

Predicting Distortion and Residual Stress in a Vacuum Carburized and Gas Quenched Steel Coupon

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Abstract

Aerospace transmission components are typically manufactured from high strength, case carburized alloy steels such as AMS 6308 (Pyrowear[®]53). The combination of carburization and quench hardening of these steels produces residual compressive surface stresses and high surface hardness, thus enhancing both surface durability and fatigue resistance. The hard case, coupled with a tough non-carburized core, provides the foundation upon which additional processing can further improve surface fatigue response. An internal state variable (ISV) material model for carburized and heat treated gear steels has been implemented into the DANTE heat treatment simulation software for the purpose of engineering microstructural, residual stress and distortion response to meet specific steel component application requirements. This paper describes the use of heat treatment simulation to engineer residual stress and distortion response in an AMS 6308 alloy steel coupon to subsequently be used for fatigue testing. The criticality for accurate use of process-descriptive boundary conditions is presented in the context of vacuum carburizing and gas quenching. Model predicted residual stress and distortion response for a tapered, notched coupon are validated against x-ray diffraction and dimensional physical testing.

Introduction

Precision engineered gears are a critical component in rotorcraft transmission systems. These gears provide transfer of power from the horizontal drivetrain to vertically mounted rotor shafts, enabling high speed and torque with non-parallel input and output. The increasing performance requirements in both military and commercial rotorcraft necessitate improvement in transmission power density (horsepower/lb) capabilities. This provided the incentive for steel manufacturer's to shift aerospace steel production and processing towards use of specialized high strength alloy steels. These steels are characterized by a combination of high strength and high toughness, and are noted for their combined use of a carburized case and fine alloy carbide dispersions to achieve these properties. [1-3]

Carburizing steels with high alloy content are both an attractive and economically affordable alternative to addressing challenges related to the durability and power density of components used in transmission gears. The carburized case provides high strength and wear

resistance, while the non-carburized core maintains the strength and hardenability achieved through alloying while offering a combination of toughness, ductility during impact or impact resistance, and an overall high resistance to fatigue. All of this is made possible due to the low carbon content in the matrix. The influence of a fine dispersion of alloy carbides helps in providing improved fatigue resistance by inhibiting the motion of dislocations.

Maximizing and characterizing fatigue strength of these mechanical elements is therefore essential to increasing transmission performance. Current efforts towards maximizing high cycle fatigue (HCF) performance involve research into the effects of heat treatment residual stress, post heat treatment processes for increasing surface compressive stresses, and various means of enhancing gear surface finish. However, a means of quantifying these improvements from the perspective of quantifiable design metrics has been difficult, specifically due to the need to address complex part geometries such as contour surfaces, edges, and root bottoms of the gear teeth. Residual stress generated during heat treatment of these components is a critical element affecting potential fatigue life, as surface residual compression or tension affects local loading stresses experienced in the gear through the mechanism of superposition. [4] The magnitude and location of such compressive stresses affect the dynamic stresses experienced locally by the part during service. Additionally, section size changes, gear root geometry, and non-uniformities in heat treatment quenching operations may also contribute to local part distortion and require subsequent grinding or machining to eliminate.

Quantifying and predicting these residual stress and distortion responses remains a substantial challenge to the manufacturing engineer. Recent advancements in quantitative process simulation (modeling) have made it possible to study in situ the combined effects of carbon mass diffusion, heat treatment thermal strains, and strains produced from metallurgical phase changes. Developed in part by DCT Inc. in a US Dept. of Energy sponsored research project, DANTE[®] (Distortion Analysis for Thermal Engineering) is a finite element based software tool that calculates the residual stress, dimensional change, hardness and metallurgical phase volume fractions of steel parts as a result of heat treatment. [5] The DANTE database includes mechanical and thermal property data for steel microstructural phases as functions of temperature and rate, as well as the necessary phase transformation kinetics parameters to address both heating and cooling transformations. [6]

Aerospace transmission components are typically manufactured from high strength, case carburized alloy steels such as AMS 6308 (Pyrowear[®] 53, X53). The impetus for the study presented here was the development of a simple, notched four-point bending fatigue coupon which could be used to characterize residual stresses, distortion, and surface effects in the AMS 6308 carburizing steel for the US Navy and Army. [7] Steel for physical experiments was acquired by DCT Inc (Cleveland, Ohio, USA). The certified chemical composition of the acquired steel is summarized in Table 1.

Table 1 Chemistry for AMS 6308 steel used for experiments

C	Mn	Si	Cr	Ni	Mo	Cu	V
0.10	0.35	1.00	1.00	2.00	3.25	2.00	0.10

The notched coupon was designed specifically to maximize resulting loading stress in the notch center by creating a plane strain condition in the notch by use of a “funnel” geometry. Although the fatigue response of this coupon is not discussed in this paper, the geometry, directional carburization, and quenching/tempering response (distortion and residual stress) of this part are integral for subsequent fatigue studies, and are the basis for the paper presented here. Figure 1 shows a dimensional schematic and photograph (inset) of the coupon and funnel notch geometry.

