

Residual Stresses and Dimensional Changes in Ferritic Nitrocarburized Navy C-rings and Prototype Stamped Parts Made from SAE 1010 Steel

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ABSTRACT

Nitrocarburizing is an economical surface hardening process and is proposed as an alternative heat treatment method to carbonitriding. The focus of this study is to compare the size and shape distortion and residual stresses resulting from the ferritic nitrocarburizing and gas carbonitriding processes for SAE 1010 plain carbon steel. Gas, ion and vacuum nitrocarburizing processes utilizing different heat treatment temperatures and times were performed to compare the different ferritic nitrocarburizing processes. Navy C-Ring specimens and prototype stamped parts were used to evaluate size and shape distortion. X-ray diffraction techniques were used to determine the residual stresses in the specimens. Overall, the test results indicate that the nitrocarburizing process gives rise to smaller dimensional changes than carbonitriding, and that the size and shape distortion can be considerably reduced by applying appropriate ferritic nitrocarburizing procedures.

INTRODUCTION

The term "Surface Engineering" was coined in the UK in 1970s to describe "the design of a composite system (coating plus substrate) that provides a performance that can not be achieved by either the coating or substrate in isolation" [1]. The Surface Engineering Division of the Institute of Materials, Minerals and Mining has divided surface engineering into 6 sectors, namely: High value; Energy/Aerospace; Transport; Packaging; White Goods; Biomedical [2].

As pointed out by Rickerby [1], many of our modes of transport are improved by surface engineering. For example, coatings are applied to reduce rolling and frictional losses within mechanical assemblies in order to both extend component lifetimes and minimize total lifecycle energy consumption of automobiles [1]. Surface engineering has also been utilized to help overcome corrosion problems that once plagued the automotive industry [1]. Thermochemical diffusion processes such as carburizing, carbonitriding and nitrocarburizing are extensively used in the automotive industry to impart a hard and wear resistant case to steel components whilst maintaining the core properties [3].

Carburizing is a case-hardening process in which carbon is absorbed and diffused into a low-carbon steel in contact with a carbonaceous material or atmosphere at a temperature in the austenite phase field ($>A_3$). The main objective of carburizing is to obtain a high-carbon

martensitic case with good wear and fatigue resistance along with a tough, low-carbon steel core. Gas carburizing can be performed at temperatures between 800-1090 °C (1472 to 1994 °F) [4], but common industry practice finds that gas carburizing is typically performed at temperatures between 850-950 °C (1562 to 1742 °F) [5, 6].

Carbonitriding is a modified carburizing process in which ammonia (NH₃) is introduced into the carburizing atmosphere. Nascent nitrogen forms by the dissociation of ammonia in the furnace atmosphere, and diffuses into the work surface simultaneously with carbon [7, 8, 9]. Typically, carbonitriding is done at temperatures ranging between 705 and 900 °C (1300 to 1650 °F). Because the nitrogen inhibits the diffusion of carbon, and considering that carbonitriding is performed at lower temperatures and shorter times than carburizing, the carbonitrided case is relatively shallow, usually between 0.075 to 0.75 mm (0.003 to 0.030 in.) [7, 10].

Nitriding is a ferritic thermochemical method of diffusing nascent nitrogen into the surface of steels at temperatures that range from 500 to 550 °C (930 to 1020 °F). Similar to carburizing, nitriding changes the surface composition. However, nitrogen is added into ferrite instead of austenite, which means that nitriding requires no phase change from ferrite to austenite or further quenching to form martensite. As a result, it can be accomplished with a minimum of distortion and with excellent dimensional control. The solubility of nitrogen in iron allows it to form a solid solution with ferrite at nitrogen contents up to about 6%. At a nitrogen content of about 6%, Fe₄N is produced, which is called gamma prime (γ'). At nitrogen contents greater than 8%, the equilibrium reaction product is the epsilon (ε) compound, known as Fe₃N. Nitrided steels are composed of three regions—the compound layer, the diffusion zone and the core. The compound layer contains two intermixed phases, ε and γ', and is usually very hard and brittle. The compound layer is also known as the white layer because it etches white in metallographic preparation. The layer remains on the immediate surface and grows thicker with time, temperature, and gas composition instead of diffusing into the steel [11]. The carbon content significantly affects the composition of the compound layer. The higher the carbon content of the steel, the greater the ε-phase in the compound layer. On the contrary, the lower the carbon content, the greater the γ'-phase. The region beneath the white layer is called the "diffusion zone", which is made up of stable nitrides formed by the reaction of nitrogen with nitride-forming elements. The area below the diffusion zone is the core of the steel, which consists of tempered martensite or other microstructures depending on carbon content [11, 12].

