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Simulation of Quenching Treatments on Bearing Components

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Bearing components with an improved product performance are a challenging task. While the components should decrease in size, higher loads should be applied while simultaneously the life cycle time should be increased. To fulfil these requirements, the desired product properties are mainly set during the heat treatment, specifically during the quenching process, so further development of these processes is considered relevant for future generation products.

To minimize the amount of testing, computer simulations of the effects from heat treatments on the resulting properties are increasingly used as a development tool. This paper describes the attempt to simulate the quenching of a cylindrical ring made of SAE 52100 bearing steel quenched in salt, followed by an isothermal transformation, in order to understand and predict the hardening process with respect to phase transformations and residual stress generation.

Keywords: heat treatment, quenching, hardness, bainite, residual stresses

0 INTRODUCTION

It is obvious that the residual stress distribution after heat treatment is mainly influenced by the quenching history of the component as at this stage of the manufacturing process, strong temperature gradients inside the component will be present. To minimize the amount of testing, computer simulations of the effects from heat treatments on the resulting properties are increasingly used as a development tool. This paper describes the attempt to simulate the isothermal bainitic transformation of SAE 52100 bearing steel (100Cr6) in order to understand and predict the hardening process with respect to phase transformations and stress generation respectively. The simulations were performed with the FE-software SYSWELD®. The calculations are divided into two parts: a thermo-metallurgical calculation, in which the temperature field and the resultant phase transformations in the steel are simulated, and a calculation of the mechanical response of the component.

Temperature and residual stress measurements were performed on a test component to verify the results obtained from the simulations. Finally, a comparison of the measurement and simulation results is given and discussed. Here, it is shown that the isothermal bainitic transformation is strongly stress dependent. Similar tests were performed earlier, revealing a good agreement of measured and simulated values[6].

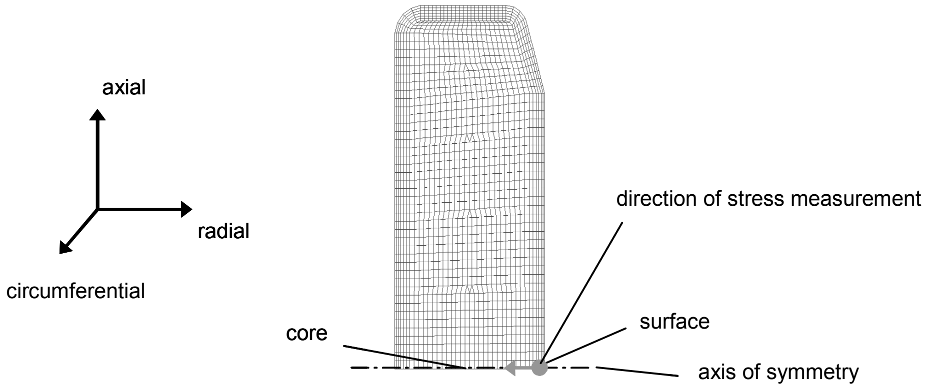

Fig. 1. *FE-mesh of a cylindrical ring*

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1 RESULTS FOR A CYLINDRICAL RING QUENCHED IN SALT FOLLOWED BY AN ISOTHERMAL TRANSFORMATION

The results below represent both, simulations and measured cooling curves and residual stress data for a cylindrical ring (outer diameter 120 mm, wall thickness 10 mm, height 46 mm) quenched and isothermally transformed in salt. The mechanical simulations were performed considering kinematic strain hardening.

1.1 Cooling Curve Analysis

Fig. 2 gives a direct comparison between measured and simulated cooling curves for saltbath quenching. The transfer to the saltbath takes around 30 seconds. The heat transfer coefficient value used was 2500 W/m²K for the whole surface and was obtained from literature [6]. The quench bath temperature was kept constant at 235 °C throughout the whole process. It can be observed that the simulated cooling curves coincide rather well at the beginning of the process but the deviation from the measured cooling curve becomes stronger below 550 °C. However, an acceptable curve fit should be feasible with the representative and constant heat transfer coefficient value that is characteristic for quenching in salt and cooling by convection only.

