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Effect of Oil Condition on Pinion Gear Distortion

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Abstract

As quench oil ages through use, its cooling power changes. Effectively, this means its viscosity changes, its vaporization behavior and thus its heat transfer characteristics. This paper reports the effect of new, mildly used and over-used quench oil on the distortion of a carburized 8620 steel pinion gear. The quenching characteristics for these three oil conditions, as measured by a standard quench probe, are used as the base heat transfer data sets. The local heat transfer coefficients applied to the part surface are modified according to the local velocity field as computed by a CFD model of the base oil. The predictive software DANTE is used to compute the dimensional change, residual stress state and phase distribution for the three cases, and comparisons will be presented.

Introduction

Distortion of steel parts is a common problem that is associated with quench hardening. During quenching, there are steep thermal gradients which generate internal stress. Hardening of steel necessitates transformation of austenite to martensite and other possible phases such as bainite, and these phase transformations introduce additional stress due to associated volume changes. Together, the thermal and transformation induced stresses can lead to significant dimensional change from the incoming green dimensions. The quenchant used to quickly cool the parts plays a significant role in the amount of dimensional change because the quench media dictates the nature of the thermal gradients, the stress levels, and the final phase make-up of the part.

The degradation processes of mineral oils are complex. Oxygen reacts with the free radicals of the hydrocarbons which, in turn, form hydro-peroxides. Hydro-peroxides are unstable and soon break down into ketones and water. The ketones oxidize further, forming aldehydes or organic carboxylic acids. The end products are acids, water and sludge. The acid causes corrosion and is measured using the Total Acid Number. The sludge increases the viscosity and acts to increase the resultant speed of the oil by the early initiation of nucleate boiling. As viscosity is increased, the boiling temperature also increases. This tends to increase the transition from nucleate boiling and convection. This sludge also results in increased staining of parts.

The cooling curve for marquenching oil has been found to change with use time.[1] As the oil condition changes, Figure 1 shows that the maximum cooling rate increases and the part temperature at which maximum cooling occurs also increases. These changes in the characteristics of the oil are associated with oxidation and changes in viscosity.

Agitation of the oil also plays an important role in terms of heat transfer during quenching. For example, Table 1 presents data for a fast quench oil that shows heat transfer coefficient to triple as the velocity is increased from still conditions to 0.76 m/s.[2] Marquenching oil was reported to have a similar heat transfer coefficient to the fast oil at an oil velocity of 0.51 m/s.

Prior work published from a study of quenching racked pinion gears of carburized AISI 8620 steel in a marquenching oil reported distortion measurements for two rack positions.[3] Computational fluid dynamics (CFD) analysis was applied to determine local velocities of the quench media around the racked parts.[4] Finite element modeling was used to predict the dimensional change of gears at two specific locations, with overall bow of the pinion being the main measure of distortion.[3] The local heat transfer coefficients applied in these models were determined by relating the base oil heat transfer coefficient data and the local velocity by a power law. The agreement between the predicted and measured bow values was good.

In this paper the effect of oil condition on dimensional change, metallurgical phase fractions and distribution, and residual stress state of the same pinion gear is examined using finite element analysis. Heat transfer coefficients for new and oxidized oil were defined by modifying HTC data based on measured cooling curves.

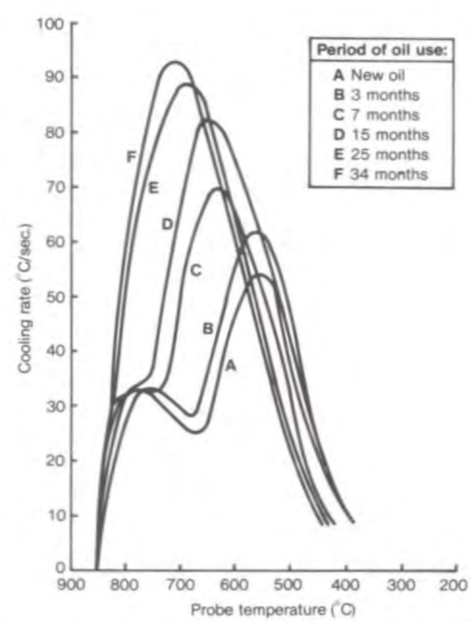

Figure 1 Effect of oil age on cooling rate.[1]