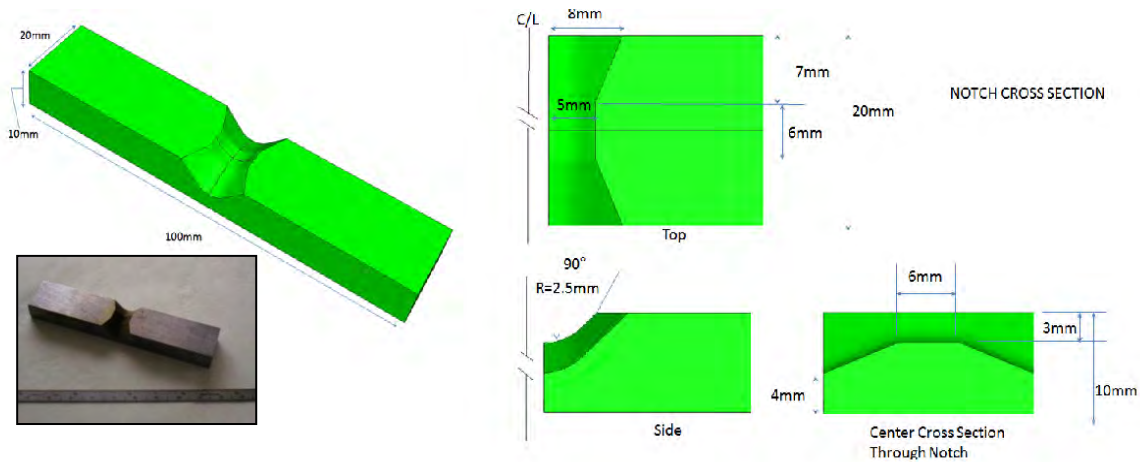


Figure 1 Geometry and photograph of AMS 6308 funnel notched bend coupon

For the subsequent fatigue study, the AMS 6308 steel was directionally carburized, gas quenched, cryogenically treated, and double tempered. This paper will discuss the use of heat treatment simulation to predict residual stress and distortion response of this coupon to the ascribed heat treatment. The criticality of accurate, process-descriptive boundary conditions, as presented in the context of vacuum carburizing and gas quenching, will be shown, and predicted residual stress and distortion response are validated against x-ray diffraction and dimensional measurement.

Fabrication and Heat Treatment of the Physical Coupons

Prior to heat treatment, a series of notched coupons were fabricated from the certified AMS 6308 steel through saw cutting and plunge EDM. The coupons were then heat treated using the process sequence outlined in Table 2.

Table 2 Heat treatment process sequence prescribed for AMS 6308 steel

Step	1	2	3	4	5	6
Heat Treatment	Vacuum Carburize	Subcritical Anneal	Austenitize	Gas Quench – 10 Bar N ₂	Deep Freeze	Double Temper

Process Modeling of Heat Treatment

The primary objective of this study was to develop a quantitative prediction of residual stress and distortion for the AMS 6308 coupon to facilitate further engineering analysis in subsequent fatigue studies. Therefore accurate predictions of cross sectional residual stresses in the coupon, as well as coupon dimensional response in heat treating, were essential. As discussed in the introduction, a DANTE heat treatment simulation for the vacuum carburizing, gas quenching and deep freeze processes was undertaken for this direct purpose.

The heat treatment simulation model used a one-quarter symmetry section taken from the full bend coupon geometry, as shown in Figure 2a.

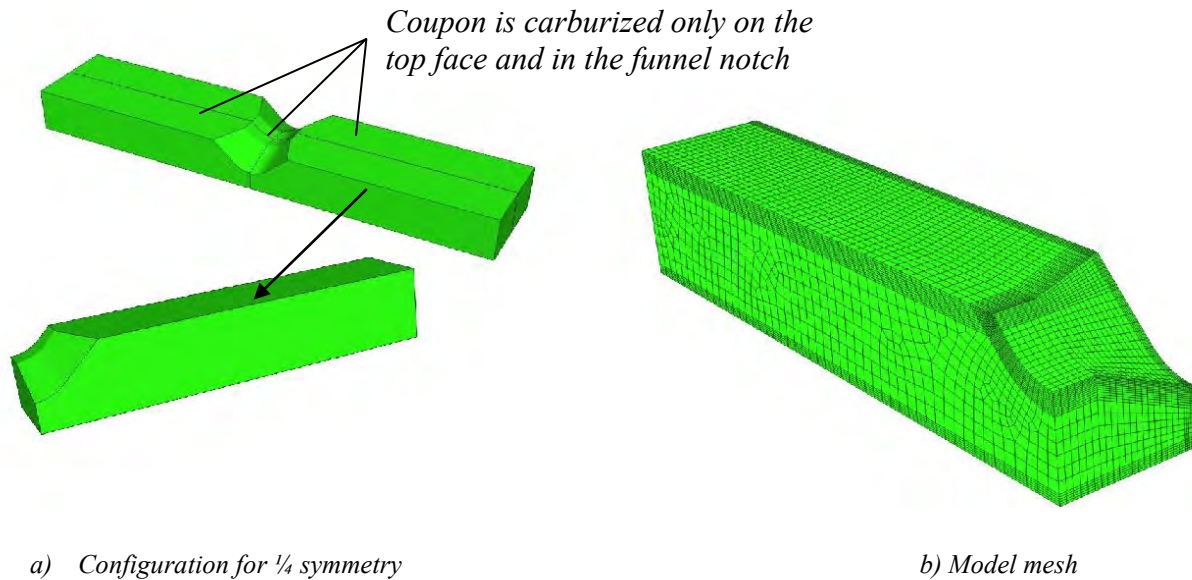


Figure 2 Solid model and finite element mesh used for heat treatment simulation of the funnel notched coupon

