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Characterizing Water Quenching Systems with a Quench Probe

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Abstract

Quench probes have been used effectively to characterize the quality of quenchants for many years. For this purpose a variety of commercial probes, as well as the necessary data acquisition system for determining the time-temperature data for a set of standardized test conditions, are available for purchase. The type of information obtained from such probes provides a good basis for comparing media, characterizing general cooling capabilities, and checking media condition over time. However, these data do not adequately characterize the actual production quenching process in terms of heat transfer behavior in many cases, especially when high temperature gradients are present. Faced with the need to characterize water quenching practices, including conventional and intensive practices, a quench probe was developed. This paper describes that probe, the data collection system, the data gathered for both intensive quenching and conventional water quenching, and the heat transfer coefficients determined for these processes. Process sensitivities are investigated and highlight some intricacies of quenching.

Introduction

Simulation of quench hardening processes requires an accurate description of heat transfer boundary conditions. This includes the quench medium, and the fluid flow interaction with the part being quenched. Conventional quench probes adequately characterize the quenchant, but the standardized tests do not provide heat transfer coefficients needed for modeling the quenching process. A custom probe was built specifically to measure cooling during intensive water quenching for the purpose of determining local heat transfer coefficients. Agitated and still water quenches were also characterized. Heat transfer coefficients were determined from the time-temperature measurements during quenching using an optimization method based on forward finite element calculations.

Probe Design

A 304 stainless steel bar was used as the probe body. A blind hole was drilled along the bar centerline to provide egress for thermocouples. The thermocouples were Inconel sheathed, type K thermocouples with grounded tips. Holes with diameters of 0.86 mm (0.034 in) were plunge EDM'ed and the 0.81 mm (0.032 in) diameter thermocouples were brazed into these holes with the tips flush to the bar surface. Figure 1 shows the design of the probe body.

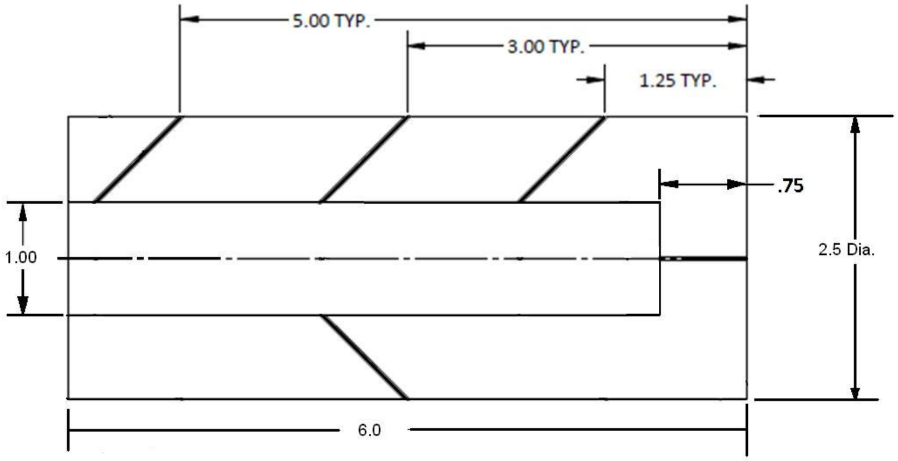


Figure 1: 304 Stainless Steel quench probe body (dimensions are in inches).

The probe had a threaded adaptor welded to end with the bore and a flexible stainless steel conduit was attached. The conduit held the thermocouple leads and protected them during service. The thermocouples were attached to a data acquisition system for recording temperature as a function of time during both heating and quenching. During heating, temperatures were stored every second for each thermocouple, and during transfer to the quench station and quenching, readings were stored at a rate of 100 data points per second for each thermocouple.

Experimental Procedures

The probe was supported in a stand during heating in a standard box furnace with a protective atmosphere, as shown in Figure 2. The probe was charged into a furnace heated to 875° C and held until fully soaked. It was then withdrawn from the furnace and transferred to either the station for intensive water quenching or to a water tank for agitated or still water quenching. For intensive quenching, the average water velocities were set at 6.6 m/s or 4.2 m/s.

