ID No.E06

Effect of Alloy on the Distortion of Oil Quenched Automotive Pinion Gears

D. Scott MacKenzie[1,a], B. Lynn Ferguson[2,b]

[1]Houghton International, Inc, Madison and Van Buren Aves., Valley Forge PA USA 19426
[2]B. Lynn Ferguson, Deformation Control Technology, 7261 Engle Road, Suite 105, Cleveland, OH 44130,
[a]smackenzie@houghtonintl.com [b]lynn.ferguson@deformationcontrol.com

In a previous work [1,2], the distortion of 8620 carburized automotive pinions was determined via CFD, FEA and actual measurements. In an effort to increase performance, and to reduce the distortion further, AISI 4320 was examined for the effect of alloy on distortion. The methodology and results of this work are shown.

Keywords: *Finite Element, distortion, residual stresses, carburizing, quenching, transformation.*

1. Introduction:

Heat treating and quenching is a complex business. The configuration of parts is endless, as is the types of furnaces available for heat-treating. Numerous variables in the quenching process alone govern the ability of a part to meet distortion requirements. Heat-treating is a constant balancing process. It is important to balance the ability of the material to achieve properties, while at the same time control distortion. Because of the complexity of the heat-treating process, it is rather difficult to understand the interaction of fluid flow and parts on part distortion and properties. Often understanding is achieved only by experience, which comes from making mistakes and learning from those mistakes. There is less tolerance for "trial and error" and the emphasis is on "doing it right the first time". Unfortunately there are few design rules that dictate the racking of a part in a given furnace.

An automotive supplier was having difficulty quenching large pinion gears for automatic transmissions. It was experiencing bowing of the stem of approximately 2 mm, which caused excessive loading of the drive-train, and excessive noise. We were requested to help understand and provide cost effective solutions to eliminate the distortion. The existing parts were AISI 8620 pinion gears that are carburized to obtain a case depth of approximately 0.7 mm. The process cycle is shown in Figure 1. The existing method of loading was pinion head down, and a new method of racking was proposed to minimize his distortion. This method was suggested to improve fluid flow around the pinions, reduce distortion and improve loading of the rack. The previous method of racking and the proposed method is shown in Figure 2.

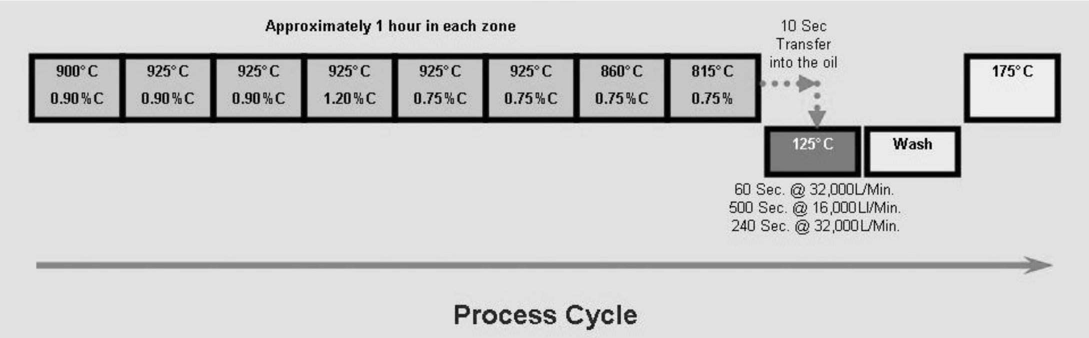

Figure 1: Process cycle to heat treat the pinion gears.

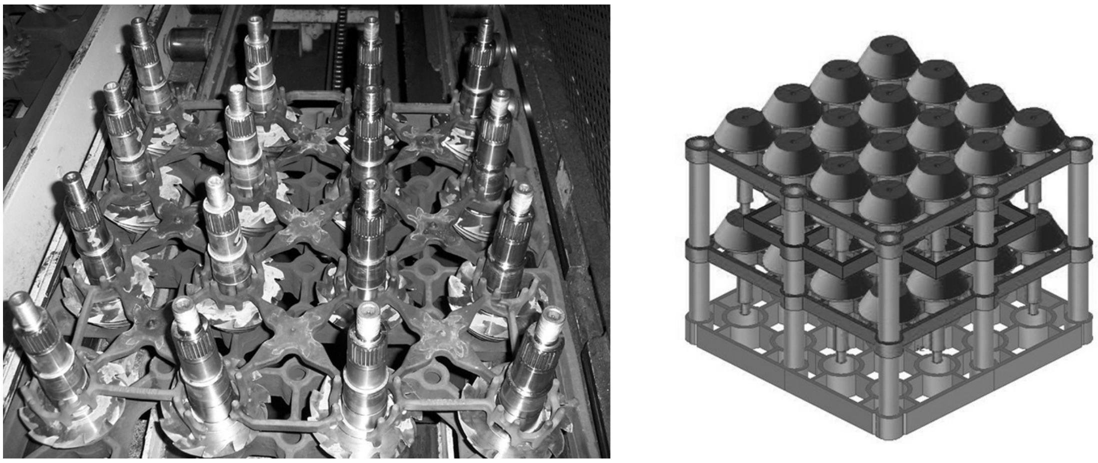

Figure 2: Comparison of existing and proposed racking methods.