Table 1. Effect of Agitation on Heat Transfer. [2]

Oil	Velocity, m/s	HTC, W/(m^2*°C)
Fast Oil at 60° C	Still	2000
	0.25	4500
	0.51	5000
	0.76	6500
Marquenching Oil at 150° C	0.51	5000
Conventional Oil at 65° C	0.51	3000

Oxidized Marquenching Oil

Figure 2 shows the cooling curves for Houghton marquenching oil 355 for virgin and oxidized conditions; the cooling curves were measured using an IVF quench probe. The testing conditions were 1 liter of hot oil (121° C) with no agitation. From these cooling curves, characteristic quenching behavior of the oils was determined and is reported in Table 1. The cooling curves and the data derived from the curves are in agreement with the published findings for the effect of oil use time on quenching characteristics.

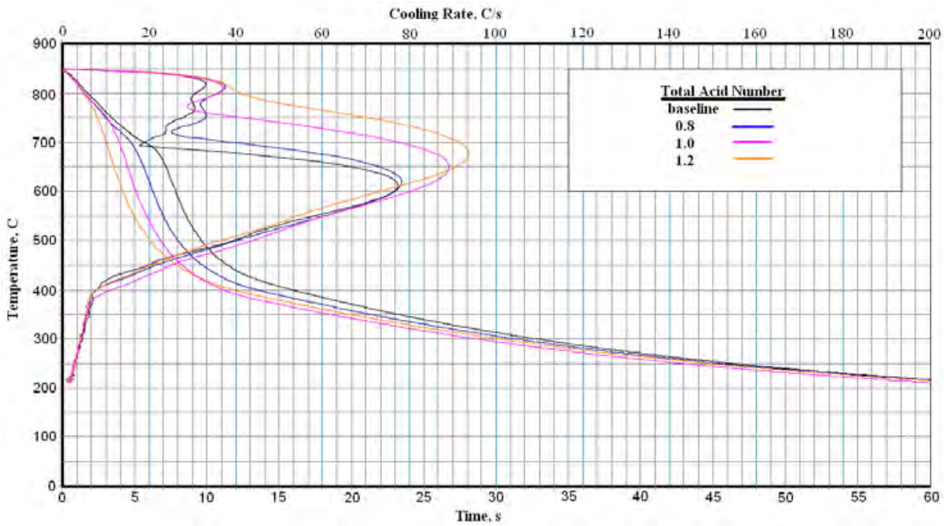

Figure 2 Cooling curves determined for Houghton 355 marquenching oil using the IVF probe.

Table2. Characteristic Data for Houghton 355 Marquenching Oil Derived from the Cooling Curves in Figure 2.

	Baseline 355 Oil	0.8 mg/l KOH	1.0 mg/l KOH	1.2 mg/l KOH
Maximum Cooling Rate	77.4 C°/s	78.2 C°/s	89.2 C°/s	93.6 C°/s
Temperature at Start of Boiling	611.4° C	614.7° C	655.6° C	683.3° C
Temperature at Start of Convection	407.5° C	388.2° C	376.1° C	393.2° C
Theta 1	700.9° C	720.0° C	771.0° C	849.6° C
Theta 2	457.5° C	464.2° C	465.5° C	494.7° C
Hardening Power	87.8	218.8	336.6	304.8

The heat transfer coefficient data predicted by Houghton from the cooling curve data using the IVF software are shown in Figure 3.[5] These curves are in qualitative agreement with the reported effects of oxidation on cooling rate and temperature. However, these curves are for quenching the IVF probe in still oil, and they cannot be used directly as heat transfer coefficients for actual quenching of a racked load of parts in an agitated oil tank. Heat transfer coefficients used to simulate the actual process should be determined by quenching parts instrumented with thermocouples to measure local cooling curves. Alternatively, CFD can be used to calculate local velocities.