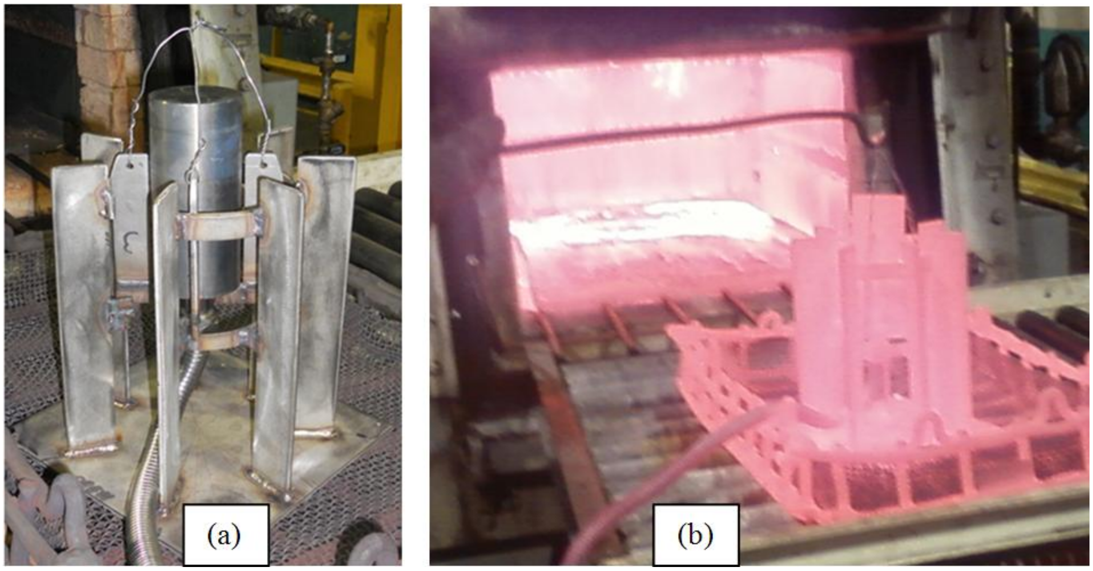
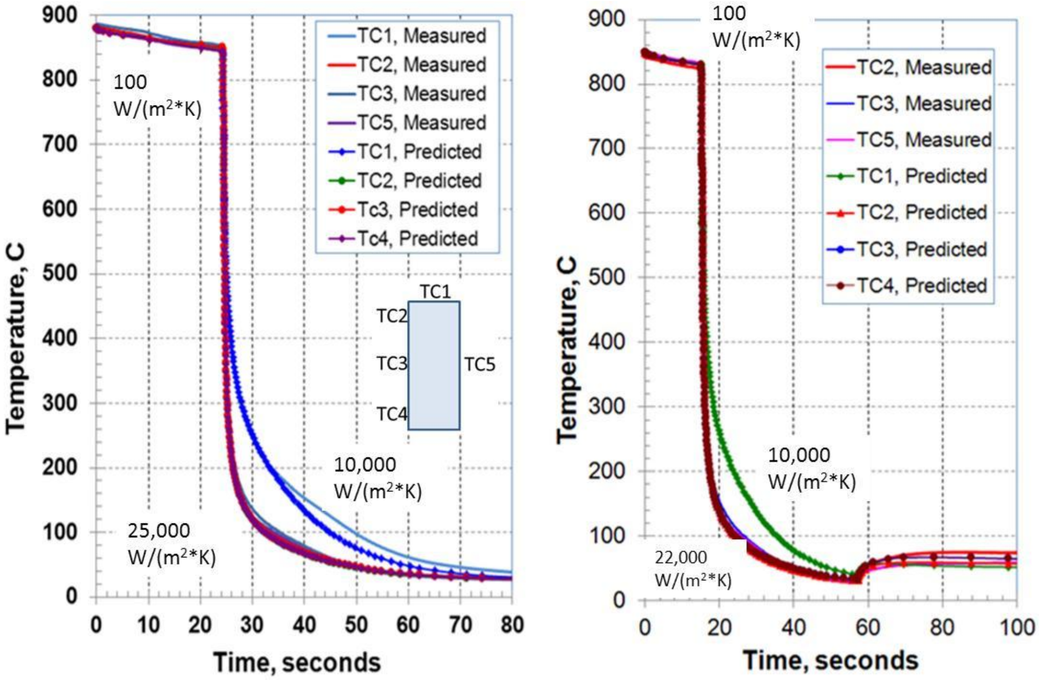


Figure 2: (a) Cold probe mounted in stand prior to heating. (b) Hot probe and stand after furnace heating.

Results & Discussion

The time-temperature data and calculated heat transfer coefficients are shown in Figure 3 for the intensive quenching experiments. The thermocouple locations are indicated in the schematic inset of the probe in Figure 3. Thermocouple #1, located at the center of the top surface, had a slower cooling rate and a lower heat transfer coefficient since a stagnant flow zone developed as the water flowed down around the cylindrical probe. The other thermocouples had nearly identical time-temperature curves and essentially the same heat transfer coefficient. The cooling conditions down the barrel of this 152 mm (6 inch) long cylinder were identical.

