disproportions are explained by differences in chemical composition and in finishing hot rolling temperature leading to undesirable coarser k-carbides formation on the austenite-austenite, resp. austenite-ferite interphase. Simultaneously, changes in selected thermos-physical parameters both after hot rolling and after subsequent aging (560 °C / 6 minutes) were studied. Between micro-hardness and those thermos-physical parameters some proportionality was observed.

Keywords: High strength manganese steel, micro-hardness, k-carbides, microstructure, thermo-physical parameter

1. INTRODUCTION

Knowledge of thermo-physical properties of each material represents important parameter for practical application, especially for material designing under thermal stress [1]. Among attractive materials, which physical properties had not been frequently studied by now, high strength manganese steels of second generation belong, especially those showing higher aluminium and manganese contents. Both mentioned elements makes the density of steel materials lower, being attractive for rotating components or lighter bodywork, and which also show higher stacking fault energy (SFE) and thus higher FCC matrix stability in wide temperature interval [2, 3]. Aluminium makes also any manganese material more resistant against corrosion and after optimised aging process, k-carbides precipitation of $(FeMn)_3AlC$ type is formed ensuring strengthening of the high manganese steel without any important negative influence on ductility [1, 4, 5]. The optimised aging process is depending on chemical composition of primary cast material, on conditions of temperatures of heating, deformation processes, cooling parameters and especially on the final temperature of forming and rate of cooling from that temperature so that none, ineffective coarser k-carbides, often of micro-size were formed. Only during aging process k-carbides of nano-size must be formed being responsible for excellent final properties of given high strength manganese steels [2]. Presence of aluminium and also silicium supports lower portion of BBC structure beside the FCC one and also represents dangerous of possible occurrence of detrimental oxides formation on the other side. Thermo-physical properties can be measured by use of lumped capacitance method based on Newton´s cooling principle with negligible conduction heat treatment and combined heat transfer of convection and radiation. Model is valid if the Biot´s number is lower than 0.1. Necessary values of thermos-physical steel properties were obtained from [6]. All theoretical background is presented in work [7].

The aim of presented paper is to show changes in micro-hardness after different treatment modes and to demonstrate differences in specific heat capacity, thermal conductivity and thermal diffusivity between hot rolled and subsequently aged (560 °C / 6´) high strength manganese steels.

2. EXPERIMENTAL

For study, three laboratory manufactured steels were used of which chemical composition is presented in **Table 1**. Iron content is balanced. In this table mathematically calculated SFE represents typical high strength manganese steel [3]. All heats were prepared by melting in vacuum induction furnace Leybold-Heraus and cast to ingot moulds with dimensions of 20 mm x 34 mm in cross section and the length corresponded to 120 mm. Chemical analyses were carried out by use of optical emission spectrometer LECO GDS 750A with glow discharge.

Table 1 Chemical composition of three cast heats (1-3) [wt. %], SFE [mJ / m^2]

Heat	C	Mn	Al	Si	Cr	Ni	P	S	Cu	V	SFE
1	0.2	26.8	2.3	1.0	0.08	0.01	0.009	0.02	0.02	0.005	70
2	0.5	27.3	2.3	1.1	0.08	0.91	0.009	0.02	0.02	0.005	105
3	0.4	27.4	2.2	0.1	0.08	0.03	0.009	0.02	0.02	0.005	106

Before rolling in laboratory rolling mill TANDEM [8] steels were heated 15 minutes at 1100 °C. All rolling process was described in work [4]. Final thickness of strips corresponded to 43 mm (width) x 54 mm with 1.9 mm in thickness. After rolling aging processes at 560 °C / 6, 12, 30 and 60 minutes were realized and micro-hardness HV0.2 (LECO 2000) in cross section evaluated. Micro-hardness was also measured after casting and forming. In second step samples approximately of 10 mm x 10 mm x 1.9 mm both from hot rolled and from aged material were prepared for evaluation of thermo-physical parameters including specific heat capacity (c_p), thermal conductivity (K) and thermal diffusivity (α) at ambient temperature. Results of thermo-physical parameters were compared with evaluated micro-hardness and analyzed microstructure using light microscope Olympus IX70, resp. SEM JEOL JSM-6490 LV.

