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Computer Modeling and Validations of Steel Gear Heat Treatment Processes using Commercial Software DANTE®

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The heat treatment process of a gear made of carburized steel AISI 9310 is modeled using the commercial heat treatment simulation software DANTE. Both carburization and quenching processes affect the residual stress distribution and distortion of heat-treated parts, which are important to service quality and fatigue life. DANTE/VCARB is used to design the Boost/Diffuse schedule of a vacuum carburization process. Oil quenching is modeled following the vacuum carburization process. Thermal gradients and phase transformations are two main sources of distortion and residual stresses in quenched parts. The relation of the carbon distribution, thermal gradient, and phase transformations during quenching is studied through the gear modeling example. Because of geometry, the residual stress distribution after quenching is non-uniform along the gear surface. In general, the tooth fillet has higher residual compression than either the root or tooth face locations after traditional oil quenching of carburized gears. The predicted residual stresses from the oil quenching model are imported into a single tooth fatigue bending model. The gear stresses under bending load indicate the possible cracking locations during bending fatigue test. The importance of heat treatment residual stresses during gear design is pointed out, which is commonly ignored in the gear design and manufacturing industry.

Keywords: *vacuum carburization, distortion, residual stress, phase transformation.*

1. Introduction

Most steel gears are used in high power density and high load conditions, such as powertrain systems. All steel gears working under high load conditions should be heat treated for improved strength and fatigue life. The carburization and quenching processes are commonly used to increase the material's hardness and strength by martensitic transformation. For well-designed and controlled carburization and quenching processes, residual compressive stresses in the final part surface are expected. High residual compressive stresses in the part surface have been proved to improve the fatigue life [1]. With the help of computer modeling, why and how to obtain surface compressive residual stresses have been investigated and validated for various steel grades, part geometries, and heat treatment processes [2, 3]. However, heat treaters and researchers often ignore the part geometry effect on residual stresses. Using the same carburization and quenching process, the residual stresses of a heat treated cylinder are significantly different from the residual stresses of gears with similar size. The residual stresses along a gear surface are nonuniform after quenching due to its irregular tooth geometry effect. Understanding the relation among gear geometry, heat treatment process, and residual stresses is important. In this paper, the effect of non-uniform tooth cooling on the residual stress distribution in the gear is investigated.

2. Gear Geometry and Finite Element Model

The gear discussed in this paper is made of carburized steel grade AISI 9310. The assumed AISI 9310 steel chemistry is 0.11% carbon, 0.7% manganese, 3.19% nickel, 1.26% chrome, 0.25% silicon,

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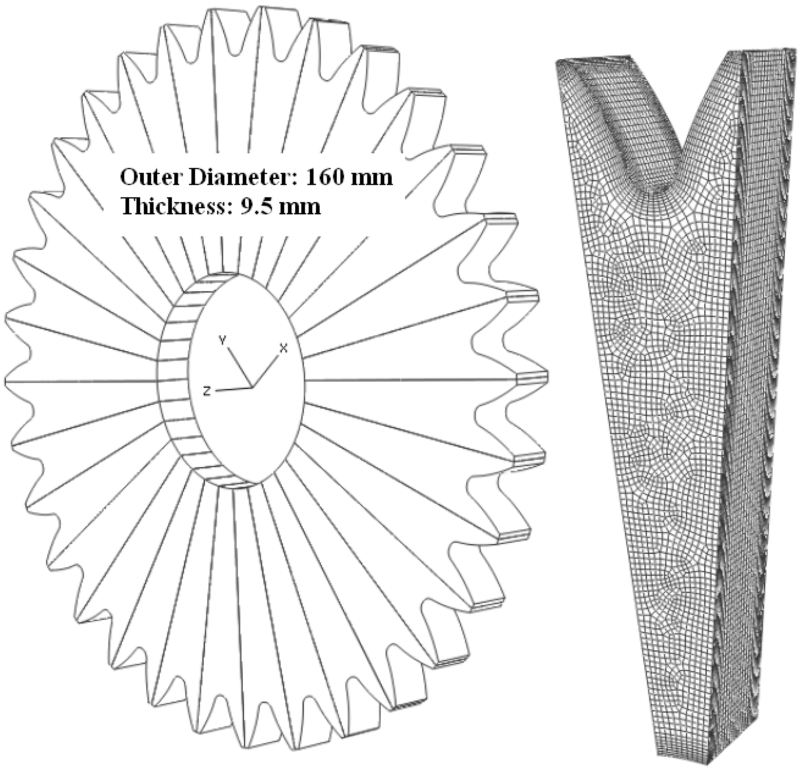
and 0.11% molybdenum. To model the quenching process, both the phase transformation kinetics and mechanical properties for 93XX with up to high carbon case level are required. The BCJ internal state variable mechanical model is used to describe the mechanical behavior of different phases during heat treatment [4].