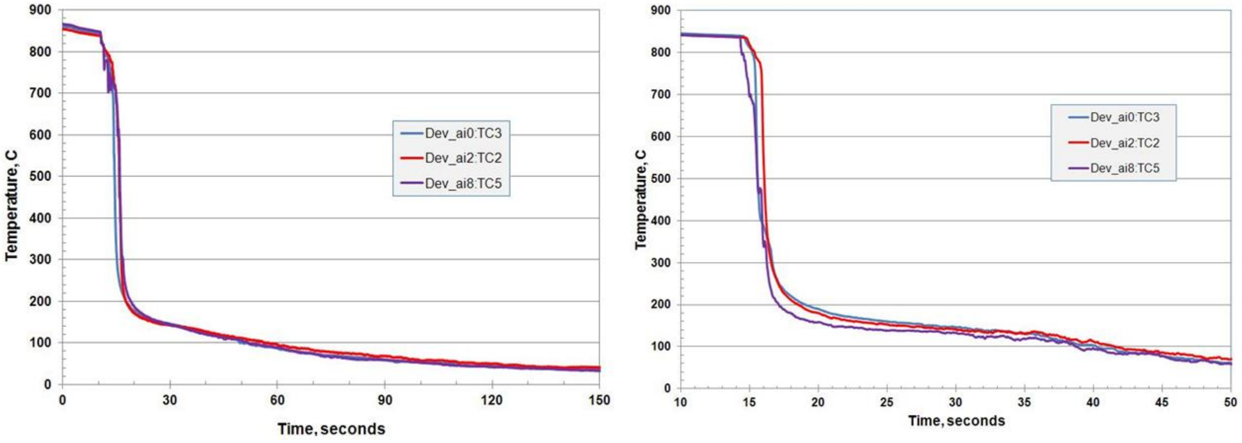
The heat transfer coefficient (HTC) values reported in Figure 3 were determined using an optimization method to drive the DANTE® heat treatment models. Several points are important in this calculation. First, the method is forward based, meaning that the temperature of the probe is initially at the furnace temperature and the entire cooling process is simulated. The HTC during the short air transfer time was considered and determined to be 100 W/(m^2·C), as reported in Figure 3. Second, by performing a forward calculation, the phase transformation behavior of the material can be accounted for and latent heat can therefore be included. In this case, the probe was austenitic and there were no phase transformations that occurred so this is a moot point. However, for time-temperature measurements made on actual parts from alloy steels with transformations, the capability to include the phase transformations in determining HTC's is critical. Third, by virtue of using thermocouples that measure surface temperature while having a negligible impact on local surface phenomena, the calculations to determine HTC's are simplified. Fourth, the value of the HTC was found to be relatively constant during both intensive quenches, indicating that film boiling did not occur and that nucleate boiling of the water was present only briefly, if present at all. The values along the barrel of the probe were calculated to be 25 kW/(m^2·C) and 22 kW/(m^2·C) for the 6.6 m/s and 4.2 m/s water flow rates, respectively.



(a) 6.6 m/s water flow rate. *(b) 4.2 m/s water flow rate.*

Figure 3: Measured and predicted time – temperature curves for intensive quenching.

Figure 4 shows time-temperature measurements for agitated and still water quenches of the probe. The data show the air transfer period, film boiling immediately upon immersion into the water tank, nucleate boiling, and final convective cooling. Both quenches exhibit a boiling plateau where the rate of temperature drop suddenly decreases above the water boiling point. As boiling subsides, the rate increases slightly as convective cooling becomes dominant.



(a) Agitated water quench. *(b) Still water quench.*

Figure 4: Thermocouple data for the indicated water quenches.

HTC values calculated for the still water data are plotted in Figure 5. For the case where the mode of heat transfer changes dramatically during cooling, i.e. from film boiling to nucleate boiling to convective cooling, the HTC values change with the part surface temperature. During film boiling, the values are low. They rise to a maximum value as nucleate boiling occurs, and then they fall as convective cooling becomes dominant and ambient temperature is approached.

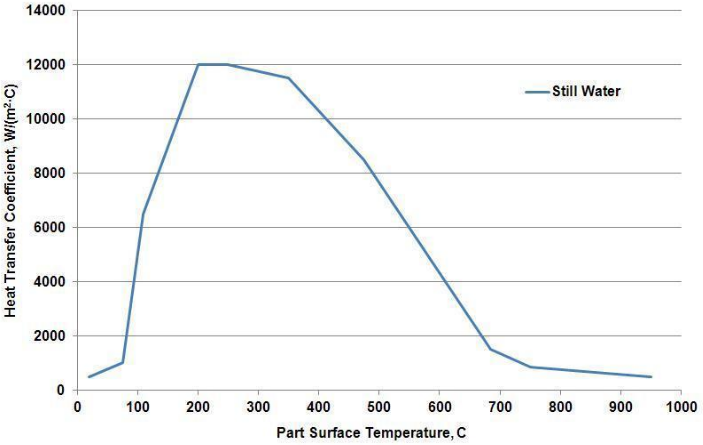


Figure 5: Heat transfer coefficients for still water quench calculated from data in Figure 4b.

Comparison of the HTC values for intensive quenching and immersion water quenching is interesting. Quenching in still water produced peak HTC values of about 12 kW/(m^2·C), while the intensive quench values were 22 kW/(m^2·C) and 25 kW/(m^2·C) for the two flow rates. The peak HTC for still water quenching was above the HTC of 10 kW/(m^2·C) at the probe top surface where a low flow rate zone was established. The key difference was that intensive quenching was found to maintain the high level of heat transfer over the entire quenching period while immersion quenching experienced high heat transfer only over a limited range of part surface temperatures where nucleate boiling created high local water flow.

Summary

A quench probe was successfully built to measure rapid temperature changes during both intensive quenching using highly flowing water and immersion water quenching. The measured temperature data were used to determine local heat transfer coefficients that could then be used for subsequent heat treat simulations.

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