NUMERICAL SIMULATION OF GAS QUENCHING OF TOOL STEELS AND THE INFLUENCE OF HARDENABILITY ON DISTORTION

A Thuvander

Swedish Institute for Metals Research
Drottning Kristinas väg 48
SE-114 28 Stockholm
Sweden

Abstract Gas quenching of tool steel and the resulting distortion were studied with numerical simulation using FE analysis.

Previous results from gas quenching experiments on blocks of ORVAR SUPREME and DIEVAR were used to verify the model predictions. These two hot work tool steels differ significantly in hardenability, with the recently developed DIEVAR as the steel of the highest hardenability.

The experimental and numerical results indicate the influence of hardenability when the higher hardenability is utilised to provide higher hardness, and accordingly quenching the two steels under identical conditions. If on the other hand the higher hardenability is utilised to minimise distortion, different cooling can be used to produce the same hardness in the two steels. Simulations were run to illustrate how the distortion of the two steels differ after applying a milder quench to the steel of higher hardenability.

Keywords: Tool steel, distortion, gas quenching

INTRODUCTION

Tool distortion from hardening is influenced directly and indirectly by the hardenability of the steel. The direct influence comes from the fact that the time history of phase transformations will influence the stress and strain history during hardening. The indirect influence comes from the possibility to use a milder quenching for steel of higher hardenability.
The present work aimed at testing with numerical simulation how the TTT-diagram, especially the bainite nose, influences the heat treatment distortion of tool steels. Both the direct influence of the choice of steel on the distortion under similar cooling conditions and the indirect effect using different cooling were tested. The term hardenability in general is certainly not restricted to the position of the bainite nose. Holding back the precipitation of carbides and pearlite may be even more essential than reducing the amount of bainite. However, it has been shown in a previous work [1] that carbide precipitation has a limited influence on distortion and the amount of pearlite should in general not be large enough to influence distortion.

FEM simulations of gas quenching were performed for blocks of the tool steels ORVAR SUPREME and DIEVAR. Comparison is also made with previous experiments made by Uddeholm Tooling.

Materials
The steels of the present study are the hot work tool steels ORVAR SUPREME and DIEVAR. Their chemical composition given is in Table 1.

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Cr</th>
<th>Mo</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>ORVAR SUPREME</td>
<td>0.39</td>
<td>1.0</td>
<td>0.4</td>
<td>5.2</td>
<td>1.4</td>
<td>0.9</td>
</tr>
<tr>
<td>DIEVAR</td>
<td>0.35</td>
<td>0.2</td>
<td>0.5</td>
<td>5</td>
<td>2.3</td>
<td>0.6</td>
</tr>
</tbody>
</table>

EXPERIMENTS
The present study did not include any new experimental work. For verification of the simulation model and as a basis for some of the simulations an experimental work by Uddeholm Tooling was utilised [1]. It consisted of gas quenching experiments on large blocks of ORVAR SUPREME and DIEVAR. From that programme the experiments on quenching with 3 bar nitrogen gas and block dimensions $610 \times 203 \times 500$ mm and $508 \times 127 \times 500$ mm were selected.

The temperature was recorded with thermocouples at the centre and the surface of the blocks. Here only the temperature at the centre is utilised.

The distortion was taken as the change in block dimensions from measurements before and after the heat treatment. Nine measurements were
made on each face according to Fig. 1. One measuring point was located at the centre of each face and the remaining eight measurements were made 5 mm from the edge, at the corners and the mid-point of the edges. The measurements were made relative to the opposite face for all points except for the mid-surface points in the thickness direction. Here the measurements were instead made with a steel ruler producing measures relative to other points on the same face. This made it possible to construct a diagram of the distortion in a section of the block that included the most dominant asymmetric distortion modes.

![Distortion measurement locations on ORVAR SUPREME and DIEVAR blocks. The triangle indicates the point measured with a ruler along the dotted line. Filled circles denote locations of measurements used for height, length and width measurements (Distance to opposite face). Crosses denote locations of measurements that are not used in the present work.](image)

**HEAT TREATMENT SIMULATION MODEL**

The present computations were performed with a numerical model previously used for specimens of tool steel K326 and ORVAR SUPREME and for the high speed steel ASP 2023 [1, 2, 3, 4, 5]. Here an overview of the model is given.
The computations are performed in two steps. First the temperature and phase transformation history is simulated. In the second step the mechanical response to temperature changes and phase transformations is simulated. Both simulation steps are run with the general FEM-code ABAQUS [1] utilising a package of user subroutines specially developed for heat treatment simulation.