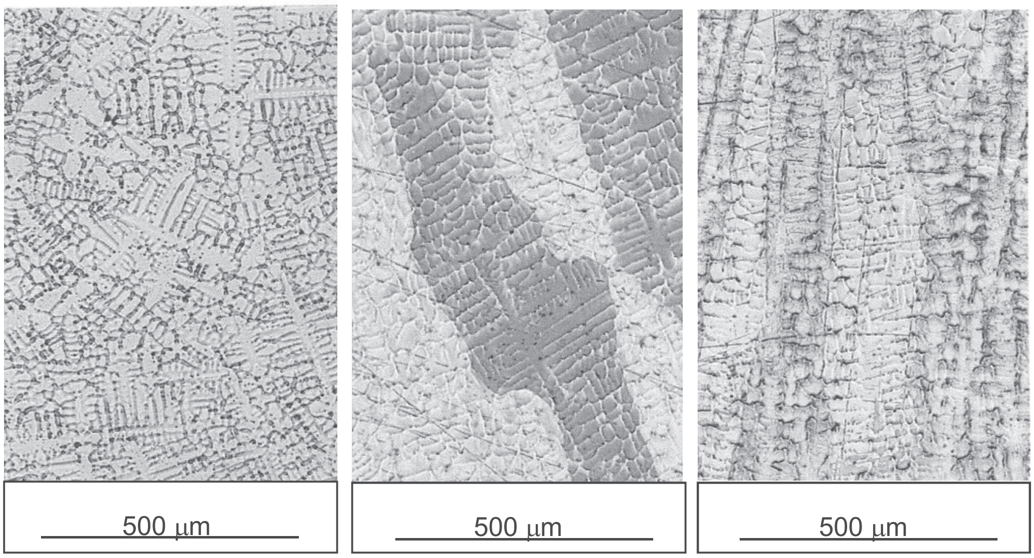

Figure 1 Microstructure image of heat 1(left), 2 and 3 (right) after cast

3. RESULTS AND THEIR ANALYSIS

Microstructures of studied steels after cast and after hot rolling show **Figures 1** and **2**. Heat 1 shows the highest porosity and the finest microstructure (**Figure 1**), whereas heat 3 demonstrates the coarsest microstructure (**Figure 1**), which can be also observed after hot deformation as it from differences between **Figure 2a** and **Figure 2c**, resp. **Figure 2c** and **Figure 2f** in detail follows. In all three cases, especially after hot rolling, slight portions of δ-ferrite can be also observed, which is in accord with chemical composition of elements supporting the BCC structure (see **Figure 2**). Undesirable is presence of white k-carbides of micro-size after hot rolling as can be clearly seen in **Figure 2b** or in **Figures 2d-2f**, especially. That fact is given due to high finishing hot rolling temperature and relatively slower cooling process from that temperature [2, 4, 5].