In comparison, nitrocarburizing is a modified form of nitriding, which involves the diffusion of both nitrogen and carbon to the surface of ferrous materials at temperatures completely within the ferrite phase field. Nitrocarburizing is carried out at temperatures between 525 and 650 °C (975 to 1200 °F) [11, 13]. During this process, nitrogen is considerably more soluble in steel than carbon and therefore mainly diffuses into the material, while the carbon forms iron or alloy carbide particles at or near the surface [14].

The common result of nitrocarburizing is a thin single-phase layer of epsilon (ε) iron-carbonitride (Fe_{2.3}(N,C)), a hexagonal ternary compound of iron, nitrogen, and carbon—formed between 450 and 590 °C (840 to 1095 °F). The thickness of this compound layer is a function of temperature, time, gas composition and volume, and pretreatment of the steel, and is usually between 10 and 40 μm (0.0004 and 0.0016 in.) for most applications. The compound layer is responsible for improvements in wear, scuffing resistance and corrosion resistance. Beneath the compound layer is the diffusion zone which contains varying amounts of gamma prime (γ') and epsilon (ε) phase, cementite, and various alloy carbides and nitrides. The exact composition depends on the nitride-forming elements in the steel and the composition of the atmosphere. The diffusion zone improves fatigue endurance and also responsible for some of the increased hardness of the nitrocarburized case [10, 11, 15].

One very important difference between nitrocarburizing and carbonitriding is that nitrocarburizing is a low-temperature process whereas carbonitriding is a high temperature process. "Low temperature" refers to a temperature below which the transformation to austenite starts (A₃) and "high temperature" is above the same A₃ temperature. The major advantages with nitrocarburizing are the minimal dimensional changes and distortion of the treated parts, due to the low process temperature and the fact that no phase transformation occurs. These advantages eliminate costly grinding operations, shorten the production cycle, and decrease the costs [16].

A carbonitriding process was being used to improve the hardness and wear resistance of an automotive transmission component, namely a torque convertor piston [17]. Although the desired surface case was achieved using the carbonitriding process, there were issues associated with the quenching step to form martensite, particularly the changes in final size and shape of the part. In order to meet the dimensional specifications, the size and shape distortions resulting from heat treatment were corrected using finish grinding, a technique in which excess material is removed from the surface of the steel [18]. While this method ensures

that dimensional specifications are met, the added manufacturing step contributes to longer production times and higher part costs, and also raises the risk of grind burns.

In order to reduce distortion in thin-walled automotive components that are fabricated from low carbon steel, e.g., torque convertor pistons, gaseous ferritic nitrocarburizing has been investigated as a replacement for carbonitriding [19, 20, 21]. When comparing nitrocarburized and carbonitrided 1010 plain carbon steel, it has been demonstrated that overall part distortion is smaller in nitrocarburized samples [20].

The present study investigated a number of different nitrocarburizing methods and heat treatment schedules for the nitrocarburizing of SAE 1010 plain carbon steel. Two types of specimens were used for the study, namely Navy C-rings and prototype stamped parts. Navy C-rings are specially designed specimens used to examine distortion in heat-treated components [22]. As well as distortion (size and shape) measurements, the microstructure of the nitrocarburized samples and the surface residual stresses, were characterized. Specimens that were carbonitrided to production practice schedules were also characterized for comparative purposes.