Because the multiple boost and diffuse cycles in vacuum carburizing introduce a multiple sequence of highly localized carbon gradients during the carburization cycle, and to accurately account for the final surface carbon gradient in the coupon, a fine mesh is required on the top flat surfaces and in the funneled notch, corresponding to surfaces receiving the carburization. The finite element mesh consisted of 39,078 nodes and 35,350 hexahedral elements. The model mesh is shown in Figure 2b.

Carburization Process

Specification called for an effective carburized case depth of 1.0mm (0.0394”), defined as HRC 50. The coupon is carburized only on the top face, including the notch (see Figure 2a). Side and bottom faces are masked. Figure 3 shows the achieved case hardness profile as measured in the notched root corner and on one of the flat carburized surfaces. The plot also shows the DANTE model predicted carbon and hardness profiles at these locations, with the addition of the predicted profile at the notch center. Figure 4 shows the associated Knoop microhardness indents in metallographic sections taken at these locations (ASTM E29).

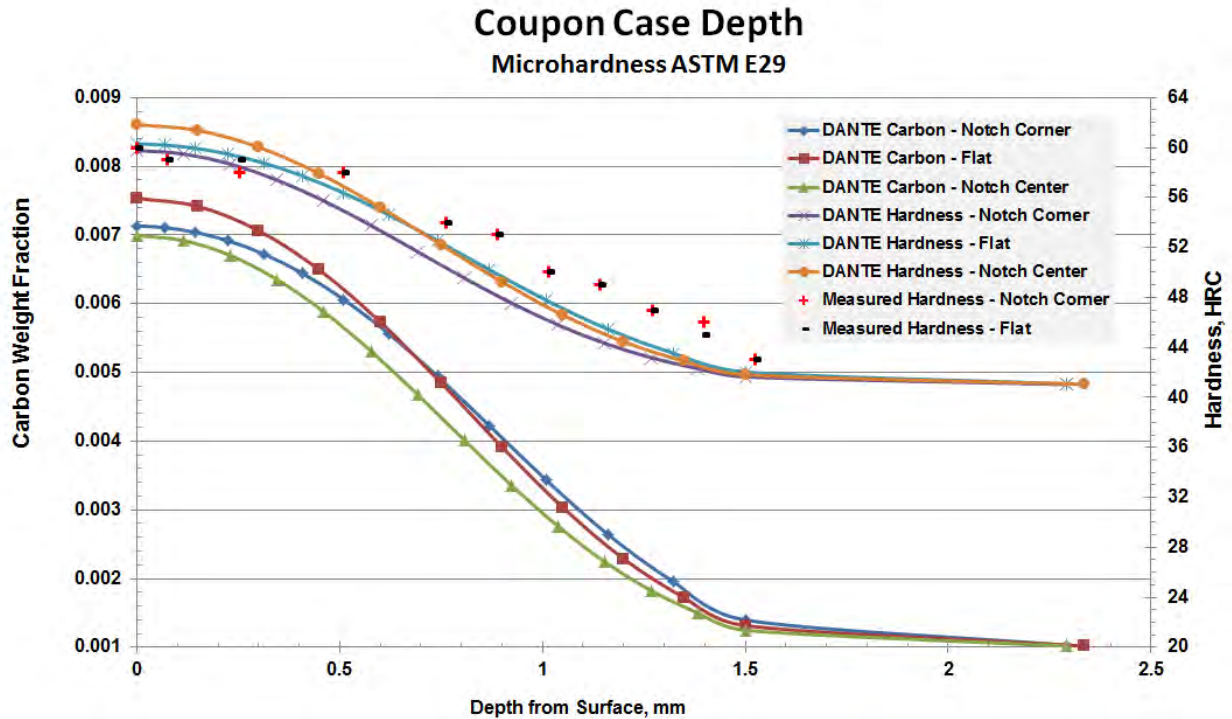
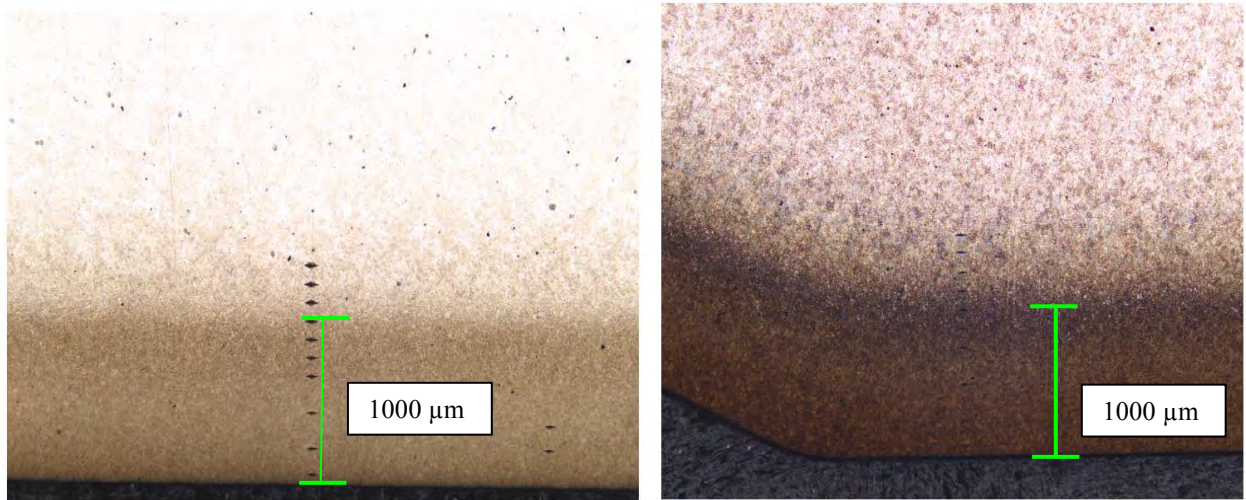


