

Distortion and Residual Stresses in Nitrocarburized and Carbonitrided SAE 1010 Plain Carbon Steel

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ABSTRACT

The focus of this study was to determine the residual stress and retained austenite profiles for carbonitrided and nitrocarburized SAE 1010 plain carbon steel and to relate these profiles to one another and to the distortion resulting from heat treatment. Navy C-ring specimens were used for the purpose of this study and X-ray diffraction techniques were used to measure both residual stress and retained austenite. The findings from this research are then applied to a manufacturing application involving the surface hardening of a thin shelled, plain carbon steel automotive component.

INTRODUCTION

Low carbon steels (0.06 – 0.25% carbon) constitute the highest tonnage of all steels produced each year and continue to be a popular material choice among manufacturers across several industries [1]. Plain carbon steels containing over 0.10% carbon are capable of successful heat treatment as a means of increasing material strength and hardness [2]. Surface hardening techniques are often applied to these steels as a means improving the strength and wear resistance of the material while maintaining its core properties [3]. Surface hardening through diffusion methods involves the chemical modification of the surface and substrate of the material [3]. Through such diffusion techniques, manufacturers can successfully achieve a hard case on the surface of low carbon steels while reducing part distortion [3].

Carbonitriding is a widely accepted thermochemical diffusion process used by industry in the production highly stressed parts including gears, shafts, and bearings [4]. Carbonitriding is a modified form of carburizing in which austenitized ferrous metals are placed within a furnace containing carburizing gases and ammonia (NH_3); the carbonitriding temperature ranges between 705 to 900°C (1300 to 1650°F) [2,5,6]. During this process the NH_3 dissociates at the surface of the

steel [7]. Both the carbon and nitrogen diffuse into the workpiece and upon quenching from the austenite phase field form a hard, wear resistant case with a thickness between 0.075 and 0.75 mm (0.003 and 0.30 in.). This relatively shallow depth, in comparison to carburizing, is the result of reduced process time, temperature, as well as the ability of nitrogen to inhibit the diffusion of carbon into the steel [6].

While the primary effect of carbon is a notable increase in hardness [6], the addition of nitrogen to steel is helpful in forming nitrides which increase surface hardness and in enhancing hardenability making it possible to form martensite in plain carbon and low alloy steels [8, 9].

However, despite nitrogen's ability to improve the surface characteristics of plain carbon steels, this element also lowers the transformation temperature of austenite resulting in the presence of retained austenite within the final component [5]. Although the presence of retained austenite is not always detrimental, the delayed transformation of austenite to martensite at ambient temperatures can lead to both size and shape distortions which can be problematic, particularly for components in close fitting assemblies [5]. If not addressed, this distortion can give rise to serious in-service performance issues including binding, seizing, and freezing [5].

Gaseous ferritic nitrocarburizing is another form of surface hardening that involves diffusion of carbon and nitrogen into the surface of steel [1, 7, 10]. During this process both nitrogen and carbon diffuse into the solid solution of iron becoming trapped within the interstitial lattice spaces of the steel [11]. Process temperatures for nitrocarburizing range between 525 and 650°C (975 and 1200°F) [11]; the process takes place completely within the ferrite phase field [10,12]. Due to the absence of the phase transformation from austenite to martensite, as is observed with carbonitrided steels, the nitrocarburizing process results in the formation of a hard, wear resistant case composed of a compound layer and a diffusion zone. The compound layer is formed at the surface of

the steel and is associated with many attractive tribological properties that include wear, scuffing, and corrosion resistance [7, 10, 11]. The layer consists of a thin single-phase layer of epsilon (ϵ) iron-carbonitride ($\text{Fe}_{2-3}(\text{N,C})$) which ranges in thickness between 10 and 40 μm (0.0004 and 0.0016 in.) [13]. The diffusion zone is located beneath the compound layer and is associated with improved fatigue properties, particularly in carbon and low alloy steels [11-13]. This region consists of iron (and alloy) nitrides and absorbed nitrogen [13]. The combined thickness of both the compound layer and diffusion zone can reach up to 1 mm (0.04 in.) [13]. The major advantages of the nitrocarburizing process, as it applies to this application, is the ability to produce a hard, wear resistant case with minimal part distortion. Since the nitrogen and carbon are added to the steel at temperatures below the Ac_1 [1, 7], the process takes place in the absence of a phase transformation thereby significantly reducing part distortion.