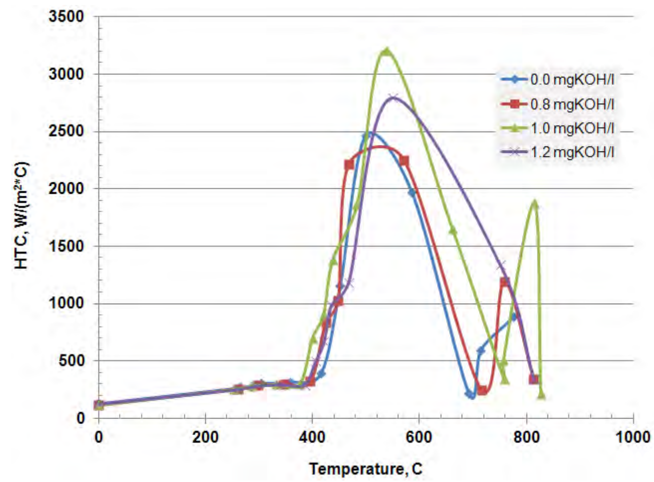

Figure 3 Heat transfer coefficient data supplied by Houghton for baseline and oxidized marquenching oil.[5]

Because experimental data for oil velocity and oxidized conditions using a commercial quench tank were not available, arbitrary HTC data were defined to use in models for baseline and heavily oxidized conditions (TAN=1.2). This was done to explore the effect of the HTC curve shape on predicted distortion for these carburized 8620 pinion gears. The method for defining the HTC data to be used in the models was to first modify the HTC curves reported in Figure 3 (high temperature end), and then use equation (1) to determine HTC values over the range of oil velocities and part surface temperatures experienced in the quenching process. Equation (1) shows that local velocity and temperature are thought to impact the HTC value.

$$HTC_{mod}(V,T) = A(V) * B(T) * V^{c(V)} * HTC \qquad eq(1)$$

Where A(V) is a multiplier that is a function of oil velocity
B(T) is a multiplier that is a function of temperature
$V^{c(V)}$ is a multiplier that is a power function of local oil velocity
HTC is the "still" oil HTC.

Figures 4, 5 and 6 show HTC vs. temperature curves for various oil velocities. Using oil velocities calculated from CFD analysis reported in reference [3] for rack position A11, the top corner, HTC curves for the average oil velocity, the average ± standard deviation velocities denoted as major and minor, and the maximum and minimum velocities are shown in these figures. For comparison purposes, Figure 7 shows the HTC curves for the average oil velocity.

Figure 7 illustrates the key issues that were considered in this paper. The HTC data representing oxidized is noticeably higher when part surface temperatures exceed 600 C, indicating poor stability of the vapor phase and limited film boiling. Also, for the estimated HTC data for baseline oil (base2) and the "test" oil, the main difference is the peak heat transfer.

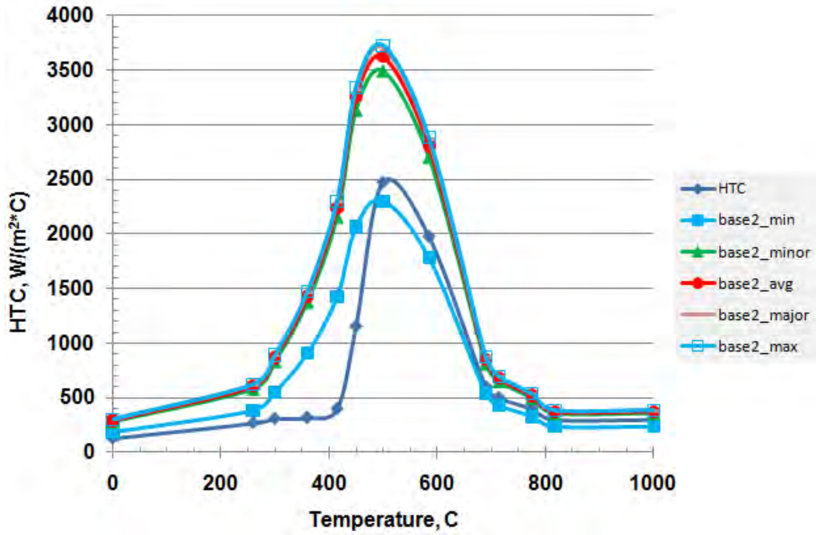

Figure 4 Estimated HTC data as affected by oil velocity for "base" marquenching oil.