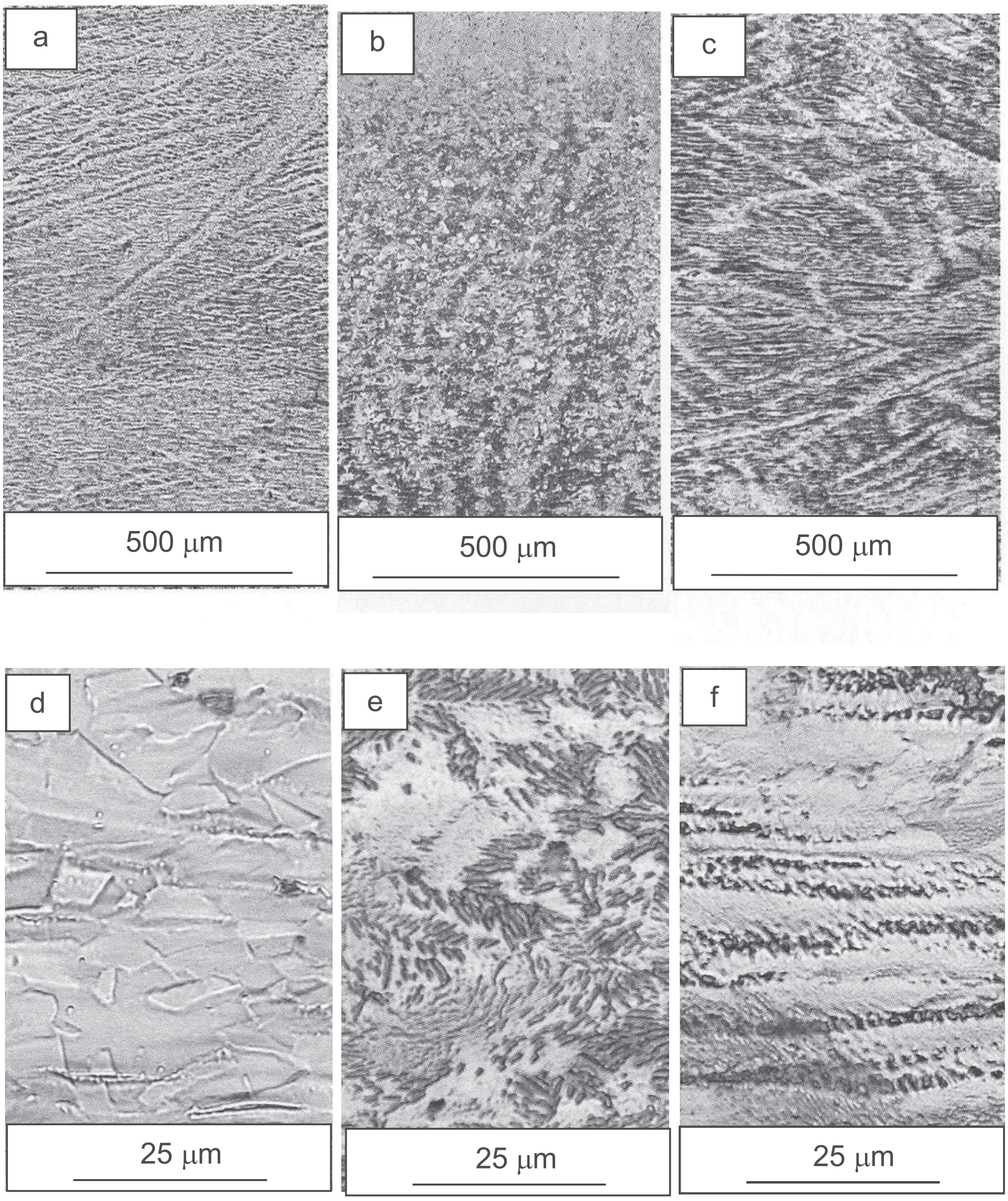

Figure 2 Microstructure image of all heats after rolling (general view and in detail) - heat 1 (a, d), 2 (b, e) and 3 (c, f)

Steel 1 showed the lowest carbon content and according Schumann [9] the 27 wt. % of Mn should be minimally connected with 0.3 wt. % of carbon. Higher carbon content is also necessary for fine $(FeMn)_3AlC$ k-carbides formation and their balance only after aging process [2]. Chemical composition and thus the SFE has been not negatively influenced from point of view of boundary value of 20 mJ / m^2 under which austenite can be transformed into ε-martensite and/or α-martensite, which is undesirable in case of studied high strength manganese steel type. Also thanks presence of aluminium and silicium, the SFE corresponds to 70 mJ / m^2 (see **Table 1**) being a condition for the structure stability of given high strength manganese steel type with main FCC structure and low portion of BCC one [2, 10]. The lower aluminium content represents lower dangerous for possible Al_2O_3 formation and/or AlN nucleation having detrimental influence on high strength manganese steel properties [2, 11] The higher is the SFE, the finer splitting of FCC structure can be awaited thus finer distances between partial dislocations, where fine k-carbides can be detected after aging process [2]. Owing to the higher carbon content heats 2 and 3 show much higher SFE as it from **Table 1** follows. After hot rolling some lower portions of coarser $(FeMn)_3AlC$ k-carbides (especially in case of heat 2) were formed. These can be detected on the austenite-austenite and/or austenite ferrite interphase (see microstructure in frame of **Figure 3**) and are undesirable, because lower portion of carbon content in solid solution is at disposal for the k-carbides nucleation of nano-size formed during final heat treatment - aging predominantly inside of primary austenite grains [2, 11], thus the final strength, resp. hardness can be generally lower finally than has been awaited [2, 4, 5, 12]. Fortunately, mentioned coarser k-carbides were not detected in extremely high portion as it from **Figures 2d-2f** follows. The finer microstructure and higher portion of fine k-carbides is observed, the higher hardness and/or strength can be found and also higher thermal conductivity (K) as well as thermal diffusivity (α) is recorded unlike specific heat capacity (c_p) which is going down. The found out results of micro-hardness and mentioned thermo-physical parameters are summarized in **Figure 3** and **Figure 4**.