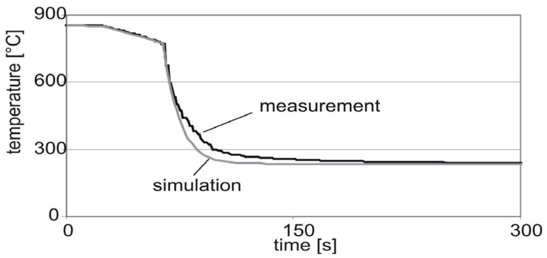

Fig. 2. *Core cooling curve during salt quenching*

1.2 Comparison of Measured and Simulated Residual Stresses

In Fig. 3a comparison of the final measured and simulated residual stress state is given. The stresses were measured with different techniques, i.e. the bore hole method where a hole is drilled into the ring while the released stresses are measure with a strain gauge and by x-ray diffraction. To achieve a depth profile, some material was removed by etching. Some near surface differences in values are visible for the three techniques. However, after 0.2 mm there is no great visible difference between the data from the three methods. The simulated results are always outside the spread of the different measurement methods. It must be stated that it was not possible to predict a compressive residual stress state in the ring as it is common for most bainitic heat treatments of SAE 52100.

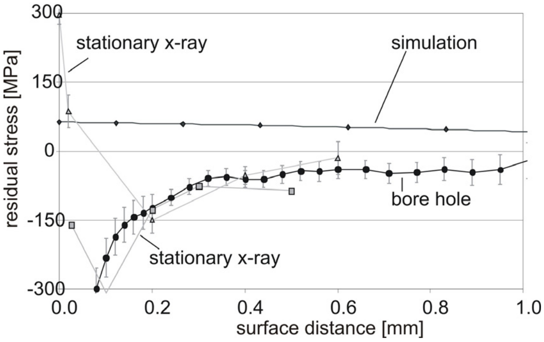

Fig. 3. *Tangential residual stresses after salt quenching*

1.3. Stress Development

Fig. 4 shows the resulting stress development of a ring quenched and isothermal transformed in salt. The increasing temperature difference between the core and the surface upon quenching initially causes the surface stresses to become tensile, while the stresses in the core become compressive, as can be seen in Figure 4.

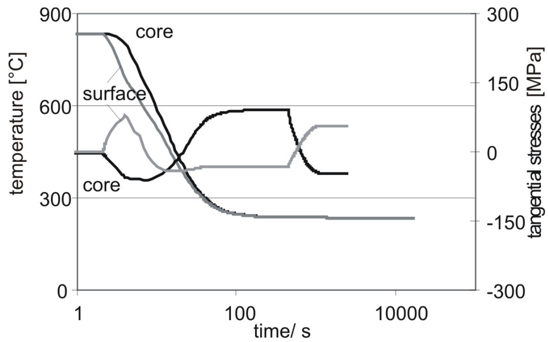

Fig. 4. *Stress development during salt quenching followed by an isothermal transformation for 4 h at 235 °C.*

At the largest temperature difference between the core and the surface, the stresses reach a maximum point and start to diminish.

Due to local plasticification, the surface stresses are becoming compressive upon temperature equalisation (~235 °C). The formation of bainite at the transformation temperature (235 °C) begins slightly earlier than the equalisation of temperature. After 4 h the whole volume of the ring is transformed to bainite. However, the final residual stress state is tensile for the surface, which is contradictory to the performed measurement.

It can be concluded that the simulation of the bainitic through hardening process was not successful. As a result, further work is needed in order to understand why the chosen model delivers incorrect values for the stress development and the final residual stress state. In order to obtain a better cooling curve fit and to further improve the simulation results regarding the final residual stress state, further simulations were performed.

