

Microstructural Effects on Residual Stress, Retained Austenite, and Case Depth of Carburized Automotive Steels

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ABSTRACT

SAE 8620 and other steels are typically used in the carburized condition for powertrain applications in the automotive industry, *i.e.*, differential ring gears, camshafts, and transmission gears. Although current recommended carburizing practice involves normalizing the steel prior to carburizing, elimination of this normalizing treatment could lead to significant cost reductions. This research examines whether the normalizing process prior to carburizing could be eliminated without negatively affecting part performance. This study focused on the effects of the initial microstructure on the residual stress, retained austenite, and effective case depths of carburized SAE 8620 and PS-18 steels.

INTRODUCTION

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. SAE 8620 and other steels can be used in the carburized condition for automotive transmission gears, camshafts, piston pins, bearings, and similar parts of moderate section size for relatively severe service [1].

Gas carburizing is used most often for large-scale production, with the two-stage boost-diffuse technique being widely applied [2]. Gas carburizing can be performed at temperatures between 800-1090°C [3], but common industry practice finds that gas carburizing is typically performed at temperatures between 850-950°C [4, 5]. During the initial stage of a boost-diffuse carburizing process, the carbon potential is maintained in a range close to the solubility limit of carbon in austenite, typically 1.0 to 1.2 % carbon depending on the temperature and alloy content of the steel [6]. In the second stage, the carbon potential of the atmosphere is

lowered to a level that will maintain surface carbon between 0.8 and 0.9 % carbon [4, 6], while allowing excess case carbon to diffuse further into the steel. The steel components are then quenched in oil.

In practice, it is almost universally accepted that steel components should be normalized prior to carburizing [7-10]. Normalizing involves heating steel to a temperature above the transformation range ($>A_3$) and then cooling in still air to a temperature that is substantially below the transformation range. The normalizing temperature depends on the steel composition, but is usually around 870-925°C [7]. Normalizing acts to refine and homogenize the austenitic grain structure and generally improves machinability.

The sub-surface carbon gradients produced in the austenitic phase during carburizing allow martensite formation to occur upon quenching. As the carbon content decreases from the surface to the core, there is a transition from plate to lath martensite morphology, and the amount of retained austenite decreases continuously. The required case depth is related to the size of the part and generally increases with part size to produce desirable residual stress distributions. Case depths can vary over a broad range, with 0.13 to 8.25 mm being typical [3]. The case depth can be expressed as either the effective or total case depth. The effective case depth is the perpendicular distance from the surface to a point at which a specified level of hardness is reached; this hardness level is usually 50 HRC [10]. The total case depth is the perpendicular distance from the surface to a point at which differences in chemical or physical properties of the case and core can no longer be distinguished.

When furnace atmospheres used for production carburizing contain endothermic gas, it is difficult to avoid surface oxidation when the steel is in the austenitic state [6, 11]. Intergranular oxidation can be observed to depths up to 25 μm [2, 12]. The removal of alloying elements such as Cr, Mn, and Si [12] from solid surfaces

upon formation of oxides can have negative effects on the metallurgical and mechanical properties of the steel.

Carburized components always contain retained austenite to varying degrees in the as-hardened and also in the tempered microstructures. The M_f temperature is often well below room temperature for many hardenable steels, so that for conventional heat treating conditions, the existence of retained, or untransformed, austenite is unavoidable [13]. Retained austenite weakens the strong, hard surface of a carburized component, decreasing load-carrying capacity and wear resistance. Typical retained austenite contents in the near surface case regions of direct-quenched carburized steels range from approximately 20-30% [6]. Variables influencing the amount of retained austenite include alloying elements, carbon potential, carburizing temperature, quenchant temperature, and cooling rate [8, 13, 14].

The x-ray diffraction (XRD) method is a well established retained austenite measurement technique; it can measure retained austenite contents greater than 1% by volume with excellent precision [15, 16]. From a given diffraction pattern, the retained austenite content can be determined by comparing the integrated intensities of selected (hkl) plane reflections of the martensite and austenite phases [14, 17]. The integrated intensity of any reflection from a phase is proportional to its volume fraction or concentration [13, 17].

