SOME FEATURES OF HEAT TREATMENTS OF WROUGHT AND CAST HIGH-SPEED STEELS

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Abstract

The influence of heat treatment on the structure and properties of AISI M2 type high-speed steels obtained using conventional metallurgy and foundry technology has been studied. The primary focus was on the effects of austenitising temperatures on the behaviour of both the steels during quenching and tempering. The influence of austenitising temperature on the austenite grain size and size distribution, volume fraction and morphology of the primary carbides, MC and M_6C*, as well as the character of the secondary precipitation in the wrought and as-cast steels was investigated. Relationships between the structural parameters and mechanical properties for the steels have been established. It was found that as-cast high-speed steel heat treated in comparison with wrought one has more stable impact toughness and wear resistance in the whole range of austenitising temperatures studied in the experiments.*

Key words

high-speed steel, heat treatment, structure, properties

Introduction

High-speed steels (HSS) are used in metal-cutting tools where a combination of high strength, and red hardness, wear resistance and impact toughness is mostly required. In order to meet these requirements, HSS have special chemical compositions and structures. The solidification of a melt of HSS starts with a primary precipitation of delta ferrite followed by a peritectic reaction, which results in an austenite formation. Finally, an eutectic reaction ends the primary solidification of the melt [1-3]. As a rule, majority of the primary carbides, M_6C, M_2C, MC, M_7C_3, and $M_{23}C_6$ types, are formed during eutectic reaction [1]. The volume fraction, size, morphology and pattern of distribution of the primary carbides formed in the structure during primary solidification have very strong influence on the final properties of

HSS after full heat treatment [3]. From this point of view there exist obvious differences between HSS employed in wrought and as-cast conditions.

In as-cast HSS primarily eutectic carbides form network over the primary matrix grain boundaries that remains in the structure after quenching and tempering greatly affecting final mechanical properties [4-18]. In wrought HSS extensive hot working, is known, to break up eutectic carbide network resulting in single, structurally separated carbides particles with more homogeneous distribution in a steel matrix[1,3]. For this reason the main goal of the paper is to study the effects of heat treatments on the structural and properties changes in HSS of identical chemical compositions but with different as-cast and wrought structures.

Experiment

The chemical composition of the AISI-M2 type as-cast and wrought HSS is shown in Table 1. The as-cast steel was melted in an electric high-frequency induction furnace. The ferromanganese, ferrosilicon, and aluminium were used as deoxidisers. The melt of the steel were poured into ceramic moulds. The mass of the ingots cast was 1.2 kg. Heat treatment of specimens prepared from the rolled round bars of 20 mm in diameter and cast ingots included annealing, austenitising, quenching and tempering. Annealing was carried out at 850 °C for 2h followed by slow cooling to 720 °C and holding at this temperature for 4 h. Then, specimens were slowly cooled in the furnace to 500 °C and after it to room temperature in open air. After annealing one step preheating of the specimens prior to full austenitisation was used to minimise thermal shock. This treatment was carried out at 850 °C. When austenitising, the steels were heated to temperatures 1180, 1200, 1220, 1240 and 1260 °C and held at these temperatures for the same soaking time. Triple tempering at 560 °C for 1 h completed the heat treatments of the steels studied. After heat treatments specimens were prepared for metallographic examination. To explain structural changes in the steels took place during heat treatments different techniques of optical microscopy, electron microscopy (both scanning and transmission), X-ray diffraction(XRD), and energy dispersive X-ray analyses have been used.

CHEMICAL COMPOSITION OF THE STEELS STUDIED, mass% Table 1

Fe	C	Si	Mn	Ni	P	S	Cr	Mo	W	V
As-cast steel										
Bal.	0.85	0.24	0.29	0.25	0.026	0.028	4.08	5.30	5.67	1.87
Wrought steel										
Bal.	0.86	0.26	0.29	0.23	0.024	0.029	4.12	5.37	5.70	1.89

Impact toughness, hardness, and red hardness were determined by standard tests for HSS. Comparisons of wear resistance for the steels were done, using a plot of mass loses by specimens induced by abrasion wear with a hardmetal counterbody disk versus sliding distance (time) for both steels at sliding friction without any lubricants at a sliding speed of 0.58 m/s under a load of 200 N.