The FEM-simulation of the temperature history involves the solution of the heat conduction equation with internal heat sources from phase transformation heat and with boundary conditions characterising the surface heat flow to the quenchant. The surface heat flow to the quenchant is modelled with a heat transfer coefficient, which is here set independent of temperature but with different values on different surfaces depending on gas flow directions.

In the present calculations pearlite, bainite and martensite transformations were included. Phase transformations from austenite to bainite or pearlite was described with a model based on an equation for isothermal transformation by Avrami [1].

\[ f_i = f_{eq}^i \cdot (1 - e^{-bt^n}) \] (1)

where \( f_i \) is the volume fraction of phase \( i \) transformed, \( t \) is the time, \( b \) and \( n \) are temperature dependent parameters. The maximum amount of phase is denoted \( f_{eq}^i \). The parameters can be evaluated with data from a TTT-diagram. The equation was designed for isothermal transformation but is here generalised to continuous cooling. The generalisation is based on the assumption that it is not actually the elapsed time that controls the growth rate but the amount of phase that has already transformed. Then in a differentiated form equation 1 can give the transformation rate as a function of the amount of phase already transformed.

\[ \frac{d}{dt} \left( f_i f_{eq}^i \right) = nb^n \left[ -\ln \left( \frac{f_i - f_{eq}^i}{f_{eq}^i} \right) \right]^{n-1} (f_{eq}^i - f_i) \] (2)

The mechanical response to the temperature changes and phase transformations is modelled in a separate FEM-calculation. In each time step the increment in total strain tensor is made up of contributions from thermal strain, transformation strain, elastic strain, plastic strain and transformation
plasticity strain. An elastic-visco-plastic constitutive model with isotropic hardening was utilised.

Tempering is modelled by taking the mechanical response into account from the volume change when retained austenite transforms to martensite. This volume change is assumed to take place at the tempering temperature. The volume is assumed to increase in a single step even when the actual tempering is performed in more than one cycle.

MATERIAL DATA
CCT-AND TTT-DIAGRAMS

At the start of the present study CCT-diagrams were available for both materials but a TTT-diagram was available only for ORVAR SUPREME. Since the simulation model requires TTT-diagrams for isothermal transformation this diagram was evaluated for DIEVAR by fitting Avrami parameters according to equation 2. The CCT-diagram measured by Uddeholm Tooling and the corresponding evaluated TTT-diagrams of DIEVAR are shown in 2 and 3, respectively. The curves of the TTT-diagrams indicate 1 and 99 per cent transformation.

A measured TTT-diagram DIEVAR is now available, Fig. 4. Its bainite nose is located at lower temperature but at shorter time in comparison to the estimated TTT-diagram of Fig. 3. Although there is a difference between the two TTT-diagrams they will produce a similar result when they are converted to CCT-diagrams.

It must be pointed out that with equation 2 a given TTT-diagram can quite easily be transformed into a CCT-diagram while the reverse is more complicated. A number of trials are required in order to locate the isothermal transformation noses in such a way that an acceptable CCT-diagram is produced. It is not evident that a unique TTT-diagram exists that corresponds to a given CCT-diagram. Thus the method may produce a TTT-diagram that differs somewhat from what would be the result of a measurement.

The measured TTT-diagram of ORVAR SUPREME is shown in Fig. 5

MECHANICAL AND THERMO-PHYSICAL DATA

Some of the material data used in the present simulations have been given in previous reports. The data of ORVAR SUPREME were reported in [1]
and later re-evaluated [5]. For DIEVAR the material data except phase transformation data were taken from the data of ORVAR.

RESULT OF NUMERICAL SIMULATIONS

OVERVIEW OF SIMULATIONS

In the present study previous results from gas quenching experiments on blocks of ORVAR SUPREME and DIEVAR are used to verify the prediction of distortion and to investigate the possibility to reduce distortion by selecting a material with higher hardenability. Heat treatment simulations include gas quenching and tempering. An overview of the heat treatment parameters and simulations is given in Table 2 and Table 3.

VERIFICATION

An experimental study of gas quenching distortion of two hot work tool steels was made by Uddeholm Tooling [1]. For similar heat treatments
Figure 3. TTT-diagram of DIEVAR estimated from the CCT-diagram of Fig 2.