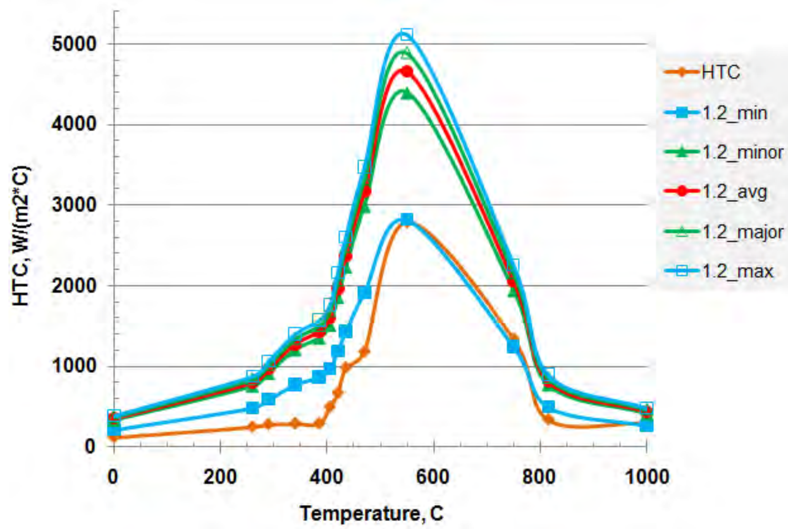

Figure 5 Estimated HTC as affected by oil velocity for oxidized marquenching oil (TAN=1.2).

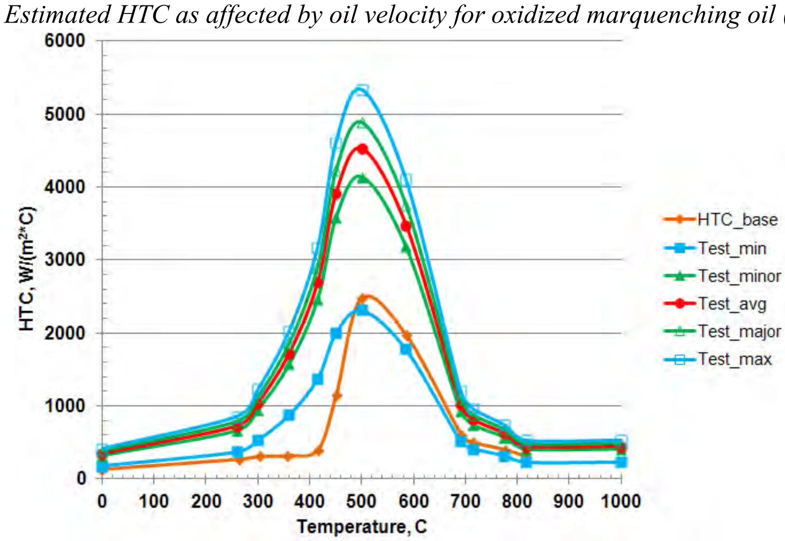

Figure 6 Estimated HTC as affected by oil velocity for "test" oil.

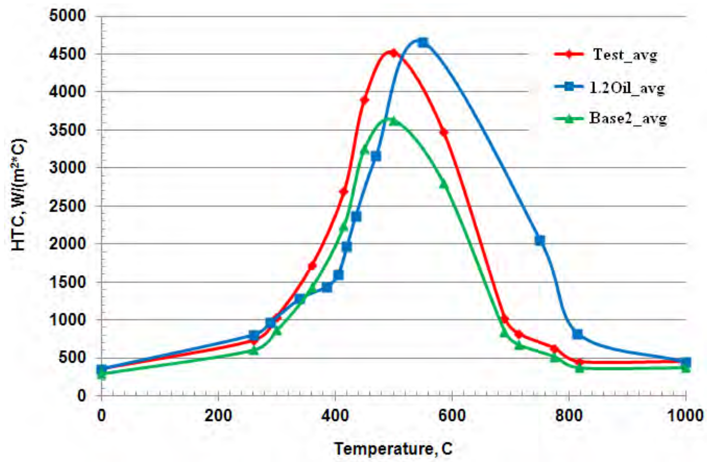

Figure 7 Comparison of HTC curves for average oil velocity for marquenching oil.