Figure 1 (a) shows the gear geometry. The outer diameter of the gear is about 160mm, the inner diameter is about 47mm, and the thickness is about 9.5mm. The gear has a total of 32 teeth. A single tooth is cut from the whole gear and used to model the heat treatment process using the cyclic symmetry boundary condition. All the 32 teeth are assumed to behave the same during heat treatment, and the single tooth model represents uniform thermal boundary condition in the circumferential direction. The finite element mesh includes 76832 nodes and 69579 hexahedral elements as shown in Figure 1(b). Fine elements are used in the surface of the part to accurately describe the steep thermal and carbon gradients.



(a) (b)

Figure 1: Gear geometry: (a) whole gear CAD, and (b) single tooth finite element mesh

3. Vacuum Carburization

Before vacuum carburization, all the part surfaces except the tooth flanks and root are copper plated, so only the functional surfaces of the gear are carburized. This is specified to avoid high carbon levels and possible carbide formation in the gear tip or edge regions. DANTE/VCARB is a finite element based software used to design the boost/diffuse schedules for vacuum carburization processes. An embedded optimization method determines the boost/diffuse schedule to best produce the aim case depth and surface carbon, which for this example are a case depth of 1.0mm and an aim surface carbon of 0.7%. The vacuum carburizing conditions are a carburization temperature of 925ºC and acetylene gas at a maximum partial pressure of 1.5 millibars. The designed boost/diffuse schedule is listed in Table 1. The gear was vacuum carburized by Solar Atmosphere, Inc. located at Souderton, PA, USA.

Table 1: Vacuum carburization boost/diffuse schedule for ECD 1.0mm

B/D Schedue	Boost(Sec)	Diffuse(Sec)
1	195	170
2	65	250
3	60	325
4	55	400
5	55	480
6	55	560
7	55	640
8	50	715
9	50	795
10	50	870
11	50	950
12	50	1030
13	50	1115
14	50	1195
15	50	1280
16	50	1365
17	50	6260

The effect of geometry on the material's response during heat treatment is important for gears. For this specific gear, three regions were selected to study the material's response during heat treating. The three regions are "Root-Middle", "Root-Fillet", and "Tooth-Face" as shown in Figure 2. The material responses of interest include temperature, carbon, phase transformation, and internal stresses. Figure 2 shows a plane at the middle thickness of the single gear tooth.

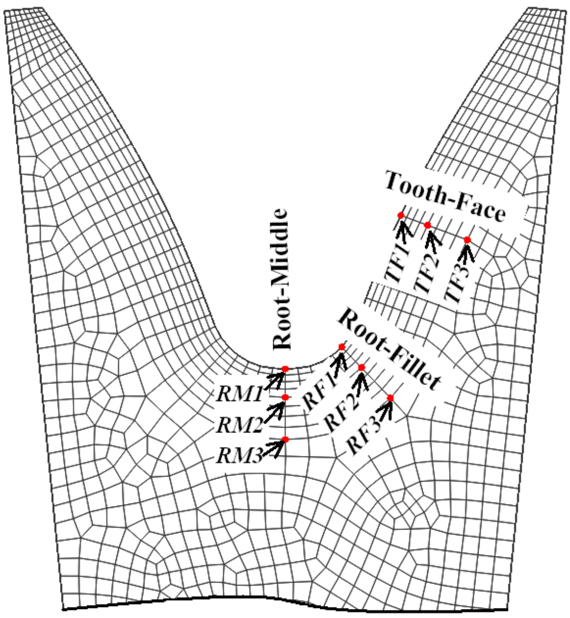


Figure 2: Selected regions and points for investigating material's response during quenching

For each of the three regions, three points were selected to track the material's responses. The three points along the "Root-Middle" line are marked as "RM1", "RM2", and "RM3" respectively. The three points along the "Root-Fillet" line are marked as "RF1", "RF2", and "RF3". The points along the "Tooth-Face" line are marked as "TF1", "TF2", and "TF3". The depths of the three points from the tooth surface are 0.0mm, 0.8mm, and 2.0mm respectively. The line "Tooth-Face" is located between the gear fillet and the tip.