Results and discussions

The microstructure of the as-cast steel after solidification is shown in Fig. 1. The steel matrix consists of bainite and retained austenite. According to the XRD analysis (Fig. 2) the carbide constituent comprises of primarily M_6C carbides and low amount of MC carbides. The eutectic is formed on the basis of M_6C carbides and its colonies form in the interdendritic areas. The major fraction of the eutectic has a rod-like morphology (Fig. 1a) and only small quantity of a fish-bone eutectic can be seen in the structure (Fig. 1b). Primary MC vanadium-reach carbides occur, as a rule, in conjunction with the M_6C-eutectic colonies (Fig. 1a).

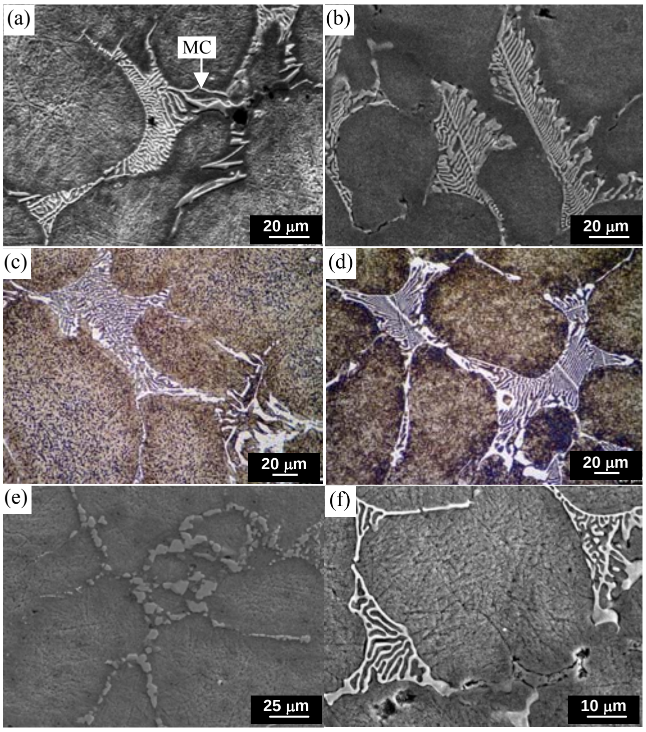

Fig. 1. *Structure of the as-cast high-speed steel after (a, b) solidification, and (c-f) full heat treatment: (c, d) austenitising at 1180 °C, (e) 1260 °C, (f) 1240 °C; (a, b, e, f) –* scanning electron microscope *(SEM), (c, d) – light microscope*

Figures 1c and 1d show the tempered microstructure of the as-cast steel austenitised at 1180 °C. The M_6C eutectic carbides of the rod-like (Fig. 1c) and fish-bone (Fig. 1d) types have started to decompose by the precipitation of the secondary carbides in the bulk of the eutectic carbides. Precipitation of the secondary carbides is more evident in the case of the M_6C rod-like carbide. These secondary carbides have been identified by electron microprobe analysis (EMPA) as V-rich carbides from the result of dispersive spectrometer (EDS) profile in Fig. 3.

Further increase in austenitising temperature is accompanied by coagulating and coarsening of the M_6C eutectic carbides, primarily with rod-like morphology, and therefore, the eutectic carbide network over the matrix grain boundaries tends to break up (Fig. 1e) in comparison with the state after solidification. In general, the higher austenitising temperature the more evident these changes in as-cast structure. Primary MC carbides seem to be very stable [19,20] in the whole interval of austenitising temperatures studied.

The structural changes in the matrix of the as-cast steel were shown to take place too. The increasing austenitising temperature results in the original austenite grains growing (Fig. 4) and the martensite coarsening, as well as the rise in amount of the retained austenite after quenching (Table 2).

