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Prediction of Quench Distortion on Steel Shaft with Keyway by Computer Simulation

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Abstract

During quenching, steel shafts tend to distort much more if they contain a keyway. Non-uniform cooling due to the non-axisymmetric shaft geometry may induce the additional distortion. Distortion measurements were obtained from a number of shaft steels and quenchants to compare alloy and cooling effects. The experiments were simulated using the Finite Element Method (FEM) system DEFORM™-HT, with estimated surface heat transfer coefficients.

Quench distortion is a commonly encountered problem in metal processing industries. It is usually due to non-uniform cooling of the workpiece during quenching. Despite the numerous studies on this phenomenon, it remains very complex and cannot be well predicted quantitatively without experiments.

The complexity of quench distortion is attributed to the numerous influencing factors involved in the phenomenon. Material, thermal, plastic, and elastic properties may play significant roles, which can be further complicated when phase transformations are involved. The properties of the quenchants and workpiece-quenchant interface are also very important and often difficult to characterize.

The quenching of a steel shaft containing a keyway was studied experimentally in order to obtain the actual processing data and distortion results. Heat transfer coefficients between the quenchants and the workpiece were measured experimentally.

The Finite Element Method (FEM) system DEFORM™-HT [1] was used for simulating the quenching processes. Input material constants and processing data were obtained from available literature and experiments. The simulation results were evaluated against the experimental data.

Experimental Method

The Japanese standard S45C steel was used in the current work and its nominal composition is given in Table 1. The starting geometry and dimensions of the test specimens are illustrated in Fig. 1, which shows a cylindrical shaftt, 10mm diameter and 100mm in length, containing a keyway, 2.5mm deep and 4mm wide. Certain specimens were instrumented with thermocouples to measure local temperature as a function of time during quenching.

Table 1. Nominal composition of S45C steel.

Steel	C	Si	Mn	P	S	Cu	Ni	Cr
S45C	0.44	0.20	0.77	0.015	0.024	0.01	0.03	0.15

Prior to quenching, austenitizing was carried out on the specimens via electric furnace heating for 20 minutes at a temperature of 850°C. Two types of quenchants, city water and 10% polyalkylen glycol (PAG) solution, both at 30°C were employed without agitation.

Heat transfer coefficients for the workpiece and quenchant combinations were calculated using the Lumped-Heat-Capacity method, from cooling curve data of a silver probe, 10mm in diameter and 30mm long, immersed in the same quenchant [2].

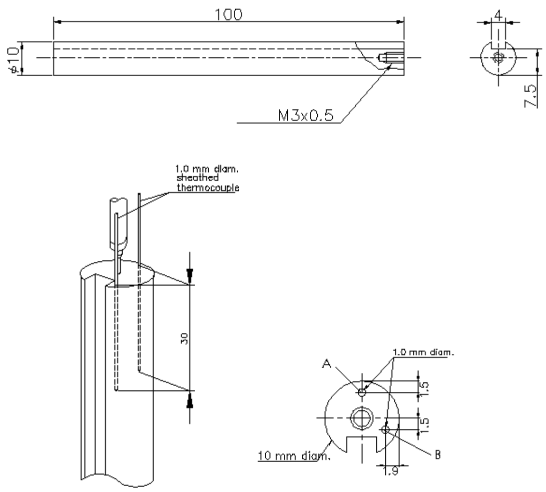


Figure 1. Specimen dimensions and location of instrumented specimen thermocouple holes.