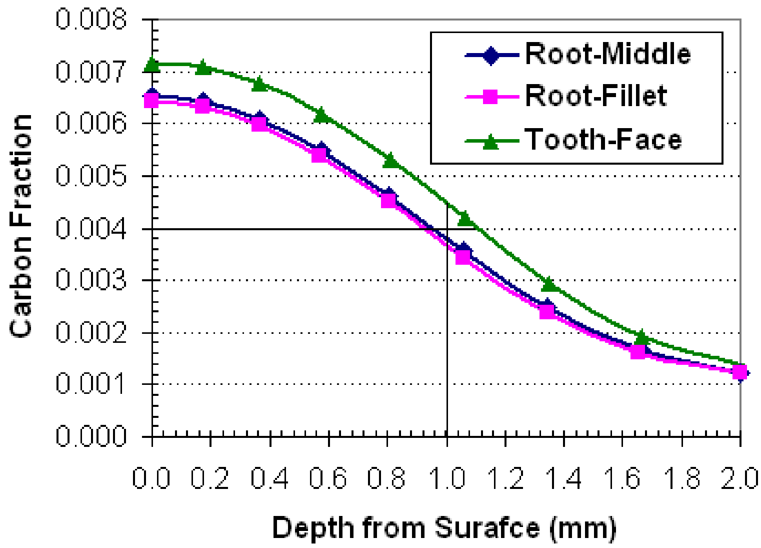


Figure 3: Carbon distribution along the three selected lines

Using the vacuum carburization schedule listed in Table 1, the carbon distributions at the three locations are compared in Figure 3. The X-axis is the depth from surface, and the Y-Axis is the carbon in weight fraction. Figure 3 shows that the "Tooth-Face" region has higher carbon content than the "Root-Middle" and "Root-Fillet" regions, which is caused by the difference of surface to mass ratios of these regions. The carbon weight fractions at the three selected points at regions "Root-Middle" and "Root-Fillet" are about 0.65%, 0.45%, and 0.1% respectively. At the "Tooth-Face" region, the carbon fractions are 0.7%, 0.51%, and 0.1% at the three points, starting from surface. The geometry effect (or surface to mass ratio effect) on carbon distribution is shown by the comparison. The geometry effect is more significant in vacuum carburization than traditional gas carburization process.

4. Finite Element Modeling of Oil Quench Process

The gear was oil quenched after vacuum carburization. The oil temperature was 65°C. Deep freeze and low temperature tempering followed after oil quench. The deep freeze and low temperature tempering process have minor effect on the residual stress state, and these steps are not included in this paper.

Figure 4a shows the cooling histories of the three selected points at the "Root-Middle" region during oil quenching. Defining the tangent of the cooling curve as the cooling rate, this section examines cooling rates at different time segments during the quench. During the first 3.0 seconds in quenching, the cooling rate at the surface point (RM1) is higher than the cooling rates at the interior points (RM2 and RM3); as expected the surface is cooling faster than the part interior. The highest calculated cooling rate at point RM1 is about 250°C/sec, which occurs at about 3.0 seconds in quenching. After 3.0 seconds in quenching, the cooling rates at RM2 and RM3 increase, while the cooling rate at RM1 on the surface decreases. The internal cooling rates at RM2 and RM3 surpass the cooling rate at surface point RM1 after about 4 seconds of quenching. Note that the surface temperature is always lower than the temperature of inner points. Figure 4b compares the cooling rates of the surface points at the three selected regions. The cooling rate at the "Tooth-Face" region is higher than the cooling rates at the "Root-Middle" and "Root-Fillet" regions. However, the cooling rates at the "Root-Middle" and "Root-Fillet" regions are close. Higher cooling rate at the "Tooth-Face" region is due to its higher surface to mass ratio.