Heat Treat Process to be Simulated

The heat treat process simulated was identical to that reported in reference [3], and it is shown in Figure 8. The racked parts are preheat to 510 C and then transferred to a multiple zone furnace for carburization and preparation for quenching. The DANTE software was used for these simulations. This included the material data for carburized 8620 resident in DANTE's database. Tempering was not modeled as distortion and changes in residual stress during low temperature tempering are considered to be negligible.

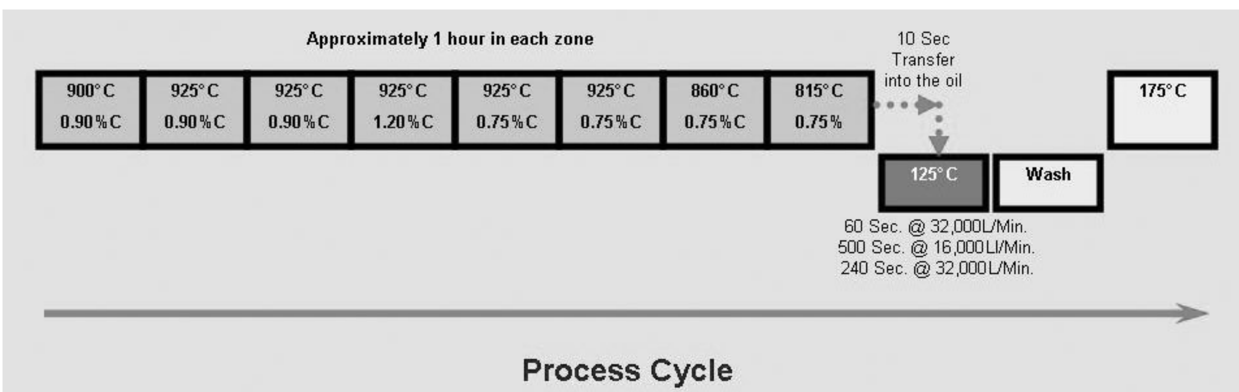

Figure 8 Process cycle use to carburize and quench harden 8620 steel pinion gears.

A three dimensional model was built to represent the pinion; the same model used in references [3 & 4] was used for this study. Gear teeth were not modeled as the CFD model in reference [4] considered the pinion head to be a truncated cone. As mentioned, gear A11 positioned at the top outside corner of the rack was the gear modeled in this study. The predicted CFD velocity map is shown in Figure 9, and these were the velocities used to define the local heat transfer coefficients.

Results of the three simulations are best reviewed by comparing the predicted bow distortion, the final residual stress states and differences in the timing of phase transformations that were predicted by the quench hardening process.

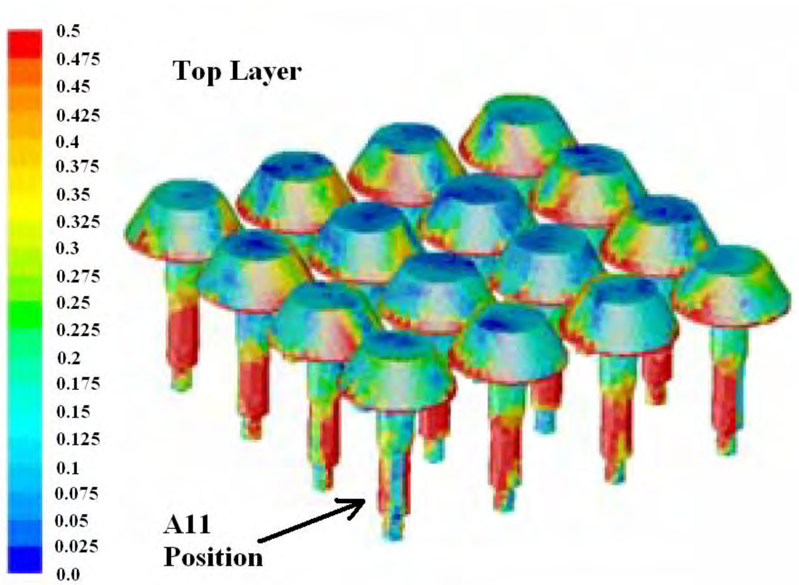

Figure 9 Oil velocity profiles (m/s) predicted by CFD.[4]

