INFLUENCE OF VACUUM HEAT-TREATMENT ON MICROSTRUCTURE AND MECHANICAL PROPERTIES OF HIGH-SPEED STEEL

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Abstract

The microstructure of AISI M2 high-speed steel can be substantially modified by vacuum heat treatment in order to optimise the ratio between hardness and fracture toughness. This ratio is significantly affected by the volume fractions of retained austenite and undissolved eutectic carbides, as well as the mean distance between these carbides. Calculated fracture toughness values, which were obtained using a newly developed semi-empirical equation, based on the stress-modified critical strain criterion and the quantified microstructural parameters, gave us an opportunity to choose the optimum composition and processing for high-speed steel and the best heat treatment process to obtain an optimum combination of basic characteristics for a given tool application.

Keywords: high-speed steel, vacuum heat treatment, quantified microstructural parameters, hardness and fracture toughness

INTRODUCTION

The vacuum heat treatment of high-speed steels for cold-working applications must satisfy ever greater demands, particularly in respect of greater toughness while maintaining or even increasing hardness, and in respect of
the smallest possible dimensional changes of such tools. A high fracture toughness \( K_{IC} \) means that the tools will be more resistant to shock loadings and the propagation of cracks.

The microstructure of high-speed steel, which has been vacuum quenched and tempered, consists of relatively large eutectic carbides in a martensitic matrix, hardened with finer secondary carbides. In the matrix, in which the eutectic carbides are distributed more or less in stringers, there is also some retained austenite. The fracture toughness of such a steel is determined by the stress concentrators in the microstructure (e.g. carbides in stringers, carbide clusters, individual larger carbides, and non-metallic inclusions). When tools are subjected to loads, local stress concentrations occur next to the above-mentioned microstructural features and if these stresses cannot be released through micro-yielding of the matrix, accelerated tool breakage can occur. By means of heat treatment, the microstructure of high-speed steel can be changed, and, within fairly wide boundaries, the properties of the matrix, too. Due to secondary hardening under different tempering conditions, high-speed steels having the same hardness but different microstructures and consequently different fracture toughness can be obtained, so that the optimisation of the heat treatment of high-speed steels is an important task.

**THEORY**

The Rockwell-C hardness as determined by a normal indentation test, is primarily a feature of the matrix of the high-speed steel: provided that the indentation is not made at a position where the carbide size or quantity is excessive. In the as-quenched condition, hardness may give some indication of the temperature from which the specimen has been quenched. In the tempered condition, hardness is essential from the user’s viewpoint, although this value alone is not capable of differentiating between specimens hardened and tempered by different routes. For example, a similar hardness may be obtained by varying quenching and tempering temperatures, or merely by taking a tempering temperature either side of the peak hardness. For this reason, in addition to hardness a second mechanical property such as the fracture toughness \( K_{IC} \) can be used for differentiation concerning the influence of vacuum heat treatment. In other words, fracture toughness tests on high-speed steels show a better differentiation concerning the influence of heat treatment than the data obtained from bend tests [1].
Influence of Vacuum Heat-Treatment on Microstructure and Mechanical Properties of High-Speed Steel

An overview of the literature has shown that several methods can be used for measuring the fracture toughness of high-speed steels. These include standard methods, which use compact tension (CT) and single edge notched bend specimens (SENB) test specimens [2], and non-standard methods [3, 4, 5]. Recently, a semi-empirical equation has been developed [5, 6], where the fracture toughness of the high-speed steel is quantified on the basis of microstructural parameters and several other material properties:

\[ K_{IC} = 1.363 \left( \frac{H_Rc}{H_Rc - 53} \right) \cdot \left[ \sqrt{ \frac{E \cdot d_p \cdot (f_{\text{carb}})}{(1/6) \cdot (1 + f_{\text{aust}})} } \right] \] (1)

Since the above correlation is a semi-empirical one, derived by taking into account the critical strain criterion [7, 8, 9, 10], and the experimentally determined effects of the microstructural parameters and hardness, it is necessary to take great care with the units. The constant, 1.363, was obtained by assuming that the modulus of elasticity \( E \) is expressed in MPa, the mean distance between undissolved eutectic carbides \( d_p \) in m, the Rockwell-C hardness in units of HRc, and \( f_{\text{carb}} \) and \( f_{\text{aust}} \) as volume fractions of undissolved eutectic carbides and retained austenite. In this case the fracture toughness \( K_{IC} \) is obtained in units of MPa\( \sqrt{\text{m}} \). It is important to note that the calculated fracture toughness values, which were derived using a newly developed semi-empirical equation 1, agreed well with the experimental results obtained by the authors [5, 6], as well as with results obtained by other authors [11].