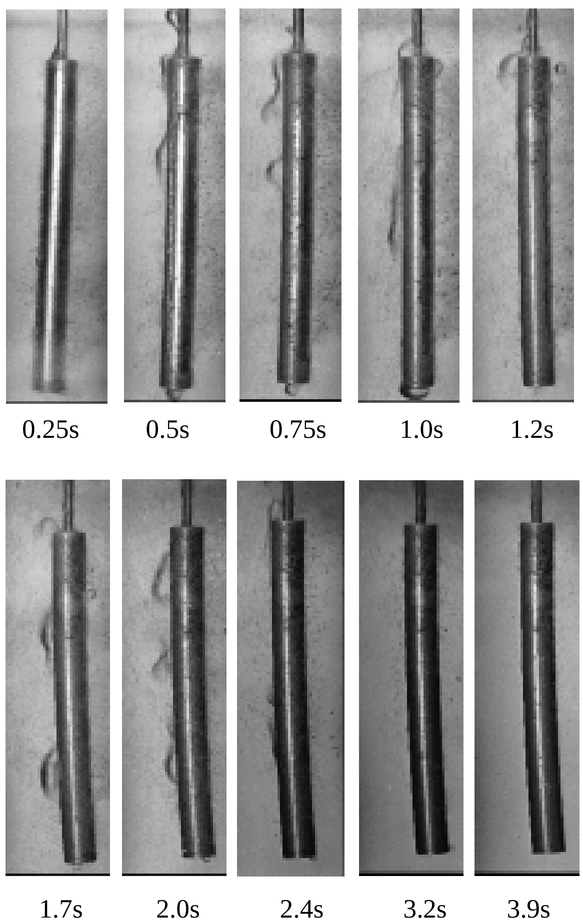


Figure 2. Boiling behavior and distortion during quenching in still city water at 30°C. Keyway is on left side of specimen.

Experimental Results

The boiling characteristics and specimen distortion during quenching were recorded by video, as displayed in Figs. 2 and 3. Significant differences were observed between the boiling characteristics of the city water and the PAG solution quenchants. During water quenching, the progressive collapse of the vapor blanket started from the keyway side (the left side in Fig. 2). In contrast, the polymer quench provided an all over, explosive vapor film collapse, followed by polymer separation (Fig. 3).

The cooling curves from locations A and B (Fig. 1) and the distortion of the shaft were measured with thermocouples and a Formcorder EF-150 from Kosaka Lab. Ltd.

The hardness distribution of the final workpiece cross section is displayed in Fig. 4. For both the water and PAG solution quenching, the hardness values are almost all in the range 55 ~ 60 HRC suggesting that the steel is primarily martensite.

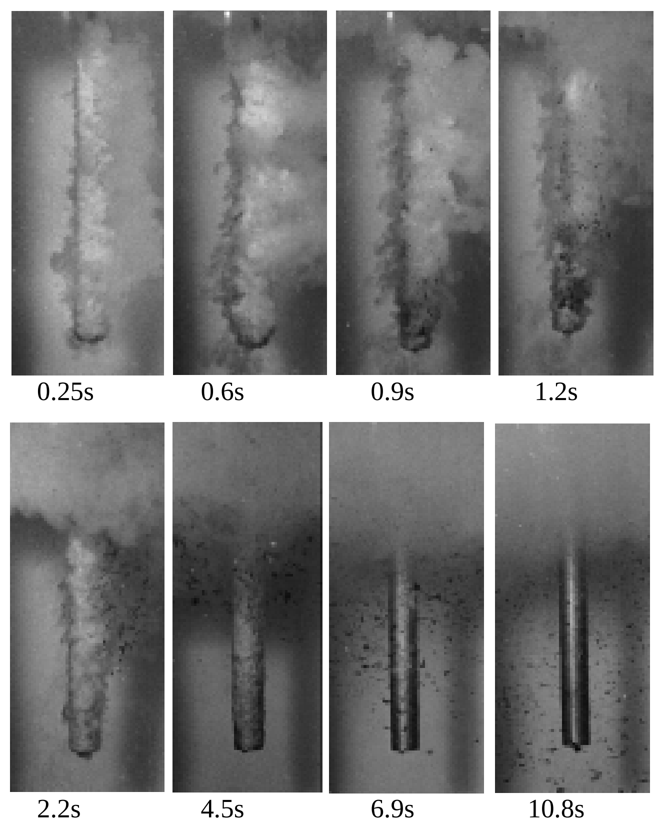


Figure 3. Boiling behavior and distortion during quenching in still 10% PAG solution at 30°C. Keyway is on left side of specimen.

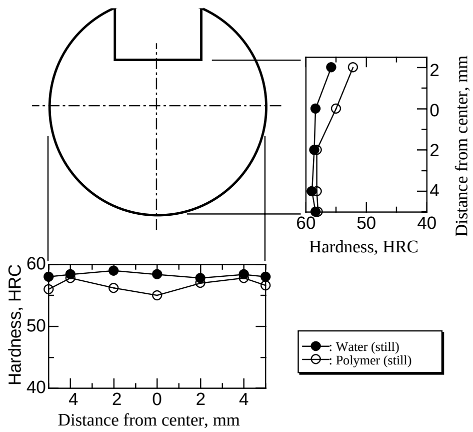


Figure 4. Measured hardness distribution of the shaft cross-section.