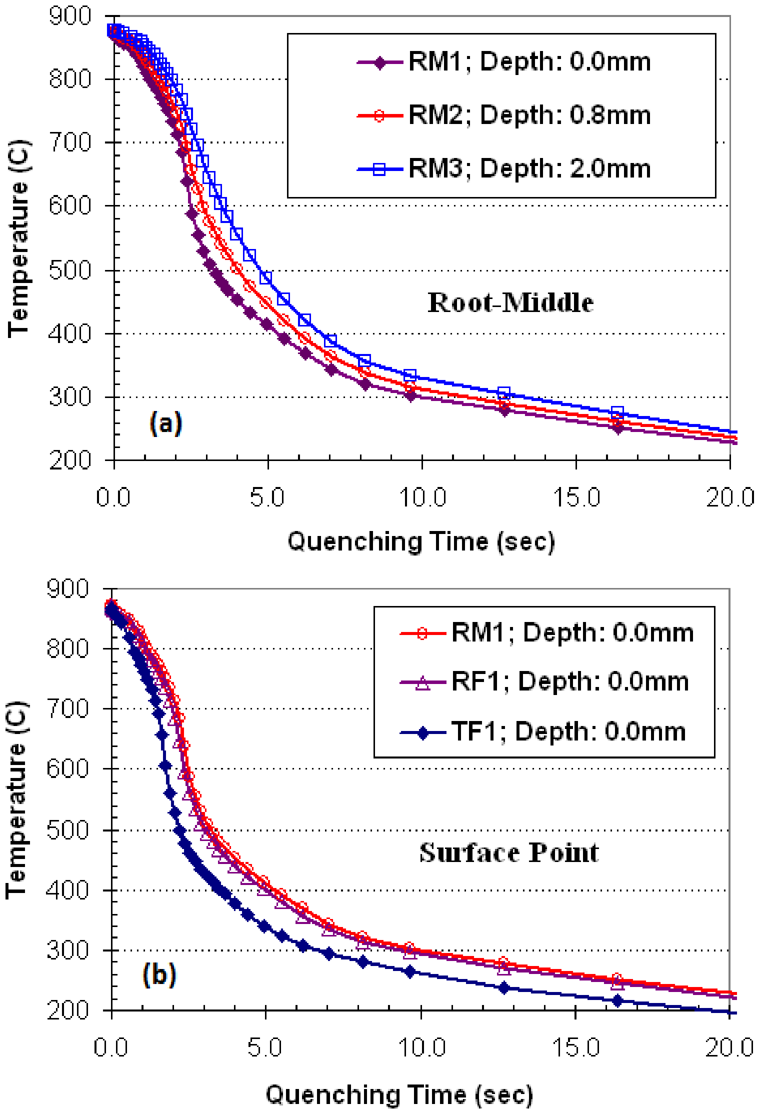


Figure 4: Comparison of cooling histories during oil quench at (a) "Root-Middle" region, (b) surface points of all three regions

Steel grade AISI 9310 has relatively high hardenability. For this specific gear, there is no diffusive phase transformation during oil quenching. Figure 5 plots the austenite volume fraction changes during the oil quench at the "Root-Middle" region. The martensitic phase transformation is affected by temperature and carbon level, with the martensitic transformation starting temperature decreasing with the increase of carbon content. Because of this, the martensitic transformation starts at the case-core location instead of the surface for oil quenching of most carburized steel parts. At the three selected points starting from the surface, RM1, RM2, and RM3, the martensitic phase transformation starts at about 35 second, 25 second, and 10 second in quenching respectively. The cooling rate on the surface is higher than the internal cooling rate during early quenching stage, and the surface temperature is always lower than the internal temperature. However, the martensitic phase transformation is delayed on the surface during quenching due to the high carbon on the surface.

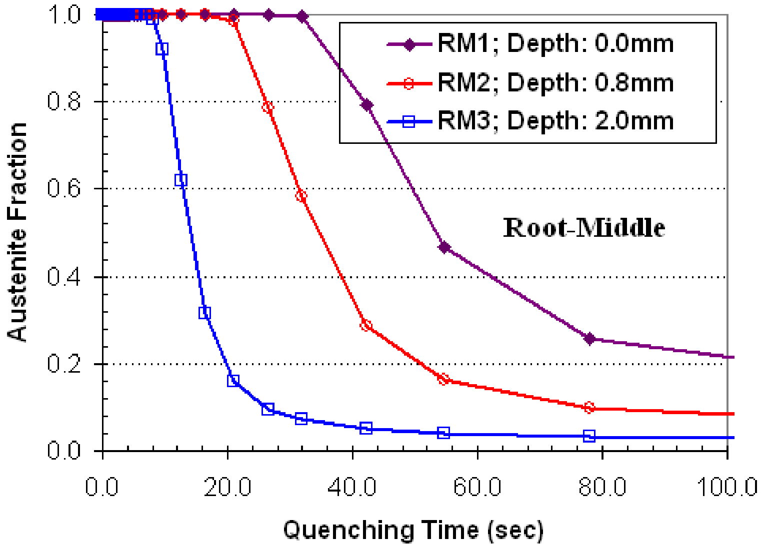


Figure 5: Phase transformation histories during oil quench along the "Root-Middle" line