Table 2. Heat treatment parameters for the two steels

<table>
<thead>
<tr>
<th>Steel</th>
<th>Austenitising temperature [°C]</th>
<th>Tempering Temperature/time</th>
</tr>
</thead>
<tbody>
<tr>
<td>ORVAR SUPREME</td>
<td>1020</td>
<td>2 × 2 h at 525 °C</td>
</tr>
<tr>
<td>DIEVAR</td>
<td>1020</td>
<td>2 × 2 h at 560 °C</td>
</tr>
</tbody>
</table>

the distortion was quite similar for the two steels DIEVAR and ORVAR SUPREME. One of the heat treatments studied was gas quenching at 3 bar pressure of blocks with dimensions 610 × 203 × 500 mm. The temperature was recorded at the centre of the block. After quenching and tempering the distortion was measured.

It was here attempted to reproduce this heat treatment with numerical simulation. From the temperature curve the heat transfer coefficient was evaluated by fitting. Initially a single constant heat transfer coefficient for
Figure 4. Measured TTT-diagram of DIEVAR austenised at 1025 °C.

Table 3. Heat treatments simulated in the present study

<table>
<thead>
<tr>
<th>No.</th>
<th>Heat treatment</th>
<th>Component geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ORVAR SUPREME</td>
<td>Gas cooling with 3 bar (N_2)</td>
</tr>
<tr>
<td>2</td>
<td>DIEVAR</td>
<td>Gas cooling with 3 bar (N_2)</td>
</tr>
<tr>
<td>3</td>
<td>ORVAR SUPREME</td>
<td>Gas cooling with 3 bar (N_2)</td>
</tr>
<tr>
<td>4</td>
<td>DIEVAR</td>
<td>Gas cooling with 3 bar (N_2)</td>
</tr>
<tr>
<td>5</td>
<td>ORVAR SUPREME</td>
<td>Gas cooling with 15 bar (N_2)</td>
</tr>
</tbody>
</table>

all surfaces was tested. The best agreement in experimental and computed temperature was obtained with a heat transfer coefficient of 95 Wm\(^{-2}\)K\(^{-1}\). However it was evident from the distortion that the cooling was not uniform. Thus, since the flow was parallel to the thickness direction of the block it was assumed that one of the surfaces perpendicular to the flow had a lower heat transfer coefficient. An attempt with heat transfer coefficient of 130 and 32.5
Wm$^{-2}$K$^{-1}$ respectively gave a reasonable agreement for the temperature at the centre, as shown in Fig. 6.

The difference between the computed cooling curves of the two materials is due to the fact that ORVAR SUPREME produces more bainite than DIEVAR and accordingly produces transformation heat at higher temperature.

The computed distortion of the ORVAR SUPREME block is shown in Fig. ???. The main distortion is the thickness growth, which takes place mainly on the top surface due to the non-uniformity in cooling.

The computed and experimental distortion in three sections of the block is compared in Fig. 8. The computed distortion is presented at the locations where the measurements were made. The agreement between computed and experimental distortion must be considered as fully satisfactory.

The corresponding heat treatment for the DIEVAR block of the same dimensions gave a similar distortion pattern. The experimental and computed results are shown in Fig. 9. It also shows approximately the same agreement with experiments.
Figure 6. Experimental and computed temperature at centre of block during gas quenching. Computations of ORVAR SUPREME and DIEVAR differ during phase transformation.

Figure 7. Computed distortion of ORVAR SUPREME block of dimensions $610 \times 203 \times 500$ mm after gas quenching at 3 bar gas pressure. The displacements are magnified 50 times.

The same heat treatment, gas quenching with 3 bar pressure, was also applied to blocks of smaller dimensions. In the simulation of this heat treatment the same heat transfer coefficients were used as for the larger block. The experimental and computed distortion of blocks with dimensions $508 \times 127 \times 500$ mm are compared for ORVAR SUPREME in Fig. 10 and for DIEVAR in Fig. 11. The agreement between experimental and computed
distortion is similar or even better than what was obtained for the larger blocks.