Figure 3 Measured microhardness profile and model predicted carbon profile for the funnel notch coupon



a) Flat surface

b) Coupon Notch

Figure 4 Metallographs showing the carburized case with associated Knoop microhardness indents at the a) Flat surface; and b) Notch root

Carburization was modeled using mass diffusion model. The vacuum carburizing process consisted of a sequence of paired boost and diffuse cycles designed to successfully achieve 1.0mm effective case depth, as shown in Figures 3 and 4. The specific cycle pressures and times are proprietary to the heat treater, and are not given here. However, they were shared with the authors for use in the carburizing model for this study. The predicted carbon profiles in the gear

root and flat surfaces, as calculated from the DANTE carburization model, are also plotted and shown in Figure 3 relative to the associated microhardness profiles. The model shows the internal carbon gradient extending from the surface, with predicted carbon of 0.002 wt. pct. at 1.00mm with an associated HRC 50. This conforms well with reported literature data. [8]

The DANTE heat treatment model also enables visualization of the internal carbon gradient at cross sectional locations of interest. Specifically, localized carbon build-up or dispersion at corners and radii are readily visualized. For the notched coupon, Figure 5 shows the internal carbon profiles in both the notch and flat areas. A slight dispersion in the carbon distribution in the notch can be seen visually, which conforms with the slight notch microhardness drop witnessed in the Figure 3 microhardness profile at 0.20mm depth.

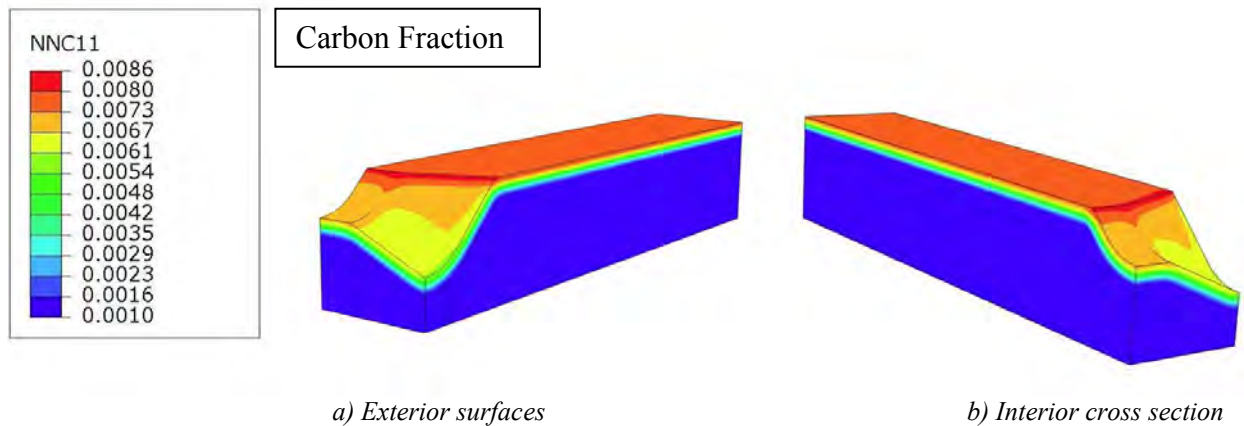


Figure 5 Carbon profile on a) Outer surfaces and b) Inner cross section of the heat treated AMS 6308 coupon, as predicted by the DANTE mass diffusion carburization model

Gas Quenching Thermal Boundary Conditions

The carburized notched coupons were hardened by gas quenching in a vacuum chamber pressurized to 10 bar with nitrogen quench gas. Prior experience in both physical experiments and simulation of gas quenching of commercial parts has shown a high degree of localized cooling sensitivity for convection cooling in gas quenching. [9] Consequently, for these simulations it was necessary to fit local convection cooling heat transfer coefficients for the coupon surfaces by employing cooling curve data provided by the gas quench heat treater – Solar Atmospheres. Solar provided cooling data from a thermocoupled test block placed in the array of the parts during processing. A photograph of this arrangement is shown in Figure 6.