Figure 6 shows the tangential stress changes in terms of quenching time for the selected points. At the surface points, RM1, RF1, and TF1, the tangential stresses have two tensile peaks during the oil quench. The first peak occurs after 3.0 seconds of quenching, and the second peak occurs after about 30 seconds. During the first 3.0 seconds of quenching, phase transformations have not started, and the thermal gradient is the only cause of stress changes. The surface cooling rates are higher than the interior rates at this time. As a result, tensile stresses build up in the shallow surface. Some plastic deformation occurs at the surface under tension because austenite has low yield strength. Between 3.0 seconds and 10 seconds in quenching, the cooling rates of inner points exceed the cooling rate at the surface. The temperature gradient in the surface reduces, and the surface stress converts from tension to compression. The reasons for the surface compression are the plastic deformation at the surface during early quenching stage and thermal contraction of the part as the interior cools. At about 10 seconds of quenching, martensitic transformation starts at the carbon case core location. The subsurface volume expansion due to martensitic formation will change the transformed region to compression and the neighboring untransformed regions to tensile stress states. Mainly due to the martensitic transformation under the surface, the surface point RM1 has a tensile stress peak of 450 MPA at about 35 seconds in quenching. At the "Root-Middle" region, the martensitic transformation on the surface starts at about 35 seconds of quenching. The surface stress changes from tension to compression with the martensite formation. At about 60 seconds of quenching, the phase transformation in the entire gear is completed. At the "Root-Middle" region, the predicted surface stress is about 400 MPA in compression.

As shown in Figure 6, the predicted surface residual compression at the "Root-Fillet" region is about 750 MPa, which is higher than the compressive stresses in the "Root-Middle" and "Tooth-Face" regions. The difference is caused mainly by the gear geometry effect. During quenching, the gear tooth cools faster than the gear root. The thermal contraction of the gear tooth generates a tensile stress concentration in the "Root-Fillet" region, which causes localized plastic deformation of austenite in this "Root-Fillet" region. With further cooling, the delayed martensitic transformation in the "Root-Fillet" region generates high compression in the carburized case.