Heat transfer coefficients for the simulations can be found in Fig. 5 (a) and (b) for water and 10% PAG solution respectively. This data has been modified to minimize the errors due to the differences in material and shape between the steel workpiece and silver probe [3]. In the case of water quenching, the edges of the keyway were treat as special regions, with heat transfer coefficients greater than the remainder of the section, for higher temperatures.

Simulation Setup

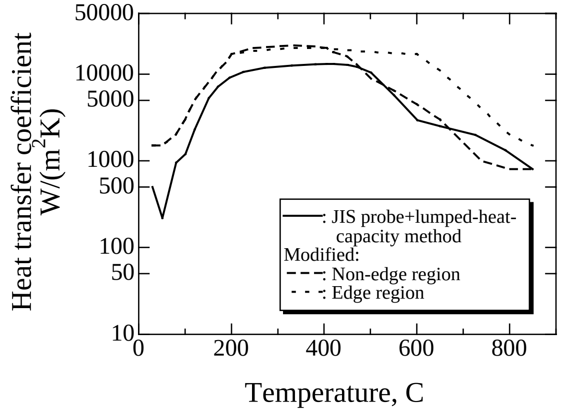
As mentioned previously, quench distortion involves a number of influencing factors: non-uniform temperature distribution, non-uniform thermal contraction and phase transformation volume changes.

Non-uniform temperature distribution is the fundamental reason for quench distortion. Thermal properties such as heat capacity, thermal conductivity, heat transfer coefficient, and phase transformation latent heat, which determine the local cooling curves, are therefore essential.

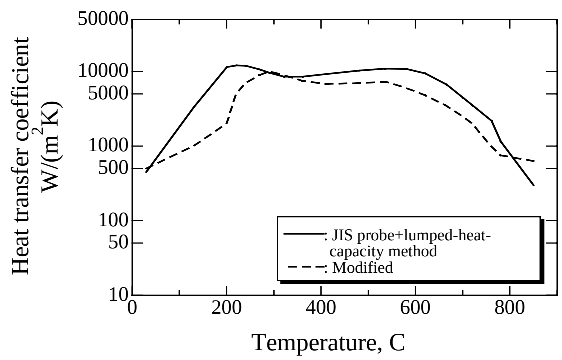
Non-uniform thermal contraction induced by the non-uniform temperature will cause tension at rapidly cooled locations and compression in less rapidly cooled areas during quenching. Plastic deformation caused by these tensile and compressive stresses is an important reason for the distortion. Thus, an elasto-plastic material model was utilized. Thermal expansion coefficients, elastic modulus, flow stress, and hardening rules are necessary material data.

Phase transformation volume changes are additional sources of distortion. Consequently, transformation plasticity data is also required.

DEFORM™-HT was used to simulate the water and polymer quench processes. All of the above mentioned influencing factors were included in the modeling runs. All material data with exception to heat transfer coefficients were obtained from the available literature. In the main part, all of the material data was as a function of temperature and/or stress.



a) Still water quenching (30°C) Edge region is defined as region within 1mm from the keyway edge.



b) Still 10% PAG polymer quenching (30°C)

Figure 5. Measured heat transfer coefficients as a function of temperature.

All metallurgical phase transformations were considered in the modeling. The material was regarded as a mechanical mixture of three phases: austenite, pearlite and martensite, each of which was assigned an independent set of material data properties.

The simulated hardness distribution was computed from individual phase hardness values using the mixture rule.

A tetrahedral mesh containing approximately 33,000 elements was applied to one half of the workpiece; symmetry conditions were applied to the center surface. The workpiece and it's tetrahedral mesh is shown in Fig. 6.

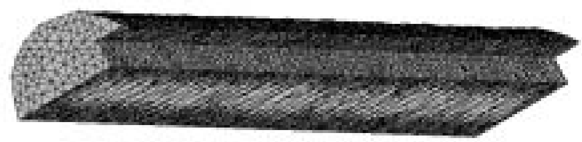


Figure 6. FEM mesh of one half of the keyed shaft workpiece.