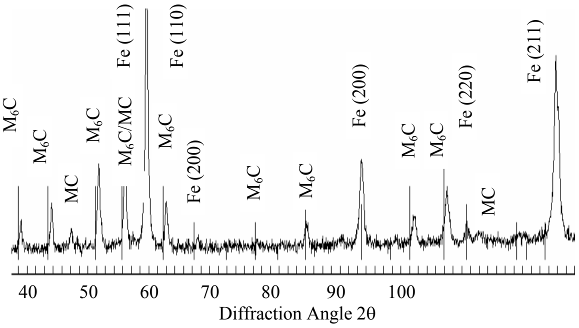

***Fig. 2.** XRD profile of the as-cast high-speed steel*

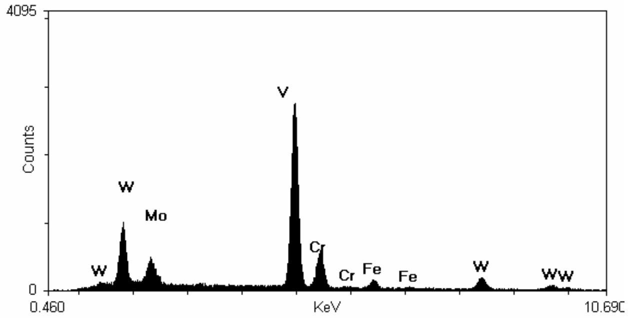

***Fig. 3.** EDS profile of the secondary MC carbide*

Beside primary carbides so-called secondary carbides are usually observed in as-cast and wrought HSS, which precipitate from the oversaturated solid solution at its cooling. Some of them precipitate from the oversaturated austenite during cooling from austenitising temperature in the form of the relatively big particles in the bulk of a matrix (Fig. 1). Considerably finer secondary carbides (Fig. 5) precipitate during tempering inducing secondary hardening in HSS. Depending on the alloying compositions of the HSS grades the stoichometry of the secondary carbides have been previously reported as M_6C, M_2C, $M_{23}C_6$, and MC [21, 22]. In the HSS studied the origin of the secondary carbides have been identified by selected area electron difraction as M_6C and $M_{23}C_6$, see Fig. 5.

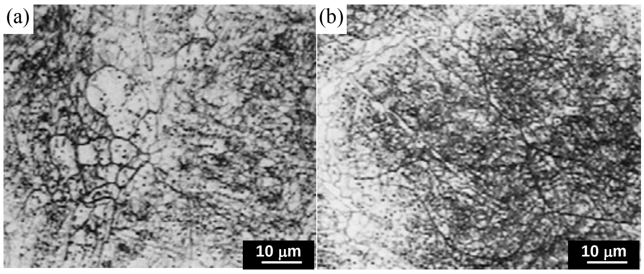

***Fig. 4.** Structure of the as-cast high-speed steel in quenched state after austenitising at (a) 1180 °C, and (b) 1240 °C*

In the wrought steel the processes of the original austenite grains growing as well as the martensite and the secondary carbides coarsening seem to be more pronounced compared with the as-cast steel (Fig. 6). That can be attributed to the stronger diffusion of the alloying elements in the wrought structure induced by initial plastic deformation during the hot working. As a reflection of these phenomena, after all, the local remelting of the matrix and resolidification of the eutectic in the wrought structure that took place during austenitising at 1260 °C can serve, see Fig. 6b.