There are two types of residual stresses experienced by carburized components: thermal stresses and transformation stresses. Thermal stresses are developed in any metallic material that is cooled rapidly from an elevated temperature and has substantial thickness [18-20]. During the quenching of carburized components, transformation stresses arise due to the volume expansion associated with the decomposition of austenite to martensite [8, 19, 20]. Ideally, carburized parts have compressive stresses in the case and tensile stresses in the core. Compressive stresses in the surface layer of carburized steels offset applied tensile bending stresses, significantly increasing fatigue resistance. The compressive stresses in the case are a result of combining two phenomena: 1) temperature gradients present during quenching, and 2) M_s gradients caused by carbon gradients in the austenite due to carburizing [6, 12, 18]. The magnitude of surface compressive residual stresses in carburized parts is controlled by surface carbon content, case depth, quenching conditions, hardenability of the case and core material, and tempering after hardening [19, 21].

XRD residual stress measurement operates on the principle that stress below the yield strength is taken up by interatomic elastic strain [17, 22-24]. This technique uses changes in interatomic plane spacing to measure elastic strain, from which the residual stress can be calculated. Residual stress gradients are generally present in the near surface area of all materials. Stress measurements as a function of depth can be performed

by sequentially removing material using electro-polishing techniques [24].

The driving force for this research was to determine whether the normalizing process prior to carburizing could be eliminated without negatively affecting part performance. This study focused on the effects of the initial microstructure on the residual stress, retained austenite, and effective case depths of carburized SAE 8620 and PS-18 steels. It complements previous investigations [25, 26] of the effects of microstructure on distortion, hardenability, and core mechanical properties of the same carburized automotive steels. The feasibility of using either a new steel or heat treatment process cycle requires acceptable properties in both the case and the core; both directly affect part quality and performance.

EXPERIMENTAL DETAILS

This study involved testing for four material conditions: as-received 8620, normalized 8620, as-received PS-18, and normalized PS-18. For each test, specimens were identified using three characters relating to the 1) material (8 for 8620, P for PS-18), 2) material condition (A for as-received, N for normalized), and 3) sample number (1, 2, 3). These specimen identification numbers, or Specimen IDs, are used when reporting experimental results.

The steels were received in the form of hot-rolled bars, which is referred to as the as-received condition. The SAE 8620 steel was air cooled from the hot working temperature. The PS-18 material received an unspecified controlled-cooling process from the hot working temperature. Both materials were normalized by heat treating the as-received materials at 924 °C for 2 h, followed by air cooling. The chemical compositions of both steels are noted in Table 1 and were determined using optical emission spectroscopy (OES) with an ARL (Applied Research Laboratories) Metal Analyzer 3460.

Table 1 Chemical composition of SAE 8620 and PS-18 steel (wt.%).

Element	8620	PS-18
C	0.22	0.27
Mn	0.84	1.00
Cr	0.51	0.57
Mo	0.19	0.15
Ni	0.57	0.12
P	0.009	0.018
Si	0.23	0.26
S	0.021	0.026
Cu	0.20	0.22
Al	0.026	0.030

For both 8620 and PS-18, the normalizing process was effective in refining and homogenizing the grain structure. Figures 1 and 2 show the as-received and normalized microstructure of 8620, respectively. Figures

3 and 4 show the as-received and normalized microstructure of PS-18, respectively. Both the 8620 and PS-18 as-received microstructures exhibit proeutectoid ferrite, Widmanstätten ferrite, and pearlite. For the 8620 material, the Widmanstätten ferrite constituent persists in the normalized condition; it is not noted in the normalized PS-18 microstructure. Scanning electron microscopy (SEM) was required to resolve the pearlite layers.