**EXPERIMENTAL SECTION**

**CHOICE OF MATERIAL AND VACUUM HEAT TREATMENT.**

For the experimental work, ESR high-speed steel AISI M2 (delivered in the shape of rolled, soft annealed bars \( \varnothing 20 \text{ mm} \times 4000 \text{ mm} \)) was used. This steel had the following chemical composition (mass content in \%): 0.89 \% C, 0.20 \% Si, 0.26 \% Mn, 0.027 \% P, 0.001 \% S, 3.91 \% Cr, 4.74 \% Mo, 1.74 \% V, and 6.10 \% W. The metallographic specimens \( \varnothing 20 \times 8 \text{ mm} \) made from these bars, were heat treated in a horizontal vacuum furnace, with uniform high-pressure gas quenching, using \( \text{N}_2 \) at a pressure of 5 bars. After the last preheat the metallographic specimens were rapidly heated (10 \( ^\circ \text{C}/\text{min} \)) to the austenitising temperature and than soaked for 2 minutes, followed by gas
quenching to a temperature of 80 °C, and double tempered 1 hour in the same furnace. An overview of the quenching and tempering temperatures, which were used in the experimental work described in this paper, is presented in Table 1.

<table>
<thead>
<tr>
<th>Group of metallographic specimens</th>
<th>Austenitization temperature °C</th>
<th>Temperature at end of gas quench °C</th>
<th>Temperature of first tempering °C</th>
<th>Temperature of second tempering °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1230</td>
<td>80</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>B</td>
<td>1230</td>
<td>80</td>
<td>510</td>
<td>510</td>
</tr>
<tr>
<td>C</td>
<td>1230</td>
<td>80</td>
<td>540</td>
<td>540</td>
</tr>
<tr>
<td>D</td>
<td>1230</td>
<td>80</td>
<td>550</td>
<td>550</td>
</tr>
<tr>
<td>E</td>
<td>1230</td>
<td>80</td>
<td>570</td>
<td>570</td>
</tr>
<tr>
<td>F</td>
<td>1230</td>
<td>80</td>
<td>600</td>
<td>600</td>
</tr>
</tbody>
</table>

For each set of vacuum heat-treatment conditions from A to F, at least 4 metallographic specimens were used, the Rockwell-C hardness and fracture-toughness values being determined as described below.

**QUANTITATIVE MICROSCOPY (QM)**

The microstructural tests were performed on the individual groups of metallographic specimens using, firstly, conventional optical metallographic techniques and a NIKON Microphoto-FXA optical microscope, and, secondly, a JEOL JSM-35 scanning electron microscope. The microstructures of the metallographic specimens of the investigated, vacuum heat treated AISI M2 high speed steel were quantitatively evaluated [12], using the following parameters: the size of the prior austenite grains, the mean diameter of the undissolved eutectic carbides, and the volume fractions of the individual microstructural phases (the undissolved eutectic carbides, the tempered martensite, and the retained austenite).

The mean diameter $D_p$ and volume fraction of the undissolved eutectic carbides $f_{\text{carb}} = (M_6C + MC)$ were determined on unetched metallographic specimens Fig. 1.

SEM images of the microstructures were obtained with back scattered electrons (BE) [13, 14], at a magnification of M 1000 ×. The images of
Influence of Vacuum Heat-Treatment on Microstructure and Mechanical Properties of High-Speed Steel

11 to 16 visible fields, obtained on each of the metallographic specimens of the investigated high speed steel, which had been vacuum quenched and tempered, were analysed using KS Lite V2.00 software for image analysis. The mean distance between the carbides $d_p$ was calculated [12] with the following equation:

$$d_p = D_p \cdot (1 - f_{\text{carb}}) \cdot \sqrt{\frac{2}{3f_{\text{carb}}}}$$

where $f_{\text{carb}}$ is the volume fraction of undissolved eutectic carbides, and $D_p$ is their mean diameter.