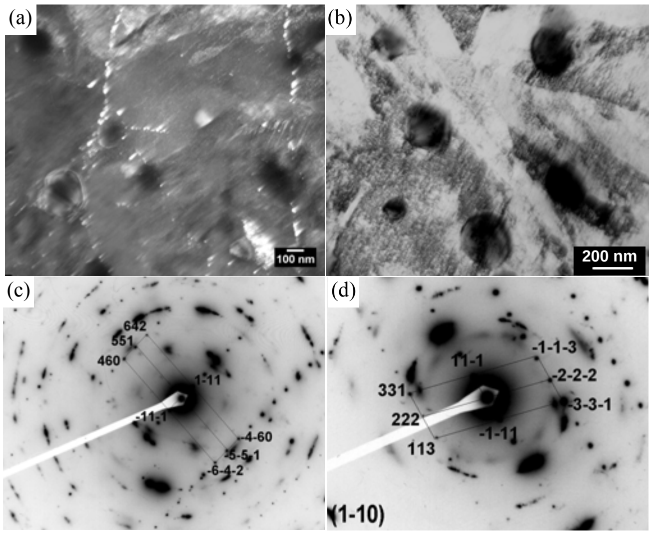

Fig. 5. *TEM micrographs of secondary (a) M_6C and (b) $M_{23}C_6$ carbides in tempered structure of the as-cast steel after austenitising at 1220 °C, electron diffraction pattern of (c) M_6C and (d) $M_{23}C_6$: (a) – DF, (b) – BF*

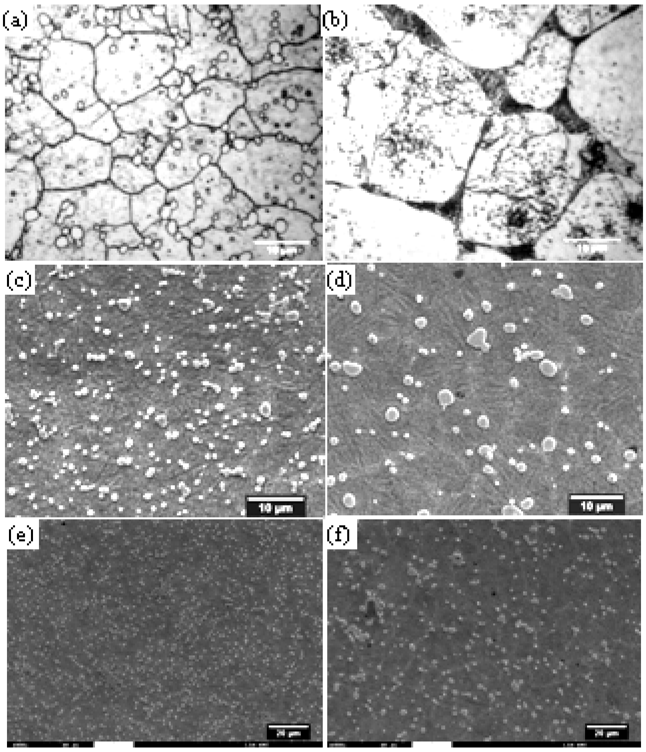

Fig. 6. *Structure of the wrought high speed steel after (a, b) quenching, and (c-f) full heat treatment: austenitising at (a) 1180°C, (b) 1260 °C, (c, e) 1200 °C, and (d, f) 1240 °C; (a, b) – light microscope, (c - f) –* scanning electron microscope *(SEM)*

Table 2 shows the effect of austenitising temperature on the mechanical properties of the HSS studied. The pattern of hardness and amount of retained austenite variations after quenching as well as the pattern of hardness and red hardness variations after tempering, in both cases with regards to the austenitising temperatures, show the identical qualitative changes for these properties in the as-cast and wrought HSS.

The reason is that these properties in HSS are primarily governed by kinetics of the secondary carbides dissolution in austenite during austenitising holding, which seems to be similar in both the steels. Slightly higher nominal values of the hardness and especially red hardness of the as-cast steel are found to be due to higher initial content of the alloying elements in the matrix (Table 3) that has been inherited from the cast state and resulted from higher cooling rate of the smaller foundry ingot (1.2 kg) compared with the 150 kg metallurgical ingot, for example [23].

More marked differences, affected by austenitising temperature, are seen from Table 2 for wear resistance, and impact toughness in both the steels. In the case of the as-cast steel, the increase of austenitising temperature is accompanied by little changes in impact toughness, while in the wrought steel by its catastrophic drop after austenitising at 1240 °C and higher. The reasonable explanation is that in the as-cast steel the main impacting factor, governing impact toughness, is the carbide structure, and in the case of the wrought steel the dominating factor is the matrix structure [24].