Navy C-ring specimens were machined from SAE 8620 and PS-18 steels in both the as-received and normalized conditions. The Navy C-ring specimen geometry is shown in Figure 5. After machining, the C-ring specimens were gas carburized in a sealed, 75 kW quench furnace. The boost-diffuse carburizing process utilized a propane-enriched endothermic atmosphere. The specimens were held at 927°C for 9.75 hours with a carbon potential of 1.05, and then at 843°C for 1.5 hours with a carbon potential of 0.88. During the carburizing process, the carbon potential was monitored using an

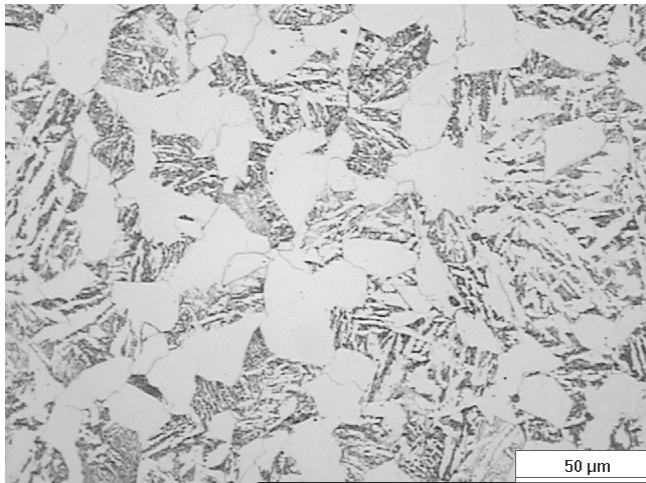


Figure 1 Optical micrograph of as-received SAE 8620, showing pearlite and both proeutectoid and Widmanstätten ferrite. 1% Nital etch.

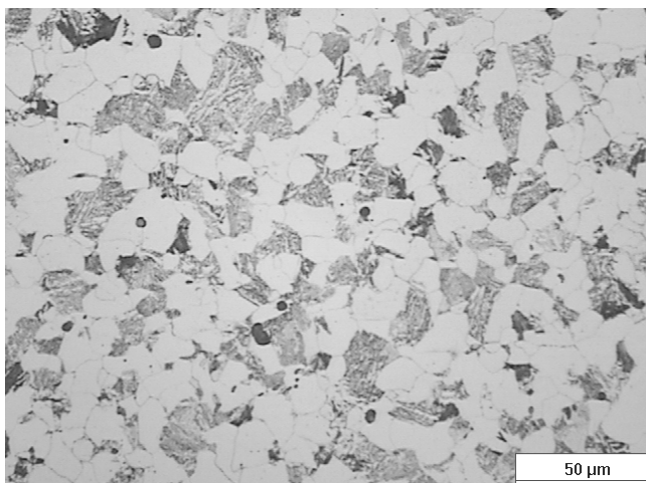


Figure 2 Optical micrograph of normalized SAE 8620, showing pearlite and both proeutectoid and Widmanstätten ferrite. 1% Nital etch.

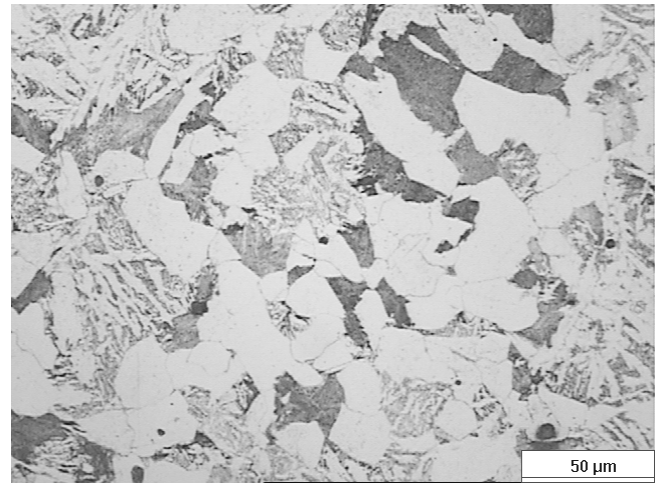


Figure 3 Optical micrograph of as-received PS-18, showing pearlite and both proeutectoid and Widmanstätten ferrite. 1% Nital etch.