1.4 Cooling Curve Sensitivity Analysis

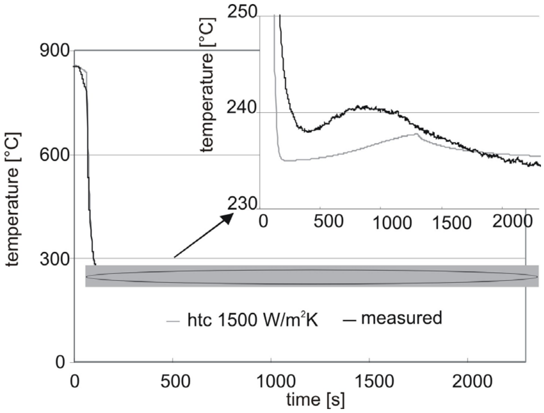

Fig. 5. *Measured and simulated core cooling curves during salt quenching*

Fig. 5 shows a comparison of measured and simulated core cooling curves. The heat transfer coefficient value was reduced from 2500 down to 1500 W/m²K resulting in a better cooling curve fit, as found in literature. Nevertheless, a certain temperature difference in the regime of 237 °C is still apparent. Attempts were made to minimize this temperature difference by changing the value of heat conduction by 50%, but the disparity was still apparent.

Further attempts were made considering a different transformation behaviour, by applying a two step JMA approach (Hunkel, et al. [5]) in comparison to the one step approach used before, and heat transfer coefficient values but with limited effect on the calculated final residual stress state.

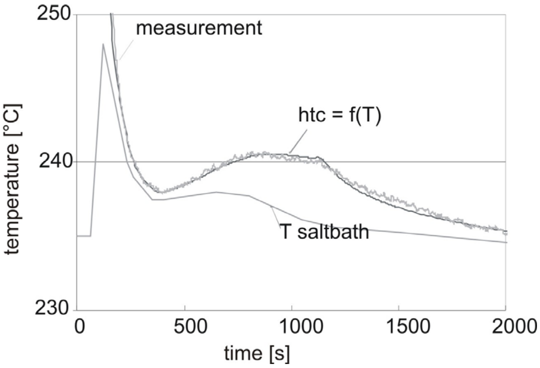

Fig. 6. *Measured and simulated cooling curves during salt quenching*

However, to finally obtain a satisfactory cooling curve fit, a temperature dependent heat transfer coefficient down to 300 °C, decreasing from 2500 to 1000 W/m²K, and at lower temperatures a constant value of 1000 W/m²K, was applied. The saltbath temperature was increased, as indicated in Figure 6, and finally the constants for the JMA-equations were varied.

Nevertheless, even with these strong changes resulting in a nearly perfect cooling curve fit, the reviewed approach had no effect on the calculated final residual stress state.

1.5 Influence of Stresses on the Isothermal Transformation

Denis (Denis et al. [4]) discovered that the effects occuring during the transformation might have an influence on the internal stress state, especially if temperature gradients are small i.e. as they are in isothermal treatments. According to Bhadeshia [1], the deviatoric stresses will decrease the transformation time, while the hydrostatic stresses will increase it.

Dalgic et al. [2] and [3] showed that tensile stresses applied during an isothermal transformation will decrease the transformation time, while applied compressive stresses resulted both in decreased and increased transformation times in comparison to unstressed test specimens, Fig. 7. The differences for -100 MPa result from a slight temperature deviation at the beginning of the transformation.