Simulation Results

Figure 10 shows the predicted bow of the pinion gear as determined by plotting the radial displacements of the model centerline over the length of the pinion. The shaft length ranges from 0 to 175mm, and the pinion head covers from 175 mm to 232 mm. As shown, the HTC data used for the baseline marquenching oil, curve labeled base2, produce predicted bow values of 32 microns. The predicted bow for the oxidized oil with a TAN of 1.2 was on the order of 17 to 18 microns. The highest predicted bow was nearly 53 microns for "test" oil HTC data.

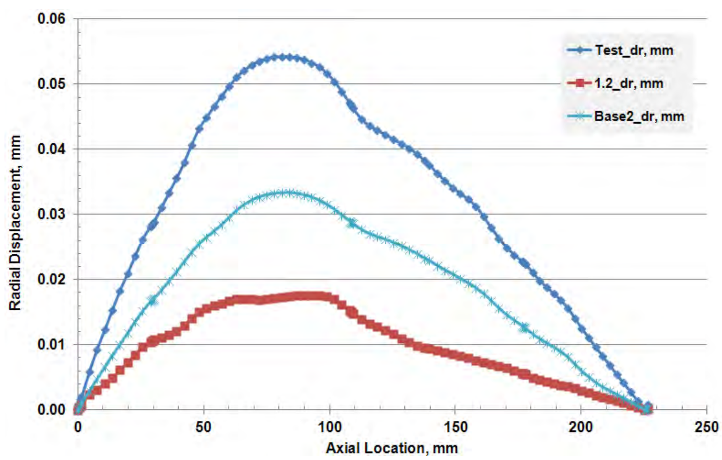

Figure 10 Bowing distortion predicted for the three HTC sets of values.

The predicted residual stress states and the phase make-up of the quenched pinions for the three different HTC data sets are slightly different from one another and reflect the differences in bow distortion reported in Figure 10. Because of the differences in local velocity of the oil during the quench, the residual stress state is not uniform in either the circumferential or lengthwise directions. Figure 11 shows minimum principal stress, and it is included as a representative for all three cases, as it illustrates the variation in surface and internal stress due to local quench condition differences. The stress magnitudes and extents of coverage are slightly different for the three cases, but the appearances are similar. Because the gear teeth have been eliminated, the stress state reported in the head is not accurate, and the focus is on the shaft. The cut view in Figure 11 is across a plane that includes the highest surface compression.

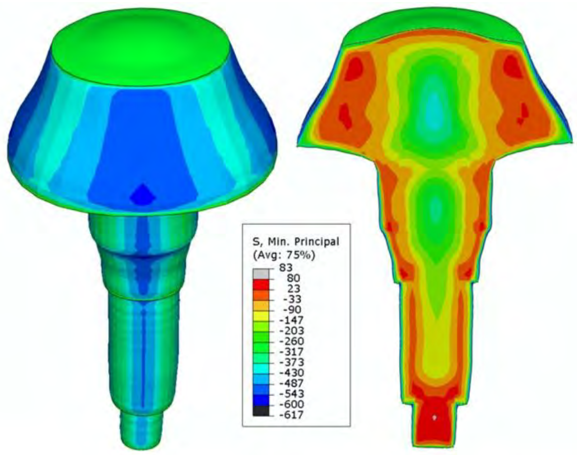

Figure 11 Surface and cross section residual stress profile for quenched pinion using baseline oil. (Units are MPa)