Table 2 Influence of austenitising temperature on the amount of retained austenite and hardness (in qenched state), and hardness, red hardness after additional tempering at 620 °C (4 h), impact toughness, and wear resistance (rate of wear) (in tempered state) for the as-cast (in numerators) and wrough (in denominators) steels

Parameter	**Austenitising temperature (°C)**				
	1180	**1200**	**1220**	**1240**	**1260**
Amount of retained austenite [mass%]	13/11	16/15	21/19	25/22	25/24
Hardness in qenched state	65/65.5	65/65.5	64/64	63/63.5	61.5/62.5
Hardness	63/62.5	63.5/63	64/63.5	65/64	64.5/65
Red hardness after additional tempering at [620°C]	56.5/55	57/56	58.5/57.5	60/58.5	61/60
Impact toughness [MJ/m^2]	0.08/0.38	0.11/0.4	0.09/0.35	0.08/0.2	0.13/0.09
Wear resistance [mg/h]	76/104	73/101	70/94	75/89	82/87

It is necessary to emphasise that the presence of the eutectic carbide network over the matrix grains in the as-cast structure seems to slow dawn processes that promote the original austenite grains growing and the martensite coarsening during austenitising. On the other hand, the effect of break-up of the continuous eutectic carbide network over the matrix grain boundaries is considered to be dominative for as-cast HSS from the enhancing impact toughness point of view. This assumption is proved by the results of mechanical tests in Table2, which show that the as-cast steel after full heat treatment has the highest nominal impact toughness value (0.13 MJ/m^2) after austenitising at the highest experimental temperature.

Table 3 Chemical composition of the matrix for the as-cast and wrough steels after full heat treatment (carbon content has not be determened)

Steel	**Content of elements (mass %)**				
	Fe	W	Mo	Cr	V
As-cast	86.78	3.80	3.72	4.21	1.49
Wrought	88.47	2.84	3.18	4.24	1.27

In the wrought high-speed steel, the processes of the matrix coarsening, as shown in Fig. 6, seemed to be more pronounced compared with as-cast steels. This may be attributed to the fact that the single, structurally isolated primary carbides of the eutectic origin do not effectively preserve steel matrix against overheating during austenitising. After all, these dramatic structural changes in the matrix in combination with the local remelting and resolidification of the eutectic constituent during austenitising at the higher temperature and followed quenching, result in the dramatic decrease of impact toughness for the wrought steel from 0.40 till 0.09 MJ/m^2.

These features of the structural changes in both the steels in their optimum heat-treated conditions reflect the fact that the crack propagation through the wrought steel mainly consisted of transgranular cleavage through the matrix (Fig. 7a), but small isolated areas of ductile failure, due to localized plasticity, also occurred in the matrix after tempering (Fig. 7c) [24]. Dramatic matrix coarsening and especially formation of the resolidified eutectic network lead in the wrought matrix austenitised at 1260°C to intergranular fracture mode (Fig. 7e). This is in a good agreement with the particularly deleterious effect of overheating on impact toughness of this steel.

In the as-cast steel, in quenched conditions, the crack travels preferentially through the eutectic carbide network, the crack propagation occurs, primarily, by debonding at the carbide/matrix interface or/and by cleavage across eutectic carbides (Fig. 7b). After tempering the as-cast steel exhibits dominantly transgranular fracture through the matrix grains (Fig. 7d), but even in this case cracks are often seen to initiate from the eutectic carbide (Fig. 7f) [24].

Tribological tests show less marked dependence of the wear resistance on austenitising temperature in the case of as-cast steel and more evident dependence for the wrought steel (Fig. 8) that can be also attributed to their carbide structures. At conditions, when abrasion wear dominates, the network of eutectic carbides, compared with single, structurally isolated carbide particles in the wrought steel, was found to be more effective to provide protection against abrasive and oxidational wear of a matrix [25]. As consequent, the worn surface of the specimen from the as-cast steel, comparing with that of the wrought steel, has less pronounced traces of the abrasive interaction produced by counterbody disk as well as smaller oxide film breakdown sites have being developed on the sliding surface at friction, see Fig. 8.