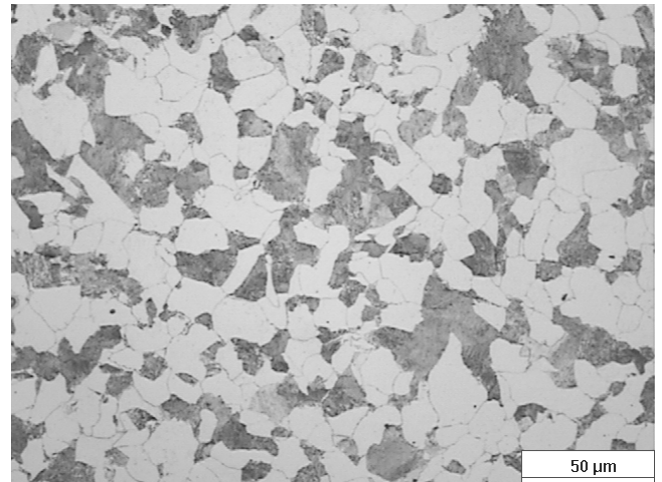


Figure 4 Optical micrograph of normalized PS-18, showing pearlite and proeutectoid ferrite. 1% Nital etch.

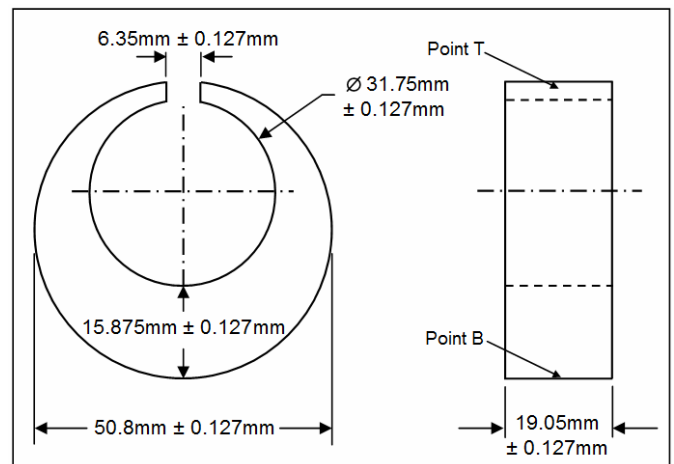


Figure 5 Navy C-ring specimen geometry.

oxygen probe. Following carburizing, the specimens were immediately quenched in oil for 15 minutes. The oil quench bath was maintained at 400°C and 1400 psi.

pressure above the oil bath was maintained at 700 millibars.

X-ray diffraction techniques were used to measure residual stress and retained austenite levels in the carburized Navy C-ring specimens. For both the residual stress and retained austenite measurements, CrK α radiation with a 2.291 Å wavelength was employed (30.00 kV, 25.00 mA). The (211) martensite peak was examined to determine the value of residual stress of each specimen at nine different ψ values (0, $\pm 5.51^\circ$, $\pm 12.00^\circ$, $\pm 19.41^\circ$, $\pm 25.00^\circ$). The Bragg angle, 2θ , was fixed at 156.00° . The amount of retained austenite was determined using the "Four-Peak Method", which utilizes the (200) and (211) martensite peaks and the (200) and (220) austenite peaks. Not only does this method allow for preferred orientation and carbide interference to be identified, but it allows a better average value of retained austenite to be obtained [14, 16]. Results were expressed as a volume percentage of retained austenite.

As indicated in a previous study [25], tangential (hoop) residual stress and retained austenite measurements were taken on the outer diameter (OD) surface at Point T and Point B (Figure 5) for two specimens in each of the four material conditions; these locations will be referred to as "top" and "bottom", respectively. The "top" location has a thin cross-sectional area, whereas the "bottom" location has a thick cross-sectional area. Based on these initial results, depth profiles of the axial and hoop stress and retained austenite were obtained for one specimen in each of the four material conditions. These profiles were measured from the OD surface at the "bottom" location to a total depth of 2.54 mm for residual stress, and a total depth of 1.53 mm for retained austenite.