For comparison of the three HTC data set effects, Figures 12 through 14 show the differences succinctly. These figures are for a ring of nodes 65.7 mm from the end of the pinion, and the radius of the nodes places them at 1.5 mm under the surface so they are inside the case-core interface diameter. The figures show temperature, radial displacement and austenite fraction over the quenching period for four nodes of the ring positioned at 90° to each other. Ideally, the temperature, displacement and austenite fractions would be identical, so the differences shown reflect the differences for the three quenches. In these figures, the spread in the temperature history curves, the differences in the radial displacement curves, and the spread in the austenite decomposition curves indicates the amount of nonuniformity at these nodal locations. The result is an axial bending moment to cause bowing and a change in the cross section from a true circle to a poorly formed oval. The noncircularity is shown in Figure 15, as simple size change would have produced horizontal lines in this graph.

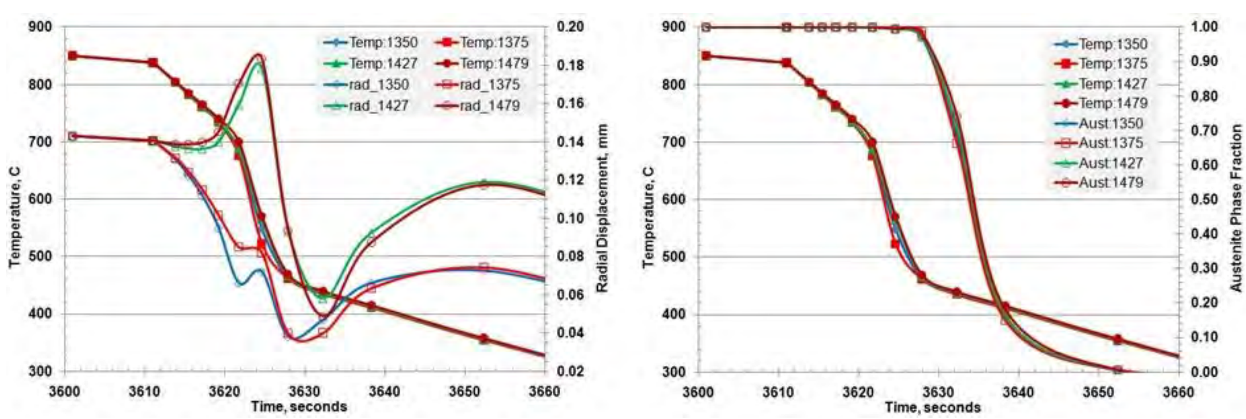

Figure 12 Temperature, radial displacement and austenite fraction predictions for the baseline marquenching oil.

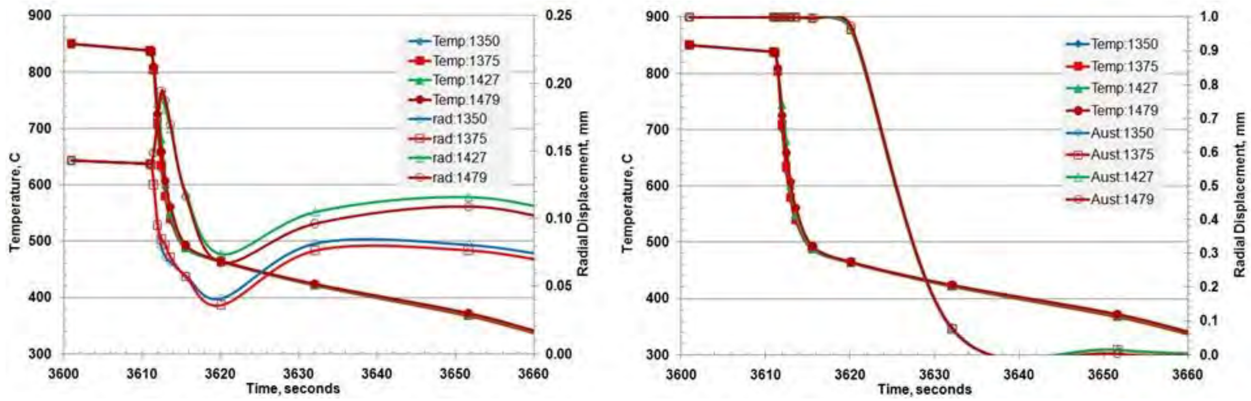

Figure 13 Temperature, radial displacement and austenite fraction predictions for oxidized marquenching oil.