The test block consisted of a hollow, square tube of 304 stainless steel, with wall thickness of 3.175mm. Three thermocouples were inserted, measuring inside wall temperature of the top, side and bottom faces. These data were used in conjunction with a simple finite element thermal model to determine heat transfer coefficients of the top, side and bottom surfaces. Model thermal response for the fit data is plotted against the measured thermocouple data in Figure 7.

The data showed a 15 second thermal response time at the beginning of the gas quench as the chamber is pressurized. The data indicated a difference in thermal response between the coupon top and its sides/bottom. Average heat transfer coefficients (htc) for each location were determined, and fit to the thermocouple test block data as shown in Figure 7.

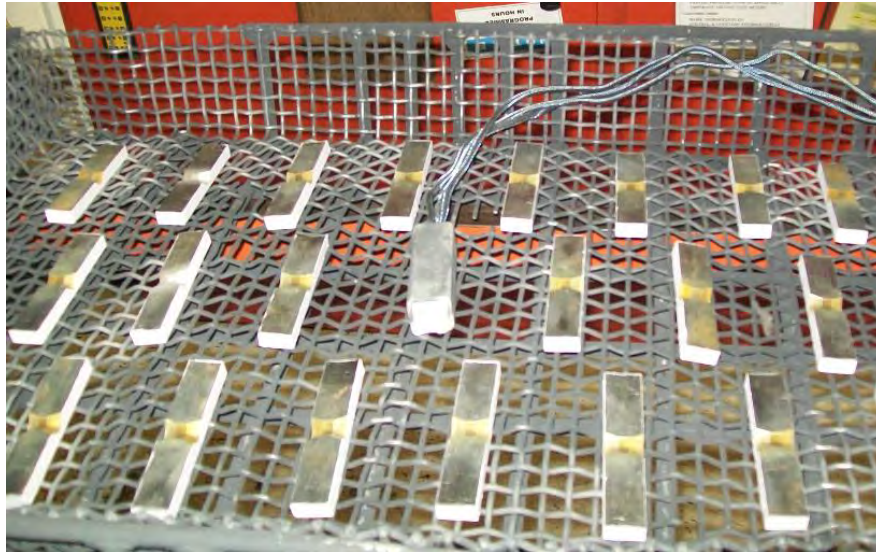


Figure 6 Quench layout for the funnel notch coupons, showing the thermocoupled test block (photograph courtesy Solar Atmospheres)

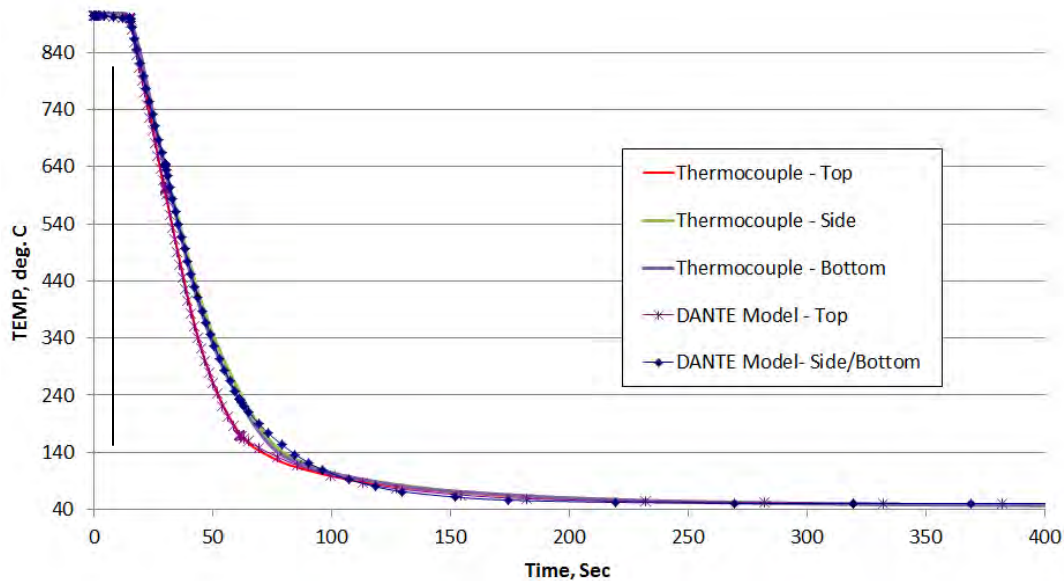


Figure 7 DANTE thermal model fit to gas quench thermocouple data obtained from test block shown in Figure 9

The average gas quench convection heat transfer coefficients for the two locations are given in Table 3.

