

Ferritic Nitrocarburizing of SAE 1010 Plain Carbon Steel Parts

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ABSTRACT

Ferritic nitrocarburizing offers excellent wear, scuffing, corrosion and fatigue resistance by producing a thin compound layer and diffusion zone containing ϵ ($\text{Fe}_{2-3}(\text{C}, \text{N})$), γ' (Fe_4N), cementite (Fe_3C) and various alloy carbides and nitrides on the material surface. It is a widely accepted surface treatment process that results in smaller distortion than carburizing and carbonitriding processes. However this smaller distortion has to be further reduced to prevent the performance issues, out of tolerance distortion and post grinding work hours/cost in an automotive component. A numerical model has been developed to calculate the nitrogen and carbon composition profiles of SAE 1010 torque converter pistons during nitrocarburizing treatment. The nitrogen composition profiles are modeled against the part thickness to predict distortion. Experimental composition profiles of torque converter pistons are reported for model validation and to determine the effect of nitrogen composition on distortion. The surface residual stresses predicted by the model are also compared to the measured residual stresses. The correlations between nitrocarburizing temperature, distortion and composition profiles are discussed using the modeling results.

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INTRODUCTION

Ferritic nitrocarburizing is a thermo-chemical diffusion process in which nitrogen and carbon are diffused into the steel surface to increase the hardness and wear resistance [1]. It is commonly used to case harden gear and many other engineering components. Gear steels made of SAE 4140, 5160, 8620 and certain tool steels are surface engineered using ferritic nitrocarburizing process [2]. During nitrocarburizing, a single-phase layer containing ϵ ($\text{Fe}_{2-3}(\text{N}, \text{C})$) and a diffusion zone containing γ' (Fe_4N), dissolved nitrogen, cementite and various alloy nitrides and carbides are formed [3]. Although nitrocarburizing improve fatigue resistance and provides high resistance to wear, distortion is still a major problem that forces the nitrocarburized material to have grinding operation.

Many researchers have investigated the composition-depth profiles during nitriding/nitrocarburizing treatments to predict the compound layer growth [4, 5, 6]. This paper discusses the distortion predictions associated with the ferritic nitrocarburizing treatment of SAE 1010 torque converter (TC) pistons using the composition-depth profiles. The paper also discusses the prediction of residual stress distribution as a function of depth. Residual stresses are the result of cohesion of the misfitting compound layer to the ferritic substrate and cohesion within the compound layer [7].

MATERIALS AND METHODS

SAE 1010 torque converter piston is a thin shelled automotive powertrain component that has an outer diameter of 0.26 m, inner diameter of 0.062 m and a thickness of 0.0028 m. Distortion was measured using a co-ordinate measuring machine (CMM). CMM is commonly used to measure the dimensional changes of materials. Inner (ID) and outer (OD) diameters were measured before and after heat treatment at two different locations. Ten torque converter pistons were used per heat treatment to measure the distortion. And the average distortion values of nitrocarburized pistons were reported. Figure 1 shows the geometry of torque converter piston.

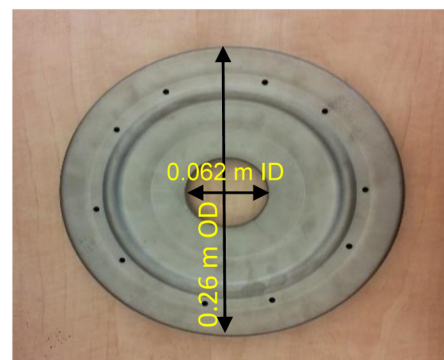


Figure 1. Torque converter piston test part.

The composition-depth profiles of two different heat treatments (gas and vacuum ferritic nitrocarburizing at 565°C/5hrs & 580°C/10hrs) were measured using Electron Probe Micro Analyzer (EPMA).