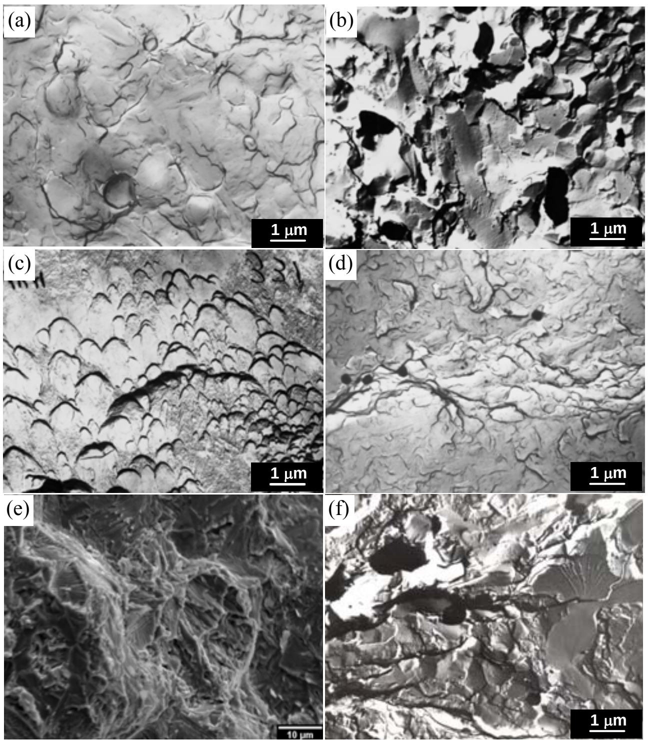

Fig. 7. *Fracture surfaces of the (a, c, e, g) wrought and (b, d, f) as-cast HSS after (a, b) quenching, and (c-d) full heat treatment: austenitising at (a-c, f) 1180°C, and (e) 1260 °C: (a-c, f) – TEM, replicas, (e) – SEM*

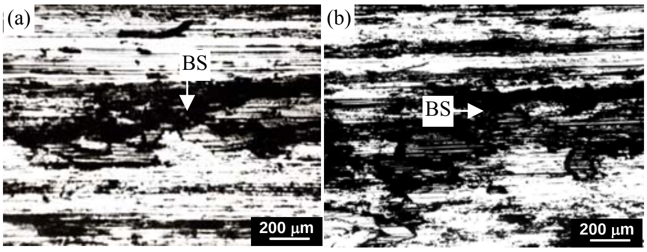

Fig. 8. *Worn surfaces of the tribological test specimens from (a) as-cast and (b) wrought HSS. "BS" indicates breakdown sites of oxide films*

Conclusions

1. The results of mechanical tests on impact toughness and wear, as well as the fractographic examinations of the HSS steels studied with regards to austenitising temperature reflect higher stability of the as-cast steel. It has been found that increase of austenitising temperature results in as-cast steel, on the one hand, in coarsening of the matrix structure being weaker than that in the wrought steel due to protective effect of the eutectic carbide network over the primary matrix grains.
2. On the other hand, strong coagulation and dissolution of eutectic carbides benefit in increase in impact toughness in the as-cast steel not affecting significantly its wear resistance. On the contrary, more intensive growing of austenitic grains and coarsening of martensite with increasing austenitising temperature, and after all, the secondary

formation of the eutectic network over matrix grains after austenitising from 1260 °C result in drop of impact toughness and wear resistance in the wrought steel.

3. Despite higher stability of as-cast structure with regards to wear resistance and impact toughness, lower nominal values of impact toughness for cast steel generally indicate that in order to exhibit good all-around performance structure refinement and impact toughness enhancement for as-cast HSS are obligatorily needed.

Acknowledgements

The financial support of the grant VEGA 1/4109/0707 is gratefully acknowledged. The author would like to thank L. Čaplovič and M. Dománková for their technical assistance.

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