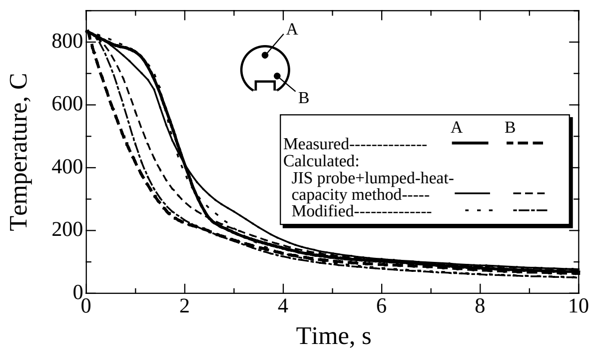


Figure 7. Measured and simulated cooling curves at locations A and B during water quenching.

Simulation Results and Discussion

The measured cooling curves at locations A and B (see Fig. 1) are shown in Figs. 7 and 8 for water and polymer quenching, respectively. In addition, predicted temperature point tracking curves for the corresponding locations in the simulated workpiece are shown in Figs. 7 and 8. Excellent correlation can be seen between experimental and predicted temperature curves.

The simulated quench distortion history was compared to the observations from the video of the actual component quenching. Excellent correlation is evident as can be seen by comparing Figs. 2 and 9. In both experiment and simulation, the shaft bent toward the keyway side initially, and then bent the opposite way after 1.2 seconds. The authors propose that the initial deflection arises from the early thermal shrinkage on the keyway side; the subsequent distortion (after approximately 1.1s) is initially a result of the early volume expansion of martensite in the keyway location. The authors believe that the final distortion results from the tensile plastic strain, accumulated during the initial second of cooling, on the keyway side of the shaft.

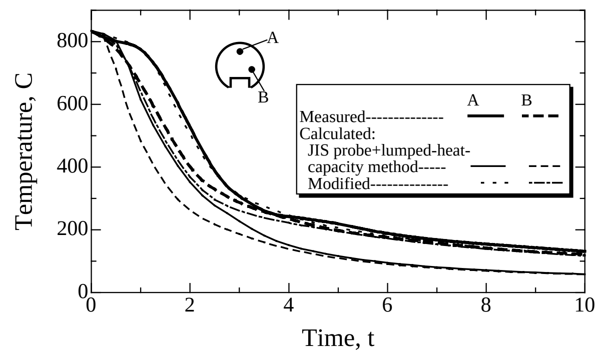


Figure 8. Measured and simulated cooling curves at locations A and B during polymer quenching.

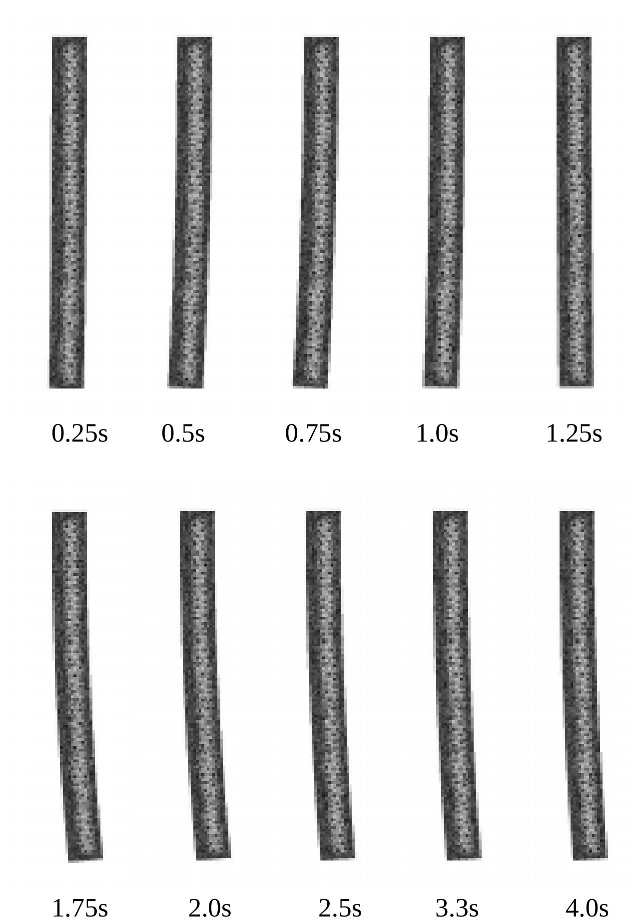


Figure 9. Simulated quench distortion history during water quenching

The final distortion profiles of the shaft can be seen in Fig. 10 in terms of deviation from the original straight center line. Predicted distortions correlated very well with experimental measurements for both water and polymer quenching.