Table 3 Convection heat transfer coefficients for coupon surfaces in 10 bar nitrogen gas quench as fitted from thermocoupled block

Location on Coupon	Heat Transfer Coefficient (W/m ² K) during Quench Period (see Fig. 7)
Top	140.0
Sides / Bottom	100.0

Application of the gas quench heat transfer coefficients was made assuming a constant value over the variable temperature range of the convective nitrogen media. Prior investigations have shown that the temperature dependent gas properties (i.e. kinematic viscosity, thermal conductivity) have only second order influence on htc, and a constant htc can be assumed. [10, 11]

Physical Results and Simulation Validation

The end use of the heat treated Pyrowear53 coupons as bending fatigue test samples necessitated physical characterization of heat treatment residual stress and distortion. Residual stresses were physically characterized at five (5) locations on the coupon (see Figure 8), and distortion was measured both in axial and transverse directions, as the coupon exhibited both bowing in the axial direction and bulging (crowning) in the transverse direction on the carburized surface.

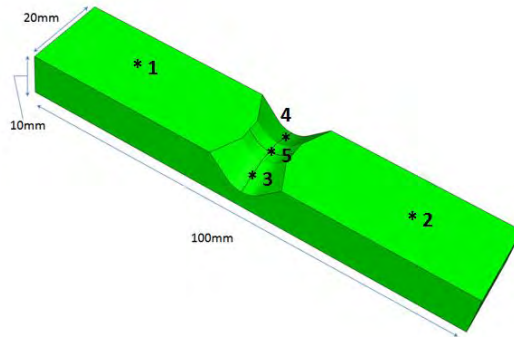


Figure 8 Locations for surface (1-5) and depth (5) x-ray diffraction residual stress measurements

Physical test results and corresponding, validated heat treatment simulation predictions will be discussed in terms of metallurgical phase volume fraction, axial residual stresses, and dimensional change.

Metallurgical Phase

As a through hardening grade, AMS 6308 transforms completely to martensite in the non-carburized condition. The high carbon case requires cryogenic treatment to eliminate the approximately 20% retained austenite remaining after quenching to room temperature. Verified in prior experimental works, the DANTE model also shows retained austenite remaining at room temperature of as-quenched condition (Figure 9a), and after the deep freeze (Figure 9b).

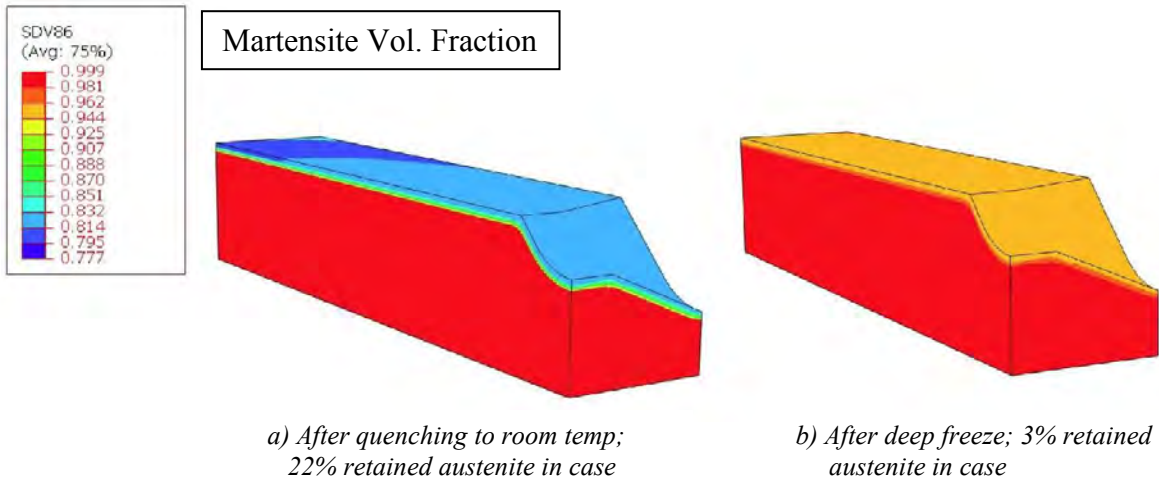
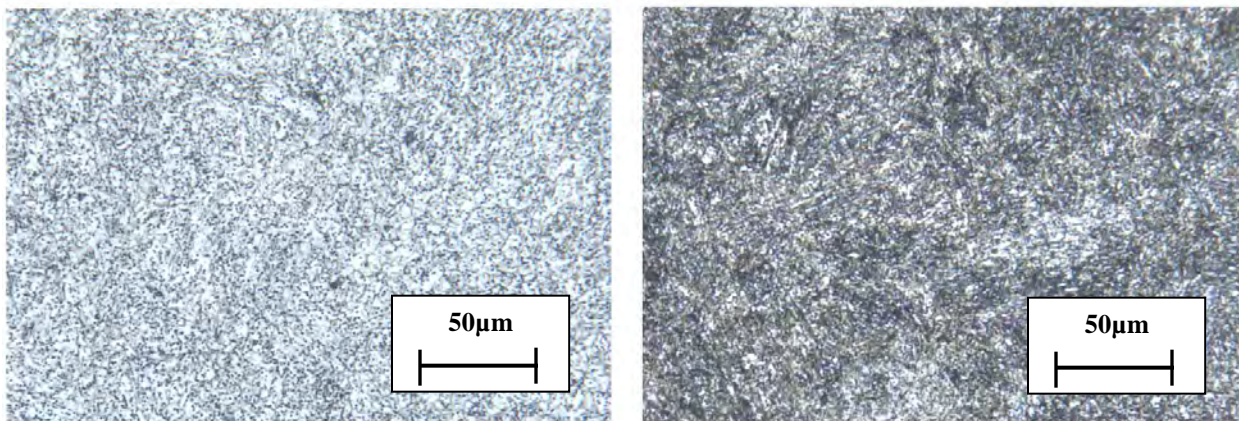