EXPERIMENTAL DETAILS

(1) Materials

A total of 21 Navy C-ring specimens and 105 prototype stamped parts were used in the testing. All parts were fabricated from SAE 1010 plain carbon steel, the composition of which is given in Table 1.

Table 1 Chemical Composition (Wt. %) of SAE 1010 Plain Carbon Steel

Element	Wt. %
Carbon (C)	0.07-0.12
Manganese (Mn)	0.43-0.61
Phosphorus (P)	0.008-0.012
Sulfur (S)	0.006-0.008
Silicon (Si)	0.03-0.07
Chromium (Cr)	0.03-0.05
Nickel (Ni)	0.01-0.03
Molybdenum (Mo)	0.01
Copper (Cu)	0.02-0.09
Aluminum (Al)	0.021-0.052
Vanadium (V)	0.001-0.002
Columbium (Cb)	Max 0.018
Titanium (Ti)	0.002-0.010
Cobalt (Co)	Max 0.01
Tin (Sn)	Max 0.01
Boron (B)	0.0003-0.0004
Calcium (Ca)	0.0001-0.0013

(2) Navy C-ring Geometry

The geometry of the Navy C-ring used in this study is shown in Figure 1. The C-rings were cut from bar stock of hot rolled SAE 1010 plain carbon steel by EDM (Electrical Discharge Machining). C-ring samples with thickness of 2.8 mm were prepared for different processes and property evaluation. Changes of outside diameter (OD), inside diameter (ID), gap width and surface flatness were used to determine the dimensional distortion.

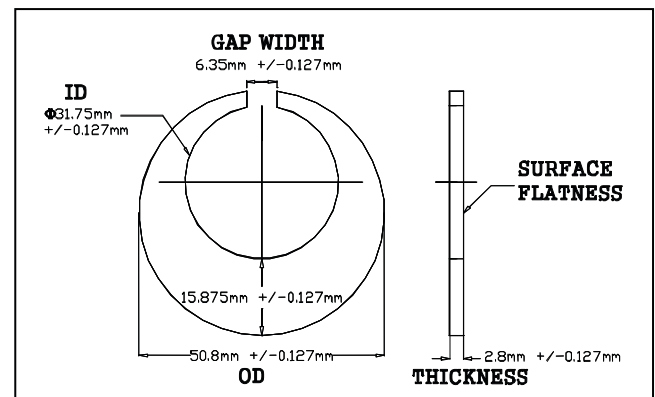


Figure 1 Navy C-ring geometry and distortion measurement positions

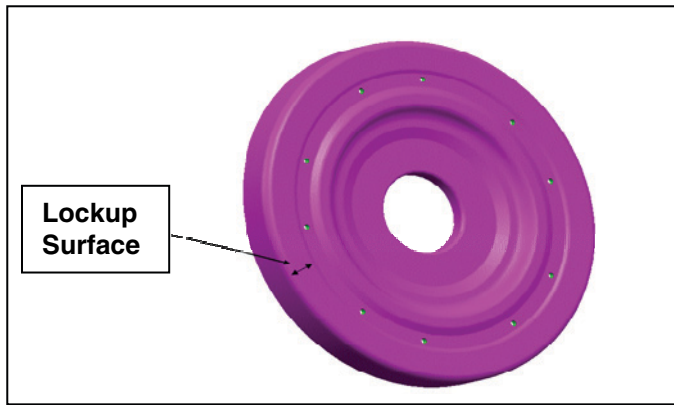


Figure 2 Profile of a piston

(3) Prototype Stamped Part Geometry

The prototype stamped part was a piston, an important component of the torque converter (see Figure 2). Beginning with a blank, the piston goes through a progressive five-stage stamping operation before heat treatment. For piston samples, changes of ID, total flatness and flatness taper were used to determine the dimensional distortion. ID was evaluated at -11 mm and -15 mm longitudinal height positions with respect to the lockup surface (as shown in Figure 2).