**UTILISING HIGH HARDENABILITY OF TOOL STEEL**

The above experiments and simulations indicate that at similar cooling rates the two steels ORVAR SUPREME and DIEVAR become similarly distorted. However, ORVAR SUPREME has a lower hardenability and will usually require higher cooling rate to assume the same hardness as DIEVAR. The present simulations do not produce exact hardness values but the computed temperature curve can be compared to given hardness values of a CCT-diagram. Also, in terms of bainite content a significantly higher cooling rate would be required for ORVAR SUPREME to produce a similar hardening result as obtained for DIEVAR. The bainite content of the large DIEVAR block was only a few per cent while the ORVAR SUPREME block had about 70 per cent bainite at the centre, see Table 4.
In order to illustrate the indirect effect of increased hardenability by choosing a lower cooling rate a simulation was run corresponding to quenching of the $610 \times 203 \times 500$ mm ORVAR SUPREME block at 15 bar gas pressure. This significantly reduced the amount of bainite but it was still somewhat higher than what was obtained with DIEVAR at 3 bar. According to the

![Diagram of DIEVAR block](image)

**Table 4.** Computed volume fractions of bainite at the core and at the surface of blocks of ORVAR SUPREME and DIEVAR

<table>
<thead>
<tr>
<th>Steel</th>
<th>Block dimensions [mm]</th>
<th>Gas pressure [bar]</th>
<th>Approximate volume fraction of bainite [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Core</td>
</tr>
<tr>
<td>ORVAR SUPREME</td>
<td>$610 \times 203 \times 500$</td>
<td>3</td>
<td>70</td>
</tr>
<tr>
<td>DIEVAR</td>
<td>$610 \times 203 \times 500$</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>ORVAR SUPREME</td>
<td>$508 \times 127 \times 500$</td>
<td>3</td>
<td>17</td>
</tr>
<tr>
<td>DIEVAR</td>
<td>$508 \times 127 \times 500$</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>ORVAR SUPREME</td>
<td>$610 \times 203 \times 500$</td>
<td>15</td>
<td>30</td>
</tr>
</tbody>
</table>

**Figure 9.** Experimental and computed distortion of gas quenched DIEVAR block. The displacements are magnified 50 times.
CCT-diagrams these heat treatments should produce similar hardness of the two materials, approximately 590 HV, as indicated by Fig. 12.

The resulting distortion involves a significant thickness growth at the centre of the block as shown in Fig. 13. This distortion is approximately twice as large as the distortion at 3 bar gas pressure. Especially the comparison with the DIEVAR block is of interest since it would probably have a similar hardness after quenching at 3 bar as the ORVAR SUPREME block quenched at 15 bar. The distortion from these two simulations is compared in Fig. 14.

This test illustrates well the potential to improve distortion by selecting a steel of higher hardenability.

DISCUSSION

The non-uniformity of the temperature field during quenching is an essential factor that creates distortion. In order to produce a high cooling rate in a large component a substantial temperature difference between surface and core is inevitable. Heat treatment distortion of large components may thus be quite substantial. Increasing the hardenability of a material that is used
Increasing the hardenability means changing the phase transformation properties. In the general case it is not evident how this will influence the distortion if the increased hardenability is not utilised for reduced cooling rate, but for increasing the hardness. In the numerical and experimental tests performed here, it was found that DIEVAR blocks produce similar or slightly less distortion than ORVAR SUPREME blocks even at the same cooling conditions.

In the present study most material data of DIEVAR were assumed to be identical to the material data of ORVAR SUPREME and furthermore the heat transfer was not measured in detail. In spite of this a reasonable agreement was found between computed and experimental distortion.
Figure 12. Computed temperature at centre of ORVAR SUPREME block quenched at 15 bar and DIEVAR block quenched at 3 bar and corresponding CCT-diagrams. Block dimensions 610×203×500 mm.
CONCLUSIONS

The distortion from gas quenching of blocks of the tool steels ORVAR SUPREME and DIEVAR was investigated with numerical simulation.

- Computed distortion of gas quenched blocks of ORVAR SUPREME and DIEVAR was well in agreement with experimental distortion from previous heat treatment trials.
The distortion of the gas quenched blocks of ORVAR SUPREME and DIEVAR was similar at a given cooling rate. For one specimen dimension, however, the distortion was somewhat larger for ORVAR SUPREME than for DIEVAR.

Similar hardness was predicted when gas quenching two blocks of 203 mm thickness, a DIEVAR block quenched with 3 bar gas pressure and an ORVAR SUPREME block quenched with 15 bar gas pressure. The distortion of the ORVAR SUPREME block was approximately twice as large as for the DIEVAR block, indicating that the distortion at equal hardness is significantly lower for the steel of the highest hardenability.

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REFERENCES