Figure 9 Predicted martensite phase volume fraction at a) After gas quench (room temp); and b) After deep freeze

Microstructural examination of both the carburized case and low carbon core after deep freezing shows the predominant martensitic structure in each, with associated fine alloy carbide dispersions. Metallography taken from a heat treated coupon is shown in Figure 10.



a) AMS 6308 core microstructure

b) AMS 6308 case microstructure

Figure 10 Martensite structure seen in the a) Core; and b) Case – with fine alloy carbide dispersions. Etched with 2% nital reagent.

Residual Stress

Coupon residual stress in the axial direction after heat treatment was measured using x-ray diffraction at the five (5) locations shown in Figure 8. Additionally, an etching method was used to obtain axial residual stress measurements in the notch center (position #5) as a function of depth.

Figure 11 shows the predicted axial residual stress from the DANTE model as a contour map of the quarter coupon section. The plot is annotated showing x-ray surface measurements obtained at noted locations.

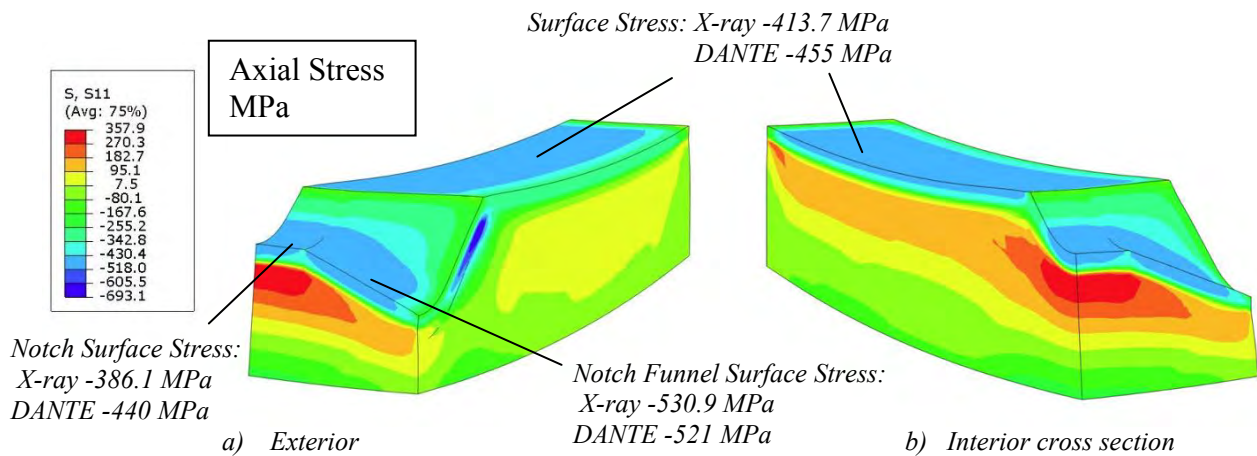


Figure 11 Axial residual stress (MPa) predicted by DANTE, showing a) Exterior; and b) Interior cross section

The predicted compressive stresses were higher than the x-ray measurements at the notch-center and top surface, but lower on the funnel surface. However, the predictions were within the reasonable range relative to the x-ray, and reflect the same trend – specifically that the funnel surface showed greater compression than the notch in both cases.

Figure 12 shows a plot comparing the measured and simulated axial residual stress as a function of depth at location #5 (notch – see Figure 8). The data show sound correlation, and also compare accurately with respect to the depth at which surface compressive stress shifts to internal tension: ~ 1.0 mm.