(4) Heat Treatment Details

The samples were divided into 11 groups to undergo either gas carbonitriding or ferritic nitrocarburizing. Table 2 lists the different heat treatment temperatures and times that were applied depending on the heat treatment process. All the processes were identified using symbols *a* to *k*.

Ion nitrocarburizing, synonymous with plasma nitrocarburizing, is essentially a variant of the plasma (ion) nitriding method. Plasma (ion) nitriding is a method of surface hardening using glow discharge technology to introduce elemental nitrogen to the work surface for subsequent diffusion into the material [23]. Compared to conventional gas nitriding procedures, plasma nitriding offers several additional possibilities of parameter variation and therefore a better control of the layer structure, morphology and service characteristics, which leads to a better reproducibility of the nitriding process [24]. Typically, plasma nitrocarburizing is carried out at 570 °C (1060 °F) to form a compound layer of thickness >5 µm and a surface hardness of ≥350 HV. The plasma atmosphere is a mixture of hydrogen, nitrogen, and a carbon-bearing gas (e.g., methane or carbon dioxide). The advantages associated with plasma heat-treatment technology include: no toxic fumes or waste produced; no risks of explosion; no significant dirt, noise, or heat pollution; reduced processing times; reduced energy consumption; reduced treatment gas consumption [13, 15].

Vacuum nitrocarburizing is a subatmospheric pressure nitrocarburizing process using a basic atmosphere of 50% ammonia / 50% methane, containing controlled oxygen additions of up to 2% [25]. The advantage of vacuum processing is that it produces a very pure starting atmosphere, eliminates the need for a nitrogen purge, and is also able to clean the surface of the parts using hydrogen prior to the nitriding step of the cycle [26].

Table 2 Heat Treatment Processing Matrix for Navy C-ring Specimens and Prototype Piston Samples

No.	Process	Heat Treatment Schedule	Symbol	Number of Samples	
				Pistons	C-rings
1	Gas Ferritic Nitrocarburizing + Nitrogen Cooling	510 °C (950 °F) / 15 hrs	<i>a</i>	10	2
2		540 °C (1000 °F) / 10 hrs	<i>b</i>	10	2
3		565 °C (1050 °F) / 5 hrs	<i>c</i>	10	2
4		595 °C (1100 °F) / 4 hrs	<i>d</i>	10	2
5	Ion Ferritic Nitrocarburizing	560 °C (1040 °F) / 15 hrs	<i>e</i>	10	2
6		525 °C (975 °F) / 24 hrs	<i>f</i>	10	2
7	Gas Ferritic Nitrocarburizing (N potential) + Nitrogen Cooling	525 °C (975 °F) / 52 hrs	<i>g</i>	10	2
8		570 °C (1058 °F) / 4 hrs	<i>h</i>	10	2
9	Vacuum Ferritic Nitrocarburizing	580 °C (1075 °F) / 10 hrs	<i>i</i>	10	2
10	Gas Ferritic Nitrocarburizing + Quenching	580 °C (1075 °F) / 2 hrs + water base solution quench	<i>j</i>	10	2
11	Gas Carbonitriding	850 °C (1562 °F) / 4 hrs + 100 °C (212 °F) oil quench	<i>k</i>	5	1

(5) Optical Metallography

The piston specimens were cut into small sections (1×2 cm) and mounted in a thermoplastic molding resin. The surface of the mounted samples was polished using 280, 400, 800, and 1200 silicon carbide papers followed by $0.1 \mu\text{m}$ and $0.05 \mu\text{m}$ alumina polishing compounds. The polishing procedure was periodically checked under the optical microscope to determine if the scratches were fading. After polishing, the surface was etched using 2% Nital to bring out the phase structure [11].

Figure 3 shows the case depth of a carbonitrided sample. In the core of the sample, as shown in Figure 4, the structure is ferrite (white), pearlite (dark islands) and bainite (needle-like). Figure 5 shows a typical white layer epsilon phase and gamma diffusion zone for a gas ferritic nitrocarburized sample [27].