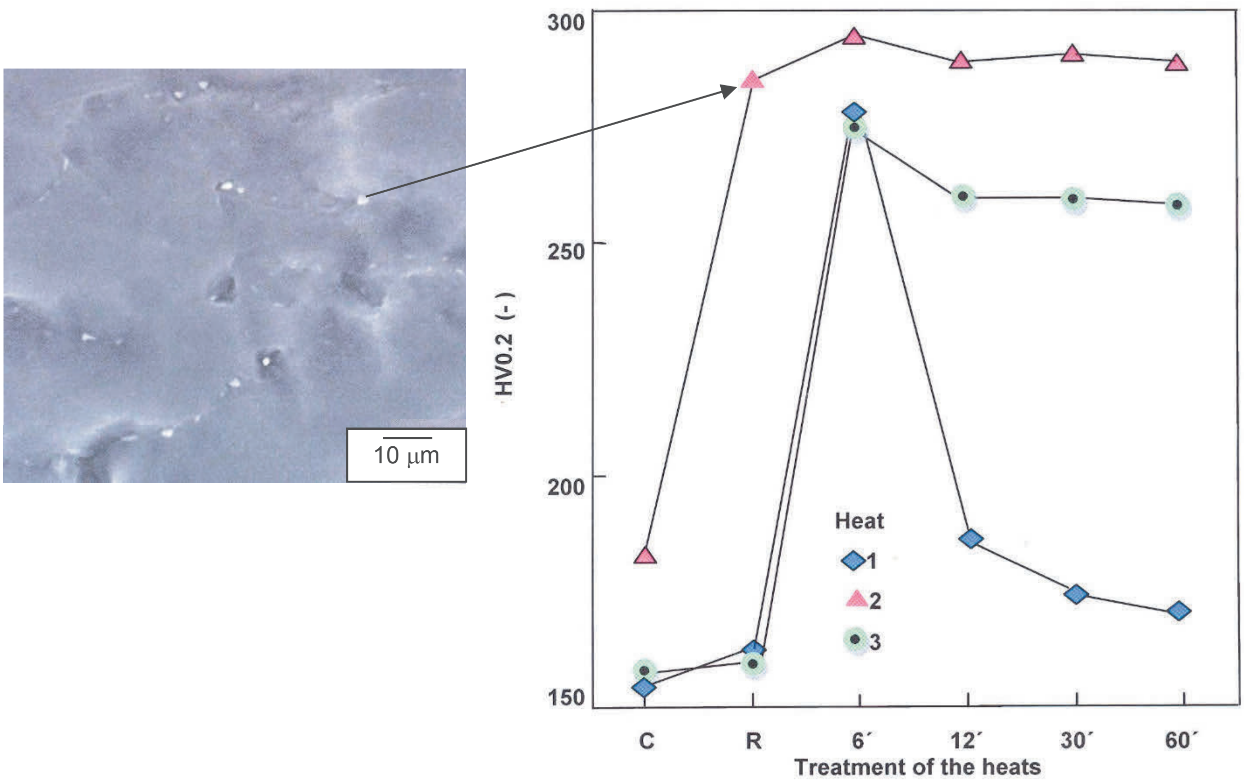

Figure 3 Hardness after different treatment conditions. C represents casting, R rolling process and 6, 12, 30, and 60 minutes dwell times after aging at 560 °C. Microstructure image of the heat 2 (on the left) shows detected coarser k-carbides after hot rolling

As it from **Figure 3** follows, after rolling process micro-hardness of all heats went up, in case of heat 2 dramatically (by 75 % approximately), which could be ascribed not only to deformations during hot rolling [13], thus microstructure refinement and higher dislocation density, however partial k-carbides formation of µm size [5, 12], especially in case of heat 2 (**Figures 2a-2f**), not being quite optimal for next aging process as it was mentioned above. After 6 minutes of aging dwell, micro-hardness went down in all cases. Heat 2 showed the highest portion of µm-size k-arbides and also the lowest micro-hardness increase unlike the other heats, because just low portion of nano-size k-carbides came into existence. In heat 2, chemical composition was the most balanced (**Table 1**) and thus the heat 2 showed the best conditions for other fine nano-size k-carbides precipitation after given aging [9]. After 12 minutes of aging, all heats demonstrated a decrease in micro-hardness. Thanks the chemical composition, the heat 2 showed the slightest micro-hardness fall and this level was practically kept after 30 and 60 minutes of aging, too. Heat 3 showed similar trend as the heat 2, whereas heat 1 demonstrated dramatic micro-hardness fall (by 31 %) already after 12 minutes of aging thanks elements shortage for other nano-size k-carbides precipitation [2, 9]. After other 30 and 60 minutes of dwell, the micro-hardness dropped by 9 and 2 % (in sequence) as can be seen in **Figure 3**. Each fall of micro-hardness can be ascribed mentioned key elements shortage and coarsening of the formerly formed nano-size k-carbides thanks longer dwell times and thus better diffusion conditions for their coarsening. Low levels of micro-hardness after longer aging times do not demonstrate further nano-size k-carbides formation, but coarsening and number decrease of the existing precipitates [4, 5].