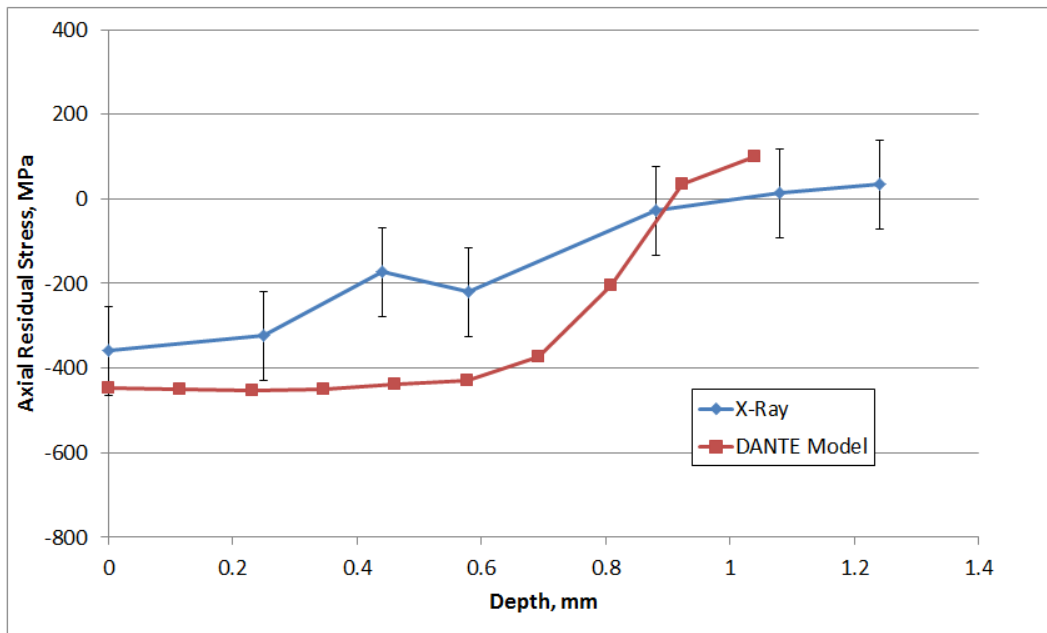


Figure 12 Axial residual stress (MPa) predicted by DANTE, showing a) Exterior; and b) Interior cross section

Distortion (Dimensional Change)

Dimensional change in the coupon is governed by the competing expansion and contraction of the carburized case and core as they are subjected to thermal shrinkage of cooling, and volumetric expansion as each transforms to martensite. The utility of the model is that it permits an in situ examination of the timing of these transformations relative to the instantaneous quenching intensity and general thermal boundary conditions. .

Final distortion of the coupon was characterized normal to the carburized surface (Y-direction) axially direction along the top carburized surface. The plot in Figure 13 compares predicted to measured Y direction distortion (bowing) in the axial direction. The data agree in direction of bowing to within +0.1 mm.

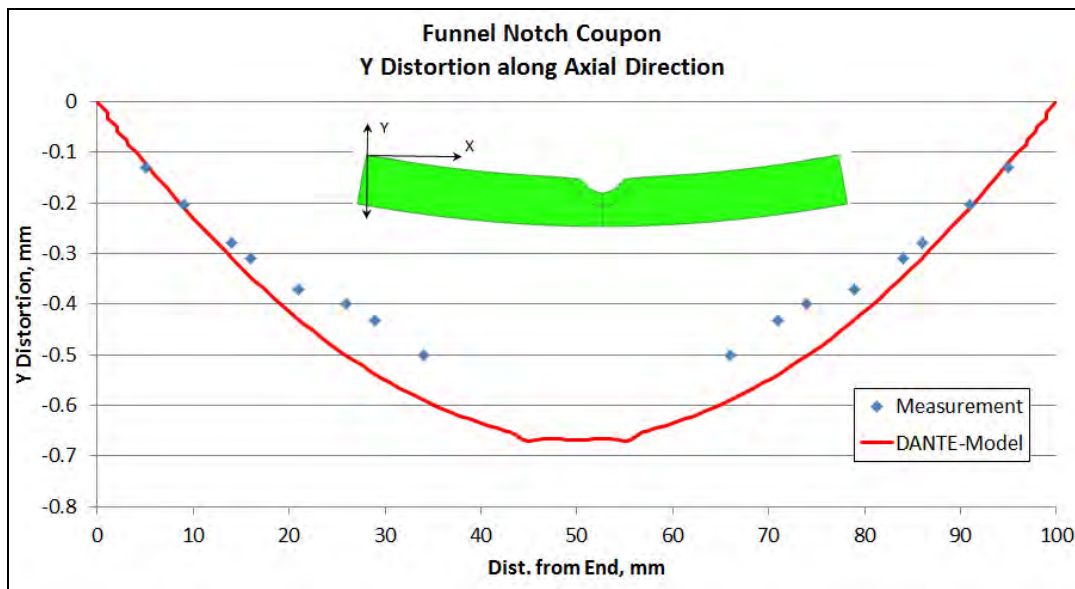


Figure 13 Comparison of measured versus DANTE model predicted Y-displacement (see inset) "bowing" of the coupon as a function of axial position

Further accuracy in distortion prediction can be achievable with more detailed gas quench thermal boundary conditions, specifically relating to both individual coupon surfaces, and variation in gas temperature.

Conclusions

The primary objective for this project was to design a coupon which would facilitate concentration of effective bending stresses in the notch center, and reduce tensile stress magnitude developed at the funnel edges during loading. The coupon design and applied heat treatment have successfully achieved this objective. Predicted residual stresses on the coupon surface at key locations, the stress profile in the coupon notch, and the predicted distortion of the part along the axial direction all compared favorably to physical measurements. Quantitative residual stress and distortion models are an effective means for bending fatigue coupon design

and analysis, particularly for complex steel alloys where residual stresses play a key role in affecting part eventual part loading stresses.

Acknowledgments

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