The developments of residual stresses are common to many surface hardening treatments [1]. In general terms, residual stresses are defined as the self equilibrating internal stresses present in a free body which has no external forces or constraints acting upon it [15]. While some residual stresses can be detrimental, others are beneficial [1]; the compressive stresses developed on the surface of steel during hardening treatments can help to further improve wear and fatigue resistance [4]. During cooling, there are two types of physical changes which can induce residual stresses [1]. In high temperature processes, such as carbonitriding, residual stresses are induced by the phase transformation of austenite to martensite during quenching [1]. In low temperature processes, such as nitrocarburizing, residual stresses result from the thermal contraction of the workpiece upon cooling [1]; the residual stresses generated are not specific to a phase transformation [14].

Residual stress profiles in polycrystalline materials can be determined in a non-destructive manner using X-ray diffraction (XRD) techniques [16, 17]. By measuring the interplanar spacing between the crystallographic planes and using Poisson's ratio, Young's modulus, and the assumption that stress is proportional to strain, values of residual stress can be obtained. Due to the limited depth penetration of x-rays, in order to determine the residual stress within the subsurface layers of the steel electropolishing techniques are used to etch back from the surface in controlled increments [1, 18].

In carbonitriding, the development of favorable compressive stresses between the case and core help to enhance the surface properties of the workpiece [4]. Figure 1 is a schematic diagram showing the relationship between the residual stress profile in a sample of hardened steel and the carbon content and retained austenite profiles in the same steel [4,19]. The maximum compressive stress does not occur at the surface of the workpiece but rather at some distance

from the surface. This effect is due in part to the presence of retained austenite within the steel. It has been suggested by Koistinen [20] that the peak compressive stresses are located at 50-60% of the total case depth and correspond to the point at which the carbon content is approximately 0.5-0.6% and the presence of retained austenite is at a minimum.

Determining the residual stress profiles in nitrocarburized steels often proves more challenging; technical difficulties with XRD techniques makes it difficult to determine the residual stresses within the compound layer [14]. While little data exists on the residual stresses in nitrocarburized steels, it has been generally agreed that tensile stresses are present within the compound layer [14]. The compressive residual stresses within nitrocarburized steels are developed within the diffusion zone [14, 19].

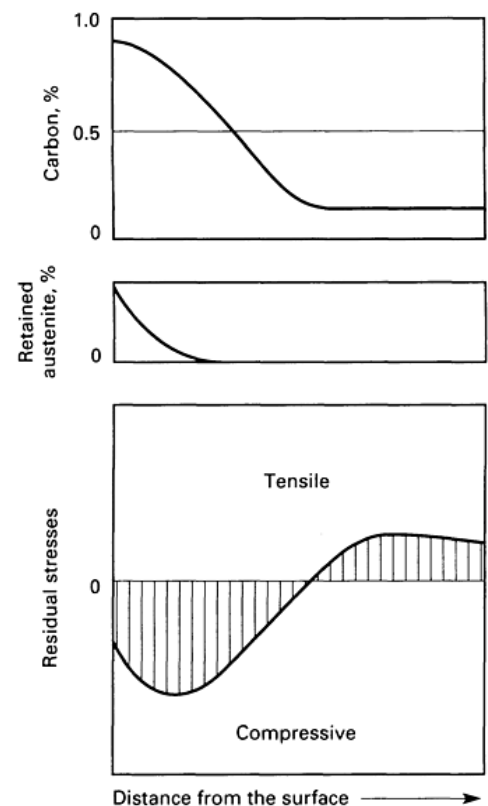


Figure 1 Relationship between carbon content, retained austenite, and residual stress pattern. The peak compressive stress is located at some distance away from the surface [4, 19].

The carbonitriding and nitrocarburizing processes are surface hardening treatments that allow manufacturers to achieve hard, wear resistant cases on the surface of plain carbon and low alloy steels. Despite differing process temperatures, both carbonitriding and nitrocarburizing are associated with changes in their residual stress profiles and both processes can lead to distortion. The intention of this study is to examine and compare the residual stress and hardenability profiles and the distortion for the carbonitriding and

nitrocarburizing processes. The results of this study can then be used in selecting a heat treatment schedule suited to a thin shelled plain carbon steel automotive component in a light loading application.