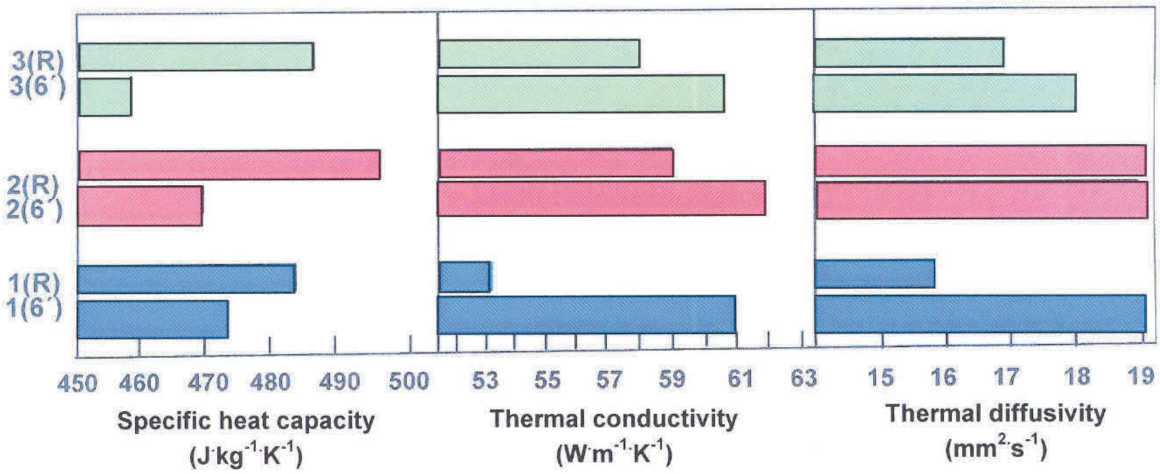

Figure 4 Dependence of specific heat capacity, thermal conductivity and thermal diffusivity on two types of treatment (hot rolling - represents R and (6´) aging at 560 °C / 6 minutes - thicker bars) in case of all three studied heats 1, 2 and 3

As it from **Figure 4** follows, thermo-physical parameters showed after aging lower specific heat capacity by 3, 6 and 6 % approximately, while thermal conductivity went up by 15, 5 and 5 % and thermal diffusivity by 18, practically 0 and 6 % approximately. Given data are mentioned in sequence for heat 1, 2 and 3. In all cases Biot´s number corresponds to 0.0004 and results are in accord with physical natural relations [14, 15]. After aging the most important increase was observed in thermal conductivity (by 8 % in average), and in thermal diffusivity (by 8 % in average, including insignificant difference in case of heat 2 - see **Figure 4**), while specific heat capacity went down and average fall was practically on the level corresponding to 6 % in average. In other words, with micro-hardness increase, respectively with higher portion of fine nano-size precipitates, the thermal conductivity and thermal diffusivity values are going up and specific heat capacity shows decreasing tendency. All investigated parameters were in good agreement with reference data.

4. CONCLUSION

After cast, hot rolling and subsequently aged at 560 °C during 6, 12, 30 and 60 minutes three laboratory manufactured and analyzed heats demonstrated different micro-hardness. The more is balanced chemical composition among C, Mn, Al and Fe [9] the highest micro-hardness studied heats can be revealed including minimal fall of these values after longer aging process than it corresponds to 6 minutes. The most important decrease of micro-hardness with unbalanced chemical composition and with minimal volume fraction of carbon content heat 1 demonstrated.

High finishing rolling temperature with slower cooling process from that temperature led to undesirable μm-size k-carbides formation that run out necessary elements for nano-size k-carbides formed during aging process being responsible for high micro-hardness and/or strength.

Aging influenced thermo-physical properties of investigated high strength manganese steels. Thermal conductivity wet up as well as thermal diffusivity and specific heat capacity revealed decrease.

ACKNOWLEDGEMENTS

This paper was created within the project No. LO1203 "Regional Materials Science and Technology Centre - Feasibility program" funded by Ministry of Education, Youth and Sports of Czech Republic.

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