To observe the carburized microstructures in the case and core material, two samples were cut from one Navy C-ring in each of the four material conditions. These samples were taken from areas near the "top" and "bottom" locations used for residual stress and retained austenite measurements, shown schematically in Figure 6. The "top" section was offset from the area

immediately adjacent to the gap in order to avoid the presence of edge or corner effects from carburizing. The "bottom" section was offset from the thickest cross-section of the specimen to avoid the electropolished area used for the residual stress depth profiles. These samples were also used for measuring the effective case depths of the four material conditions.

To determine the effective case depth, Vickers microhardness testing was performed on a Buehler Micromet II Microhardness Tester using a 500 g load and an indentation time of 12 seconds. Testing was performed in accordance with ASTM Standard E384-05a: Standard Test Method for Microindentation Hardness for Materials [27], except that the diagonal lengths of the indentations were reported in 0.5 μm increments instead of 0.1 μm increments. Hardness profiles were measured on the mounted and polished samples from near the "top" and "bottom" locations of the carburized C-rings (Figure 6). Three profiles, spaced 1 mm apart, were measured perpendicular to the OD surface near the center of the mounted specimen, corresponding to the mid-thickness of the C-ring section. The microhardness measurements were conducted every 0.2 mm beginning 0.1 mm below the surface. The profiles extended a total of 3.1 mm into the surface of the samples at the "bottom" location and either 1.9 or 2.1 mm into the surface at the "top" location. The effective case depth is generally the distance from the surface at which a hardness value of 50 HRC is obtained [10]; the equivalent hardness on the Vickers scale is 513 HV [28]. The Vickers hardness values for the three profiles were averaged, and interpolation was used to determine the effective case depth. To minimize the error resulting from interpolation, an additional hardness indentation was made half way between the two existing indentations of interest for each of the three profiles; it allowed interpolation between hardness indentations that were 0.1 mm apart, instead of 0.2 mm apart.

RESULTS AND DISCUSSION

CARBURIZED MICROSTRUCTURES - The SEM micrographs in Figures 7 to 10 document the case and core material observed at the "bottom" location for carburized C-ring specimens 8A1, 8N2, PA1, and PN2, respectively. The carburizing process has eliminated the microstructural differences that were present for material in the as-received and normalized conditions. For all specimens, the case material appears to consist of predominantly plate martensite, suggesting a carbon content close to 1%. The core material for all specimens is lath martensite, as would be expected since the carbon contents of 8620 and PS-18 steel are 0.22% and 0.27%, respectively.

Intergranular oxidation appears as dark areas outlining the prior austenite grain boundaries near the specimen surface. It was noted to penetrate the surface of the carburized specimens to a depth of approximately 15 to 20 μm . The "top" location exhibited similar oxidation patterns.

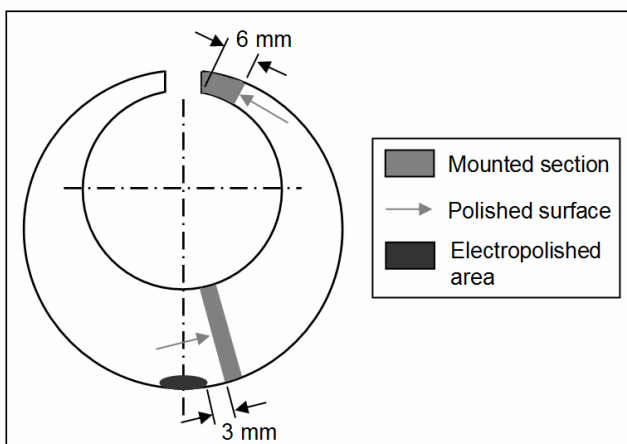


Figure 6 Location of samples used for documenting carburized microstructure.