EXPERIMENTAL DETAILS

In order to compare both the residual stress and retained austenite profiles resulting from the carbonitriding and nitrocarburizing processes, Navy C-ring specimens were used. The geometry of the Navy C-ring used in this study is shown in Figure 2. Two specimens were machined from a bar stock of hot rolled SAE 1010 plain carbon steel. The carbonitriding process was used to treat one sample (C-1) while gaseous ferritic nitrocarburizing was applied to the other (N-1). Nine other identical Navy C-ring specimens were machined for each processing condition: these were used for distortion measurements. The composition of the steel is given in Table 1.

Table 1 Chemical composition (Wt. %) of SAE 1010 plain carbon steel [2].

Element		Wt. %
Carbon	(C)	0.08 - 0.13
Iron	(Fe)	99.18 - 99.62
Manganese	(Mn)	0.3 - 0.6
Phosphorus	(P)	Max 0.04
Sulfur	(S)	Max 0.05

Sample C-1 underwent the carbonitriding process in a laboratory furnace together with 9 identical C-ring specimens which were used for the distortion measurements. The samples were held at 843°C (1550°F) for 4 hours, removed from the furnace, oil quenched to room temperature, and tempered for 1 hour at 163°C (325°C).

Gaseous ferritic nitrocarburizing was used to treat sample N-1 which was placed in a large production furnace along with 9 identical C-ring specimens. The test specimens were held at 566°C (1050°F) for 8 hours, furnace cooled to 371°C (700°F) using nitrogen gas, removed from the furnace, and air cooled to room temperature.

Following treatment, the retained austenite and residual stress profiles were measured on samples C-1 and N-1; these measurements were taken at the “bottom” of each C-ring as shown in Figure 3.

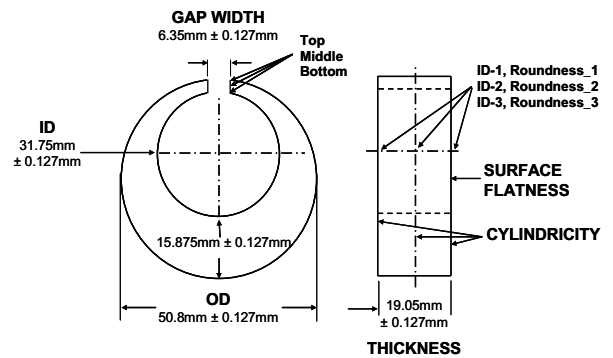


Figure 2 Navy C-ring geometry and distortion measurement positions.

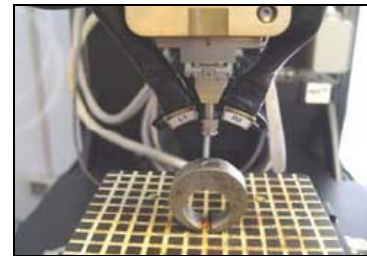


Figure 3 Location of retained austenite and residual stress measurements.

RETAINED AUSTENITE PROFILES – Determining the amount of retained austenite within the surface hardened C-ring specimens was accomplished by means of XRD techniques, more specifically, the “Four-Peak Method”, a technique which uses the (200) and (211) martensite peaks and the (200) and (220) austenite peaks. CrK α X-ray radiation with a wavelength of 2.291 Å (30.00 kv, 25.00 mA) was used with a vanadium filter in the diffracted beam [21]. Six measurements were taken for each C-ring; retained austenite profiles for both the carbonitrided and nitrocarburized specimens were measured from the surface of the steel to a depth of approximately 1.5 mm. The results obtained were expressed as a percentage of retained austenite. The percent error of the values is $\pm 2\%$.

RESIDUAL STRESS PROFILES – XRD techniques were also used in determining the residual stress profiles of the C-ring specimens. Hoop and axial stress were measured at 11 locations on each C-ring specimen from the surface of the steel to a depth of approximately 2.5 mm. The hoop stress (tangential stress) was measured in the direction perpendicular to the radius of the C-ring and axial stress was measured in the direction along the radius. Stresses were calculated by measuring the lattice deformations on the {211} martensite peak using CrK α X-ray radiation with a wavelength of 2.291 Å (30.00 kv, 25.00 mA); a filter was not used. Residual stress values were determined at the following Ψ angles: 0°, $\pm 5.51^\circ$, $\pm 12.00^\circ$, $\pm 19.41^\circ$, and $\pm 25.00^\circ$. The Bragg angle, 2θ , was set at 156° . The error in the readings ranged between ± 6.9 to ± 11.4 MPa.