NUMERICAL APPROACH

Carbon and Nitrogen Composition-Depth Profile Simulation

Fick's second law of diffusion is the governing law of the evolution of the nitrogen concentration during the nitrocarburizing process [8]:

$$\frac{\partial c}{\partial t} = D \left(\frac{\partial^2 c}{\partial x^2} + \frac{\partial^2 c}{\partial y^2} + \frac{\partial^2 c}{\partial z^2} \right) + \frac{\partial D}{\partial c} \left(\frac{\partial c}{\partial x} + \frac{\partial c}{\partial y} + \frac{\partial c}{\partial z} \right) \quad (1)$$

where c denotes the element composition, t is the diffusion time, D is the diffusion coefficient, x , y and z are the spatial coordinates. In the considered system, the diffusion coefficient is assumed constant (independent of element composition) within the same phase region (ϵ , γ' and α) such that $\frac{\partial D}{\partial c} = 0$. In addition, the thickness of the system (along the x axis) is much smaller than any of the other two dimensions $\frac{\partial^2 c}{\partial x^2} \gg \frac{\partial^2 c}{\partial y^2}, \frac{\partial^2 c}{\partial z^2}$. Therefore, the final diffusion equation that was used to calculate the composition profile is reduced to:

$$\frac{\partial c}{\partial t} = D \frac{\partial^2 c}{\partial x^2} \quad (2)$$

The composition-depth profile simulations are developed using MATLAB, in which the governing partial differential equations are converted into a set of finite difference equations. An explicit time integration scheme along with finite centered difference discretization is used for solving the equation (2) to calculate the nitrogen composition-depth profile. The following boundary and initial conditions were applied to the model:

$$c(x=0, t) = 8 \text{ wt. \%} \quad (3)$$

$$c(x=x_n, t) = 8 \text{ wt. \%} \quad (4)$$

$$c(x, 0) = 0 \quad (5)$$

In the present work, $x_n = 0.0028$ m (thickness of torque converter piston). The simulation procedure takes part in the following manner: first, the initial concentration of nitrogen is stated explicitly. By utilizing the assigned diffusion coefficients and boundary conditions, new concentration terms are then calculated based on the known ones. Finally, growth of the phases and their contribution to distortion are predicted. N and C composition-depth profiles for the nitrocarburized treatments were generated by considering ϵ , γ' and α as separate layers. Diffusion coefficient of nitrogen in ϵ , γ' and α phases were given below [9, 10, 11]:

$$D_N^\epsilon = 0.227 \times 10^{-4} e^{\left(\frac{-147600}{RT} \right)} \text{ m}^2/\text{s} \quad (6)$$

$$D_N^{\gamma'} = e^{\left(\left(\frac{-73274}{RT} \right) - 18.775 \right)} \text{ m}^2/\text{s} \quad (7)$$

$$D_N^\alpha = 4.67 \times 10^{-8} e^{\left(\frac{-75150}{RT} \right)} \text{ m}^2/\text{s} \quad (8)$$

where $R = 8.32$ J/mol K and T is the heat treatment temperature (565°C & 580°C). The above three equations ((6), (7) and (8)) were used in the numerical model to calculate the nitrogen diffusivities. The developed model simulates the nitrogen composition-depth profiles of samples subjected to vacuum ferritic nitrocarburizing at 580°C/10hrs and gas ferritic nitrocarburizing at 565°C/5hrs (refer to Fig.2).

Distortion is predicted locally using the following relations:

Distortion due to $\gamma' \rightarrow \epsilon$ phase transformation,

$$\Delta l_\epsilon = \frac{\Delta V_{\epsilon-\gamma'}}{V_\epsilon} l_\epsilon \quad (9)$$

Distortion due to $\alpha \rightarrow \gamma'$ phase transformation,

$$\Delta l_{\gamma'} = \frac{\Delta V_{\gamma'-\alpha}}{V_{\gamma'}} l_{\gamma'} \quad (10)$$

where V_ϵ and $V_{\gamma'}$ are the partial molar volumes of ϵ & γ' phases, l_ϵ and $l_{\gamma'}$ are the thickness of ϵ and γ' phases. $\Delta V_{\epsilon-\gamma'}$ and $\Delta V_{\gamma'-\alpha}$ are the change in partial molar volumes due to the $\gamma' \rightarrow \epsilon$ and $\alpha \rightarrow \gamma'$ phase transformations. From equations (9) and (10), it is clear that the thickness of the nitrocarburized layer should be predicted first in order to find the overall local distortion. The thickness of ϵ and γ' phases can be predicted if the composition of nitrogen in ϵ , γ' and α phase regions are known. The threshold nitrogen compositions required to induce the $\gamma' \rightarrow \epsilon$ and $\alpha \rightarrow \gamma'$ phase transformations are taken from the literature (see Table 1).

Table 1. Composition of nitrogen in ϵ , γ' and α phases [12, 13].

Phase	N ₂ Composition , wt. %
ϵ	> 5.56
γ'	> 0.0876 and ≤ 5.56
α	≤ 0.0876