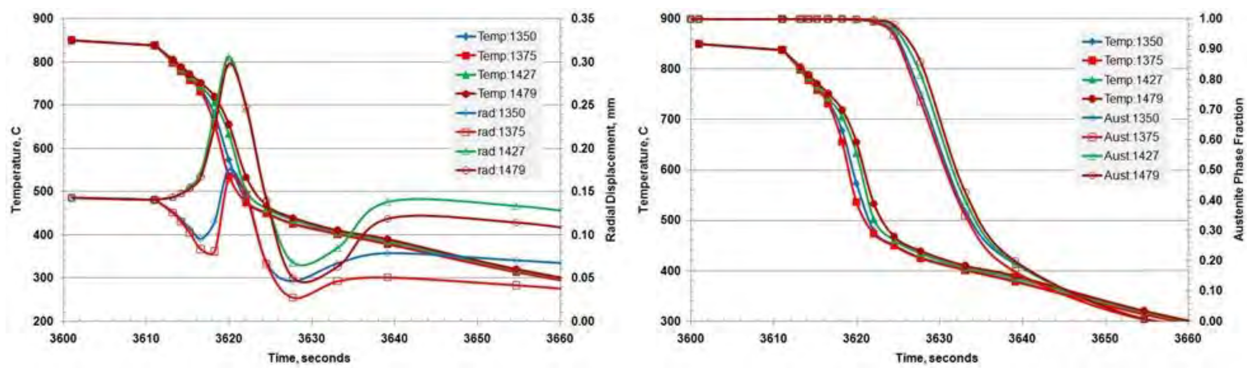

Figure 14 Temperature, radial displacement and austenite fraction predictions for"test" marquenching oil.

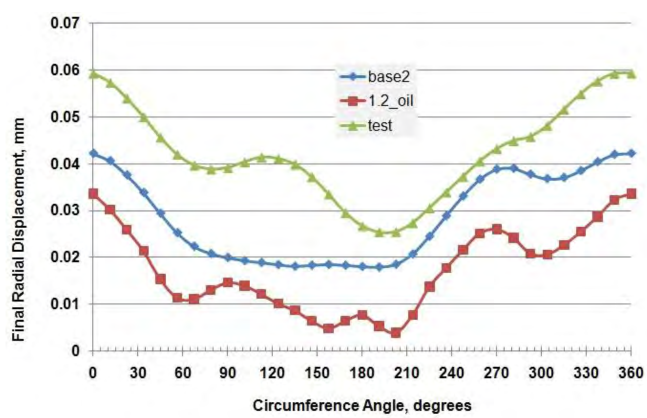

Figure 15 Radial displacement predictions for a ring of nodes along the pinion shaft showing non-circularity for the three different HTC data sets.

Summary

This study is by no means conclusive or final in nature. There is still much work to be done. For example, the original CFD model assumes a single set of static conditions from which velocities were calculated. From these assumptions, this study makes some further assumptions about differences in oil behavior in terms of heat transfer. The results are definitely interesting, but further experimental work and validation are required.

Interesting predictions from this study on these carburized 8620 gears include:

- Distortion as measured by bow of the gear decreased as the peak value of the HTC, the value of HTC during nucleate boiling, decreased.
- Bowing distortion also decreased as film boiling was decreased, which in this case was for oxidized marquenching oil.
- The nonuniformity in local oil velocity produced nonuniform decomposition of the austenite which caused bending and out-of-round distortions in all three models.

The heat transfer coefficient data used to simulate quenching processes should be determined from experimental measurements made using the process conditions. Alternatively, CFD calculations can be made to estimate the HTC values for the actual process. HTC data derived from quench probe data using a small sample of still oil are not directly useful for process simulation. Cooling curves determined by quench probes are great for providing the data for which they were intended – that is, checking the condition of the oil or comparing the basic characteristics of various quenchants.

Acknowledgments

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[5] Data supplied by Houghton International, Inc., 2012.