From the images of the microstructure, obtained using the optical microscope at magnifications of M 600 $\times$, of the same metallographic specimens, which had been etched for 2 to 3.5 minutes in a 5 % solution of nital with 10 % added HCl, and by means of image analysis using the KS Lite V2.00
software, the total volume fraction \((f_{\text{carb}} + f_{\text{aust}})\) of the undissolved eutectic carbides and of the retained austenite was determined (Fig. 2).

![Image of the undissolved eutectic carbides and the retained austenite (both white) taken by optical microscope; etched metallographic specimen from group A.](image)

Eleven to twelve visible fields were analysed on each of the metallographic specimens of the investigated high-speed steel.

From the differences between the so determined total volume fraction of the undissolved eutectic carbides and the retained austenite (which appears white in the images obtained using the optical microscope) and the volume fraction of the undissolved eutectic carbides (SEM with reflected electrons), the volume fraction of the retained austenite in the investigated high-speed steel was determined.

**HARDNESS TEST AND CALCULATED FRACTURE TOUGHNESS**

The Rockwell-C hardness was measured on the metallographic specimens using a Wilson 4JR hardness machine. The fracture toughness \(K_{IC}\) was calculated using equation (1) and the measured values for Rockwell-C hardness, the volume fractions of retained austenite \(f_{\text{aust}}\), the volume fraction of undissolved eutectic carbides \(f_{\text{carb}}\), the mean distance between these carbides \(d_p\), equation (2) and the modulus of elasticity \(E = 2.17 \times 10^5\) MPa.
RESULTS AND DISCUSSION

The microstructural data of the vacuum quenched steel from 1230 °C and double tempered at various tempering temperatures is given in Table 2. Since the undissolved eutectic carbides are fairly well dispersed, see Fig. 1, it is clear that the investigated steel was heavily hot worked (over 97% of reduction).

Table 2. The microstructural data of AISI M2 high-speed steel

<table>
<thead>
<tr>
<th>Group of metallographic specimens</th>
<th>Retained austenite and carbides data QM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$f_{\text{aust}}$</td>
</tr>
<tr>
<td>A</td>
<td>20.9± 1.9</td>
</tr>
<tr>
<td>B</td>
<td>20.3± 3.1</td>
</tr>
<tr>
<td>C</td>
<td>19.8± 2.5</td>
</tr>
<tr>
<td>D</td>
<td>11.9± 2.6</td>
</tr>
<tr>
<td>E</td>
<td>~ 7.6</td>
</tr>
<tr>
<td>F</td>
<td>—</td>
</tr>
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</table>

The mean values of the volume fraction of retained austenite determined by quantitative microscopy (Table 2) clearly show the influence of tempering temperature on the volume fraction of retained austenite. The statistical analysis of the experimental results [5] has shown that, in the investigated steel, the mean diameter $D_p$ and volume fraction of the undissolved eutectic carbides $f_{\text{carb}}$ depend mainly on the austenitizing temperature and are practically independent of the tempering temperature.

It is well known that the hardness of high-speed steels varies according to: composition; austenitizing temperature and time; tempering temperature; and the number of tempering cycles. Different heat treatment processes (i.e. salt bath, fluidised bed or vacuum heat treatment) as well as microstructure also have an effect. Fig. 3 shows the effect of tempering temperature on the secondary hardness peak of the investigated vacuum heat treated high-speed steel after double tempering.

It can be seen that similar hardness may be obtained merely by tempering at temperature either side of the hardness peak. For this reason, a second mechanical property other than hardness, such as fracture toughness $K_{IC}$,
The influence of tempering temperature on the secondary hardening peak of the investigated high-speed steel. Vacuum austenitized 2 mins at 1230 °C and double tempered for 1 h. (Measured on metallographic specimens from A to F, Table 1.)

The microstructures of the investigated high-speed steel (vacuum heat treatment conditions A–F, Table 1) examined by scanning electron microscope are shown in Fig. 4.

As can be seen from the micrographs in Fig. 4, the microstructure of the investigated high-speed steel consists of tempered martensite and undissolved eutectic carbides. There is also some retained austenite in the matrix, though less after double tempering at 570 °C(E), and more after double tempering at 500 °C(A). After double tempering at 600 °C(F), retained austenite in the matrix is no longer visible. According to the above micrographs it can be concluded that after vacuum quenching from 1230 °C and double tempering at temperatures up to 570 °C the retained austenite is very stable. The diagram in Fig. 3 and micrographs in Fig. 4 also predict that by varying the tempering temperature either side of the peak secondary hardening, a similar hardness at different microstructure and therefore different fracture toughnesses may be obtained.