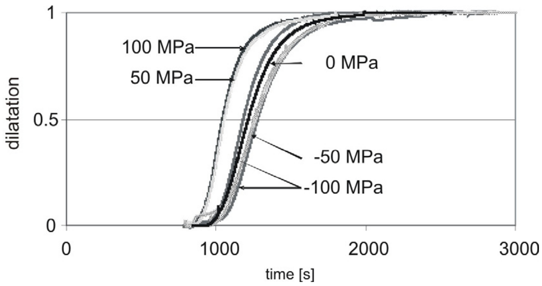

Fig. 7. *Resulting dilatation for an isothermal transformation at 300 °C under tensile and compressive stresses*

Based on these findings, it was decided to couple the thermo-metallurgical calculation with the mechanical calculation in both directions in order to establish the stress influence on the isothermal transformation. Considering the transformation parameters to be stress dependent the corresponding stress development changed noticeably in comparison to the prior calculations, see Fig. 8. In comparison to Fig. 4 where the stress influence is neglected, it was possible to influence the stress development. The calculations were performed under the consideration of optimised heat transfer coefficient values, including a transport stage from the furnace to the saltbath. The mechanical calculations were performed considering a mixed strain hardening law with 50% kinematic and 50% isotropic hardening. The stress dependency of the transformation was considered after 50 s.

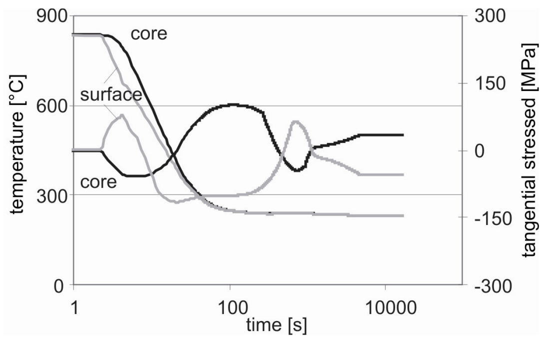

Fig. 8. *Stress development during salt quenching followed by an isothermal transformation for 4 h/ stress dependent transformation parameter*

While the stress development remains unchanged for the first 50 s, strong changes become apparent as the transformation begins. Due to the incorporated stress influence, the transformations start somewhat earlier in the core than in the surface area. This is due to the presence of tensile stresses in the core and compressive stresses in the surface area at that point. This effect results in a change in the stress development in comparison to Fig. 4. The transformation is completed somewhat later in the surface area than in the core. Due to this effect, the stress development is influenced in such a way that the surface area shows compressive residual stresses, while tensile residual stresses are present for the core, as the ring is fully transformed to bainite.

However, the stress dependence had to be implemented into the software since using a user routine as a stress influence on phase transformations is usually neglected. This resulted in a dramatical increase of calculation time for this process. However, it must be noted that this user routine was not optimized to reduce the resulting calculation time.

2 DISCUSSION OF RESULTS

The output from the performed simulations gives an overview of the stress development in a cylindrical ring during quenching. Furthermore, residual stress states and phase proportions after quenching were shown. Finally, the interaction of isothermal phase transformations in SAE 52100 steel and stress development was presented.

The simulations with a constant heat transfer coefficient value of 2500 W/m²K for salt quenching followed by isothermal bainitic transformation revealed a mismatch between measured and simulated cooling curves and resultant residual stresses. By changing the heat transfer coefficient values and the constants for the phase transformations it was possible to improve the simulation to achieve an improved cooling curve fit, although a good agreement for the final residual stress state could initially not be achieved.

The incorporation of stress dependent constants for the JMA-equations resulted in a different stress development, showing compressive residual stresses for the surface area and tensile residual stresses for the core, so that finally a good agreement between measured and simulated residual stress values could be obtained.

3 CONCLUSIONS

The performed quenching simulations with the chosen software package and selected material data revealed that satisfactory results could be obtained for bainitic through hardening of SAE 52100 components. However, the performed simulation revealed that a good agreement between the measured and simulated residual stress values could only be obtained if the thermo-metallurgical calculation is coupled with the mechanical one. This is usually not the case in the chosen software package.

It has been shown that if the calculations are coupled, a good agreement between measured and simulated residual stress values can be obtained. However, the stress influence on the bainitic transformation is difficult to establish.

Nevertheless, a final confirmation of this approach can only be obtained by applying in-situ stress measurements, recording the stress development at the surface of a test component during the whole process.

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