Computational Fluid Dynamics was used to establish the flow fields around the parts using the new method of racking. From the flow fields, an empirically derived heat transfer coefficient was assigned to each CFD surface node on the pinion gears. This was used as the boundary condition for subsequent finite-element modelling of the pinions for distortion and microstructure.

Boiling heat transfer is not considered in this analysis. While the ability to model boiling and vapor phase heat transfer would be useful for detailed analysis, the assumption that heat transfer is directly related to fluid flow, and that boiling heat transfer can be ignored, has proven to be accurate for qualitative analysis of distortion problems [2, 3, 4)].

Once the distortion was modelled, the results of the modelling effort were validated, using sixty heat-treated loads, and a total of 2400 parts. The results, reported in [2], are shown below:

Position	Predicted	Actual (mm)		
	mm	Maximum	Average	Minimum
A11	0.025	0.020	0.011	0.008
B11	0.015	0.017	0.009	0.005

Table 1: Comparison of existing and proposed racking methods.

The pinions were measured for distortion and found that the maximum distortion observed was 0.020 mm – a several order of magnitude improvement. The resultant savings to the customer were in excess of $14,000,000 USD.

2. Problem Statement and Methodology:

Based on the success of this previous analysis, the customer wanted to look at improving distortion further. To meet increased performance demands and to reduce distortion further, the customer wanted to know if changing the alloy to AISI 4320 and carburizing, would have similar distortion and achieve the desired core hardness of 35-40 HRC.

A pinion at the upper corner of the quench rack was simulated using DANTE. The oil flow rates around the pinion from static CFD analysis were exported in a spreadsheet that contained (x,y,z) positions of the centroids of the CFD cells surrounding the pinions and the magnitude of oil velocity. The data from the spreadsheet file was imported and mapped into DANTE model to calculate the local heat transfer coefficients for the pinion surface element faces. The relation between oil flow rate and the heat transfer coefficient is described using equation (1).

$$h_c=h_{oil} * v^{n} \qquad (1)$$

where h_c is the oil flow rate dependent heat transfer coefficient, h_{oil} is the average oil heat transfer coefficient, v is the oil flow rate, and the exponential n equals 0.466 in this study. The heat transfer coefficient h_{oil} in equation (1) is a function of part surface temperature, which also represents the vapour blanket, nucleate boiling, and convection phenomena during oil quenching.

3. Results and Discussion:

The results of the finite-element prediction of bowing are shown in Figure 3. The results show that the distortion of the AISI 4320 carburized pinion gear is approximately 0.15 mm – approximately one order of magnitude greater than the bow of the carburized AISI 8620 gear.

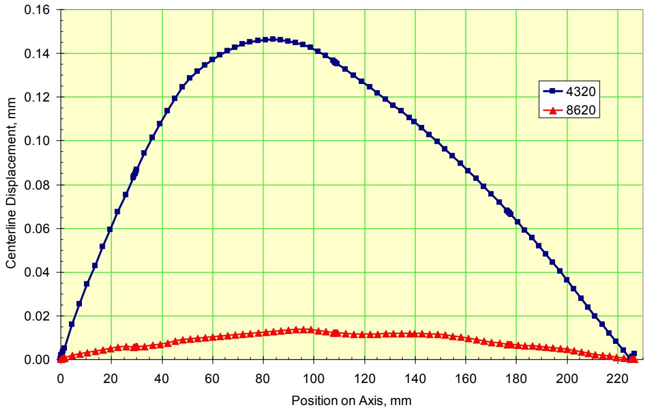

Figure 3: Comparison of bowing between AISI 8620 and AISI 4320, carburized and quenched.

The results were unexpected, and further analysis was conducted to understand the reason for this large distortion. The transformations occurring during quenching, and when the transformations occurred were examined. The results are shown in Figure 4.

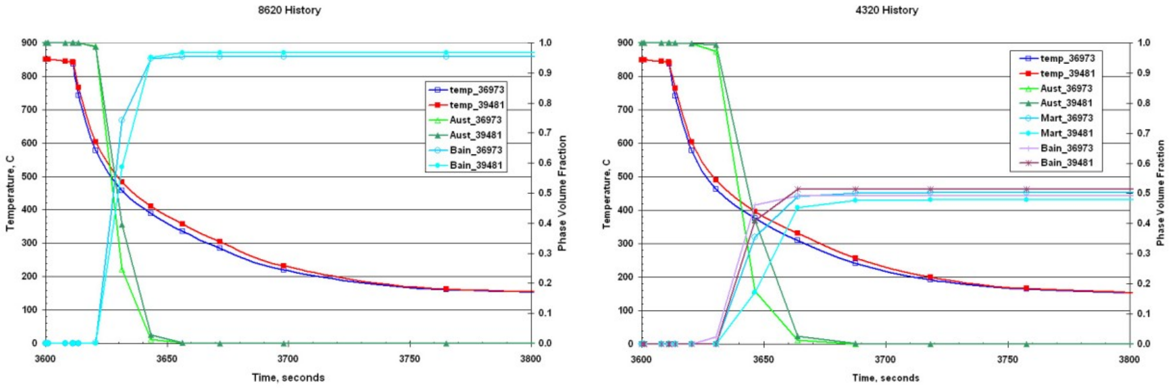

Figure 4: Comparison of the transformation history of AISI 8620 and AISI 4320, carburized and quenched.