From the results presented in [5, 6] it can be seen that, for the investigated high-speed steel, within the hardness range between 57 and 66 HRc, the measured and calculated values of fracture toughness $K_{IC}$ agree very
Figure 4. The microstructure of vacuum hardened and tempered metallographic specimens A–F.

well; the disagreement being less than 10 %, and the calculated values of fracture toughness $K_{IC}$, calculated from equation (1), are conservative when compared with the experimentally obtained values of $K_{IC}$. However, on the basis of the average measured hardness (see Fig. 3) and the above data obtained by quantitative microscopy for the set of vacuum heat-treatment conditions A to F (see Table 2), by means of the semi-empirical equation (1) the fracture toughness $K_{IC}$ was calculated, Fig. 5. In all the calculations the average values of the Rockwell-C hardness, volume fraction of the retained austenite $f_{aust}$, volume fraction of the undissolved eutectic carbides $f_{carb}$, mean distance between these carbides $d_p$ and the modulus of elasticity $E = 2.17 \times 10^5$ MPa, have been taken into account.

The net effect of tempering is attributed to a combination of stress relief and a reduction in ductility due to the secondary hardening peak. This pro-
vides a strong indication that among other possible effects, differences in retained austenite (see Table 2) cause the fracture toughness variations. In examining the course of tempering, it is observed that there is a peak value of fracture toughness for a low tempering temperature (500 °C) that coincide with relatively high volume fraction of retained austenite and a minimum corresponding to the hardness peak. From Fig. 5 it can be clearly seen that in the case of the same obtained hardness the under-tempered metallographic specimens, vacuum quenched from the same austenitizing temperature, achieve higher fracture toughness. For example, after vacuum quenching from 1230 °C and double tempering for 1 hour at 600 °C the investigated high-speed steel achieves a hardness of 63.7 HRc and a fracture toughness of $K_{IC} = 9.6 \text{ MPa} \sqrt{m}$, the same hardness but with an approximately 30 % higher fracture toughness could be obtained after double tempering for 1 hour at a temperature of 520 °C (see Fig. 5). This could lead to the conclusion that a high volume fraction of retained austenite in under-tempered high-speed steel significantly increases its fracture toughness.
CONCLUSIONS

On the basis of the results of extensive tests performed on the ESR high-speed steel AISI M2, it has been confirmed that the microstructure of the investigated steel can be substantially modified by vacuum heat treatment in order to optimize the ratio between the hardness and the fracture toughness $K_{IC}$ of this steel. It has also been experimentally proved that the volume fraction of retained austenite, the volume fraction of undissolved eutectic carbides, and the mean distance between the undissolved eutectic carbides have a significant effect on the measured fracture toughness $K_{IC}$ of this steel.

The semi-empirical correlation equation (1) derived by the authors for calculating the fracture toughness of high-speed steels demonstrates that beside the increased amount of retained austenite that is stable after tempering (steel initially vacuum austenitized at the highest temperature), fracture toughness is significantly influenced by the mean distance of undissolved eutectic carbides, and thus, at a given composition, by the carbide size.

After vacuum quenching of the investigated high-speed steel from the highest recommended austenitizing temperature the average volume fraction of undissolved eutectic carbides is 6.9 %, their mean diameter is 0.95 µm and the mean distance between them is 2.7 µm. When a crack propagates in a material with such large undissolved eutectic carbides separated by large mean distances, large ligaments are left between the voids, which form at the individual carbides or carbide clusters. The plastic deformation of these ligaments is responsible for the energy dissipation that determines the crack resistance of the material. Therefore, reasonably large undissolved eutectic carbides, with a correspondingly large mean distances, give higher fracture toughness than smaller carbides. This allows greater freedom in selecting the desired combinations of hardness and toughness, especially in applications not requiring peak hardness.

Furthermore, a good understanding of the mutual interaction of mechanical and microstructural properties on the fracture toughness $K_{IC}$, as expressed by the semi-empirical equation (1), gave us an opportunity to choose the optimum composition and processing for high-speed steel (HIP’ed, forged, sintered, ESR or conventional material) and the best heat treatment process (salt bath, fluidised bed or vacuum heat treatment) to obtain an optimum combination of basic characteristics for a given tool application.
REFERENCES