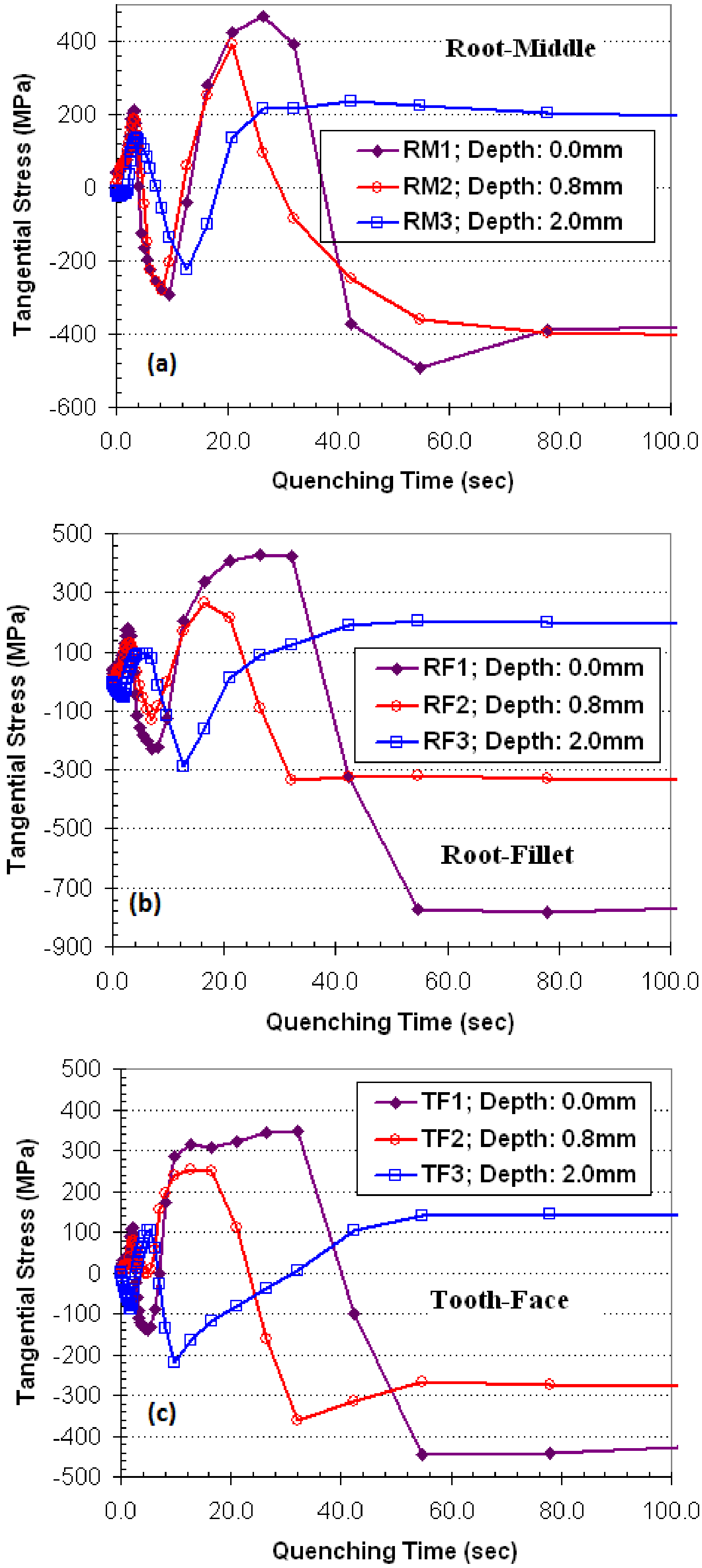


Figure 6: Hoop tress evolutions during oil quench
(a) at “Root-Middle”; (b) at “Root-Fillet”; and (c) at “Tooth-Face”

During single tooth bending fatigue test, the gear normally fails at the "Root-Fillet" location as this is the highest stress location. High residual compression in the "Root-Fillet" region is preferred for improved bending fatigue life. Figure 7 shows the internal stresses of the "Root-Fillet" region under bending load. The X-axis in Figure 7 is the depth from surface at the "Root-Fillet" region, and the Y-axis is the hoop stresses. The line with solid diamonds represents the residual stresses of the heat-treated gear. The line with hollow round marks is the stresses under a bending load of 26,600 newtons with consideration of the heat-treated residual stresses. The line with hollow triangle marks is the stresses under bending load without considering the heat-treated residual stresses; only elastic material properties are used in this bending model. The maximum surface stress in the model with consideration of the heat treated residual stress is more than 700 MPa lower than that for the purely elastic model with no consideration of residual stress. This comparison in Figure 7 between the bending stresses with and without heat treated residual stresses shows the importance of the residual compressive stress due to heat treatment. In current American Gear Manufacturers Association (AGMA) standards, safety factors are used in gear design to calculate gear stresses and residual stress is ignored. Consideration of the residual stress from carburization and quenching processes in gear design and manufacturing is necessary to reduce the gear weight, and guarantee the fatigue life simultaneously.

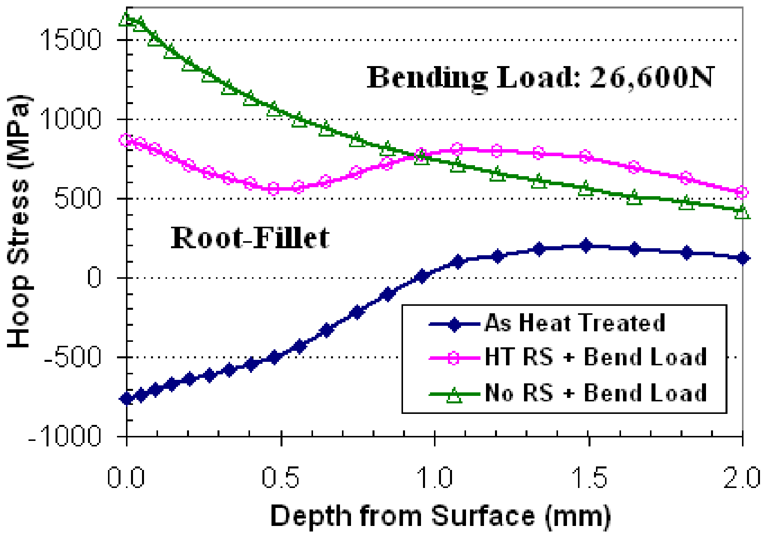


Figure 7: Stresses along the " Root-Fillet" line under fatigue bending load

5. Summary

Carburization and oil quench processes of a gear made of AISI 9310steel have been simulated using DANTE. The effect of gear geometry on carbon distribution and residual stress from quench hardening has been predicted by the model. Single tooth bending models were then run by importing the residual stress from the heat treating models. Residual stresses from the heat treatment processes should be considered by designers for more accurate gear design.

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