This behavior can be explained by the differences in the Continuous Cooling Curves of the two materials (Figure 5). The AISI 8620 material, with a short martensite shelf, has a significantly lower hardenability than AISI 4320. Fast cooling rates are required to achieve a fully martensitic structure. AISI 8620 also has a significant bainite bay at the expected cooling rates expected during quenching. AISI 4320 has a much higher hardenability, with a large martensite shelf. Slower cooling rates can still achieve a fully martensitic structure.

The cooling rates on opposite sides of the pinion were determined to be approximately 800°C/min and 400°C/min respectively. For AISI 8620, the CCT diagram predicts that the microstructure would be predominately bainite with small portions of martensite and pearlite for both cooling rates. For AISI 4320, the CCT diagram predicts approximately equal portions of martensite and bainite. However, for the faster cooling rate, martensite would form earlier than for the slower cooling rate.

For 8620, during quenching, the core transforms almost completely to bainite. While some asymmetry of transformation occurs, equal amounts of bainite are formed. There is less volume expansion due to bainitic transformation, resulting in less distortion.

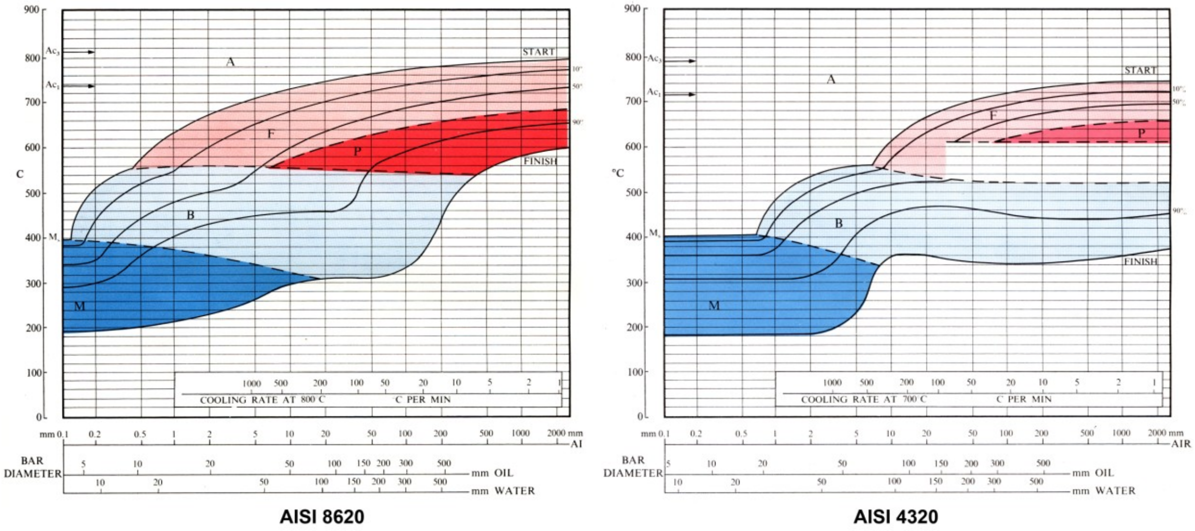

Figure 5: Comparison of Continuous Cooling Transformation diagrams of AISI 8620 and AISI 4320.

For AISI 4320, the core of the pinion shaft transforms to approximately equal portions of martensite and bainite. However, because of the differential cooling rates, one side of the pinion shaft transforms to martensite much earlier than the opposite side. This asymmetry of martensite formation and the accompanying volume change results in an initial bow of the pinion. Once the opposite side of the pinion transforms to martensite, a stress reversal occurs, with the final bow of 0.15 mm. Use of a significantly slower quench, to insure that transformation to bainite occurs uniformly, or improved agitation and fluid flow during the quenching operation to prevent asymmetrical phase transformation, were the recommendations made.

4. Conclusion:

Finite element modeling of the heat treat process steps provides a clear and efficient way to understand the part response during heat treatment, which is also helpful for eliminating severe distortion problems. During quenching, high internal stresses are generated from the thermal gradients and metallurgical phase transformations. Plastic deformation caused by high internal stress leads to permanent distortion in the part after quenching.

Acknowledgements:

The authors would like to thank Fluent Inc. for their CFD modeling work, and the management of Houghton International, Inc., and Deformation Control Technology, Inc., for the opportunity to present this work at the 4th International Conference on Thermal Process Modeling and Computer Simulation, Shanghai, China.

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