Also shown in Fig. 10 is a case involving oil quenching; the heat transfer coefficient and experimental details of which are not detailed in this paper, but simulated distortion is approximately 30% less than the actual component distortion. Nevertheless, the overall trends of the distortion still provide good correlation.

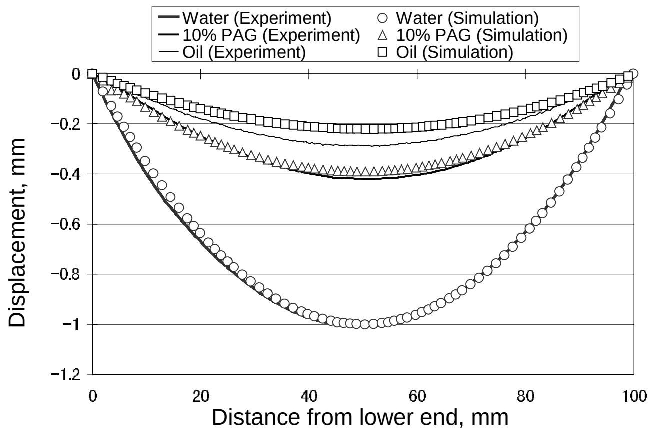


Figure 10. Final distortions of the steel shaft (positive defined as opposite to the keyway side).

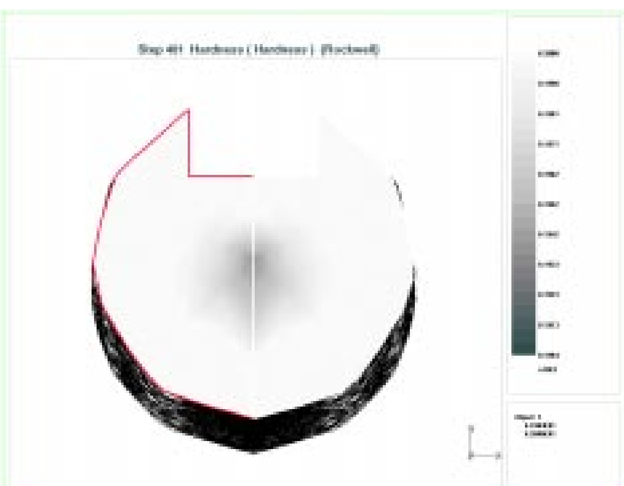


Figure 11. Predicted hardness in cross-section (PAG solution quenched).

The microstructure simulation predicted that martensite was the dominant phase after quenching. Marternsite volume fraction ranged from 0.980 to 0.994 for the water-cooled case and 0.994 ~ 0.997 for the polymer solution-cooled case. In both cases the highest hardness values were on the outer regions of the shaft geometry and the lowest occurred in the central areas.

The predicted hardness in the specimen cross-section after polymer quenching is shown as a shaded contour plot in Fig. 11. This cross-section was taken at mid length of the workpiece. Comparing to the hardness measurements in Fig. 4, the modeling has slightly overestimated the hardness values but in general good correlation was achieved.

Conclusions

Quench distortion remains a complicated phenomena involving numerous material and processing factors. This process, however, can be successfully predicted by computer simulation if necessary input data are available and reasonably accurate.

Heat transfer coefficients are among the most difficult to obtain from the literature. They can be estimated by measurements from the JIS silver probe, with subsequent calculations from the Lumped-Heat-Capacity method.

Computer simulation by Finite Element System DEFORM-HT™ has given good simulation results on the quench process of a keyed steel shaft. The comparison of the simulation with the experiment revealed good matches on thermal history and excellent resemblance on quench distortion history. Overall trends and magnitudes of the final distortion were also successfully predicted, but as large as 30% quantitative discrepancies existed in the distortion after oil quenching. The simulation also gave close results on the hardness, but it diminishes the variations within the cross-sectional area.

Reference

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2 M. Narazaki, M. Kogawara, A. Shirayori and S. Fuchizawa, Proc. 18th Heat Treating Conference, ASM International, 509-517(1998)

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