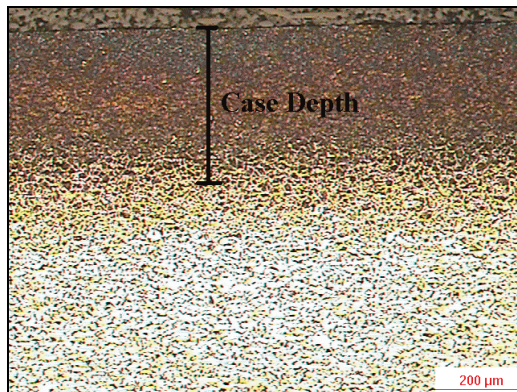


Figure 3 Case depth of the carbonitrided (polished, etched, 100X)

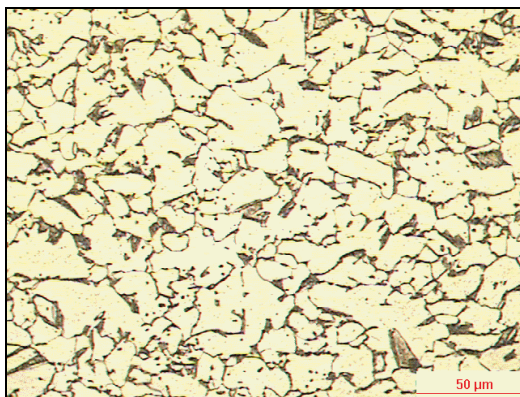


Figure 4 Core microstructure of the carbonitrided sample (polished, etched, 500X)

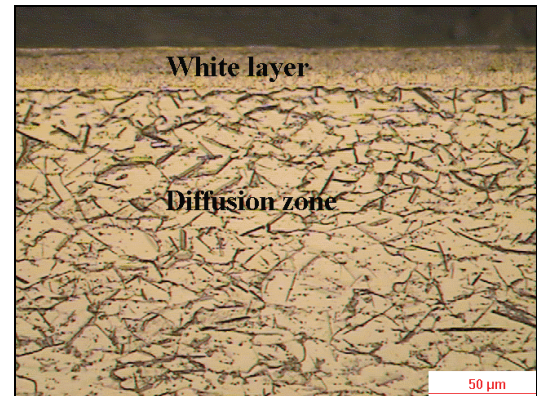


Figure 5 Microstructure of the gas ferritic nitrocarburized sample (polished, etched, 500X)

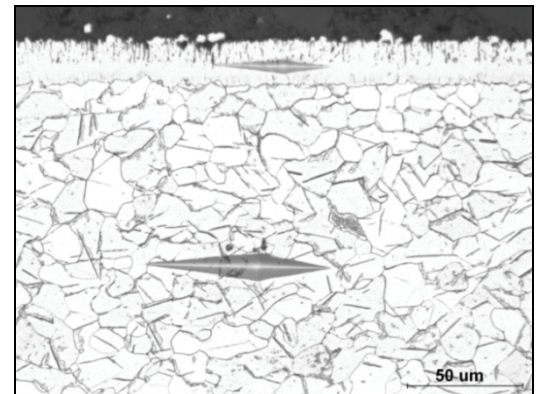


Figure 6 Hardness of case and diffusion zone

(6) Microhardness

Microhardness measurements were carried out using Tukon 2100B hardness tester under a load of 100 gram. Typical results are shown in Figure 6 for a nitrocarburized sample. The Knoop hardness of the case (white layer) was HRC 62, and Knoop hardness of the diffusion zone was HRB 25.9.

(7) Measurement of Distortion and Residual Stress from Heat Treatment

• Dimensional Measurements

Four specified dimensions on each piston and C-ring sample were measured using a Prismo Coordinate Measuring Machine (CMM) before and after heat treatment. Figure 7 is a photograph showing the location of the surface flatness measurement on the piston samples. These results were then used to compare both size and shape distortion for the different heat treatment processes.