UNDERSTANDING AND MEASURING DECARBURIZATION

Understanding the forces behind decarburization is the first step toward minimizing its detrimental effects.

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Decarburization is detrimental to the wear life and fatigue life of steel heat-treated components. This article explores some factors that cause decarburization while concentrating on its measurement. In most production tests, light microscopes are used to scan the surface of a polished and etched cross-section to find what appears to be the greatest depth of total carbon loss (*free-ferrite depth,* or FFD) and the greatest depth of combined FFD and partial loss of carbon to determine the *maximum affected depth* (MAD).

In some cases, there is no free ferrite at the surface. In research studies, this may be supplemented with a Knoop hardness traverse to determine the depth where hardness becomes constant. The Knoop-determined MAD is often somewhat deeper than the visually determined MAD, as variations in the microstructure of carbon contents close to the core may be difficult to discern. The MAD determined by hardness traverse may be slightly shallower than that determined by quantitative carbon analysis with the electron microprobe. This is especially true when the bulk carbon content exceeds about 0.45 wt%, as the relationship between carbon in the austenite before quenching to form martensite and the as-quenched hardness loses its linear nature above this carbon level.

DECARBURIZATION BASICS

Decarburization occurs when carbon atoms at the steel surface interact with the furnace atmosphere and are removed from the steel as a gaseous phase[1-8]. Carbon from the interior diffuses towards the surface, moving from high to low concentration and continues until the maximum depth of decarburization is established. Because the carbon diffusion rate increases with temperature when the structure is fully austenitic, MAD also increases as temperature rises above the Ac_3. For temperatures in the two-phase region, between the Ac_1 and Ac_3, the process is more complex. Carbon diffusion rates in ferrite and austenite are different, and are influenced by both temperature and composition.

Decarburization is a serious problem because surface properties are inferior to core properties, resulting in poor wear resistance and low fatigue life. To understand the extent of the problem, two characteristics that may be present at a decarburized steel's surface can be measured: Free-ferrite layer depth (FFD, when present) and partial decarburization depth (PDD, when free-ferrite is

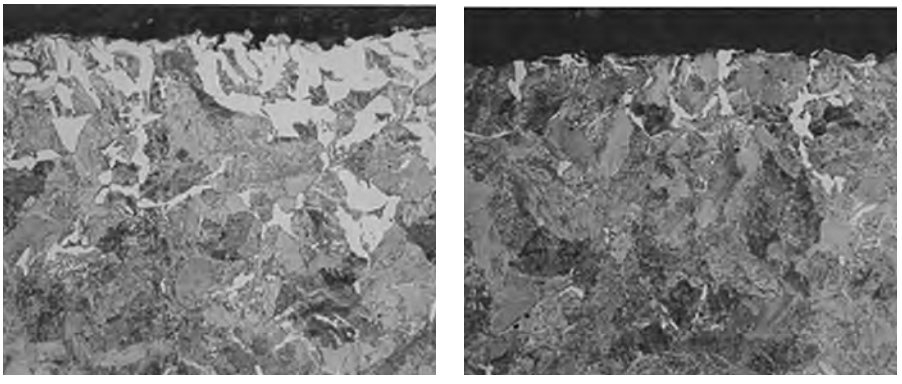

Fig. 1 — Decarburized surface of as-rolled, eutectoid carbon steel (Fe-0.8% C-0.21% Mn-0.22% Si) at two different locations around the periphery show a substantial variation in the amount and depth of ferrite at the surface. The matrix should be nearly all pearlite (4% picral etch, 500×).

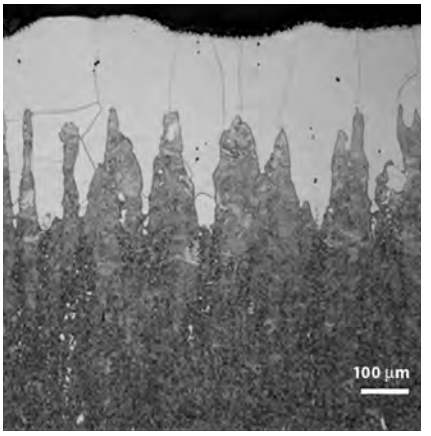

Fig. 2 — Erratic depth of free ferrite at the surface of a bar of 440A martensitic stainless steel after quenching from 2000°F (1093°C); etched with Vilella's reagent.

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not present). If free ferrite is present, the free-ferrite layer's maximum depth (often variable) plus the depth of partial decarburization to the unaffected core is measured. This total—FFD + PDD—is called maximum affected depth (MAD). These depths are not uniform and can vary substantially, leading to measurements of average FFD, PDD, and MAD, as well as maximum values for each. ASTM E1077 covers decarburization measurement.

In practice, decarburization should be evaluated on a plane transverse to the hot working axis, as depth variation is greater around the bar on the transverse plane than at a specific constant position along a longitudinal plane. Decarburization depth can vary substantially around the periphery of a bar, as shown in Fig. 1. Qualitative measurements can be subjective and biased. Free-ferrite depth can also be erratic, even over a small surface area, as shown in Fig. 2. Corners of square or rectangular sections normally exhibit greater decarburization depths than planar surfaces. Sampling schemes for large cross-sections are also illustrated in ASTM E1077.

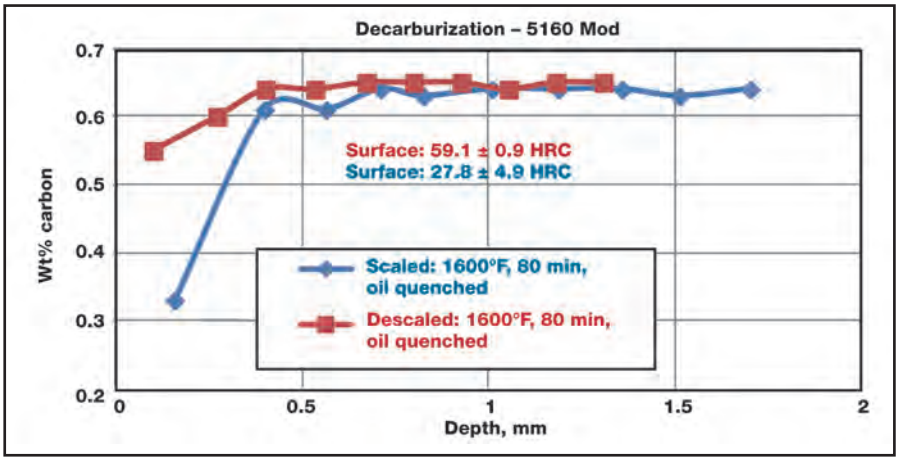

Fig. 3 — Decarburization of 5160 modified spring steel defined by surface hardness and incremental turnings analyzed chemically for carbon content as a function of whether or not the surface was descaled or was covered by mill scale, and austenitizing at 1600°F for 80 minutes.

To obtain good data, edge retention must be perfect—the surface must be perfectly flat to the extreme edge. If edges are rounded, the exact location of the outer surface is difficult to define with precision and depth measurement accuracy suffers. Good edge retention requires mounting of the specimen in a resin, such as DuroFast, that does not exhibit shrinkage gaps between the mount and specimen after polymerization. Grinding and polishing procedures must emphasize maintaining flatness. While

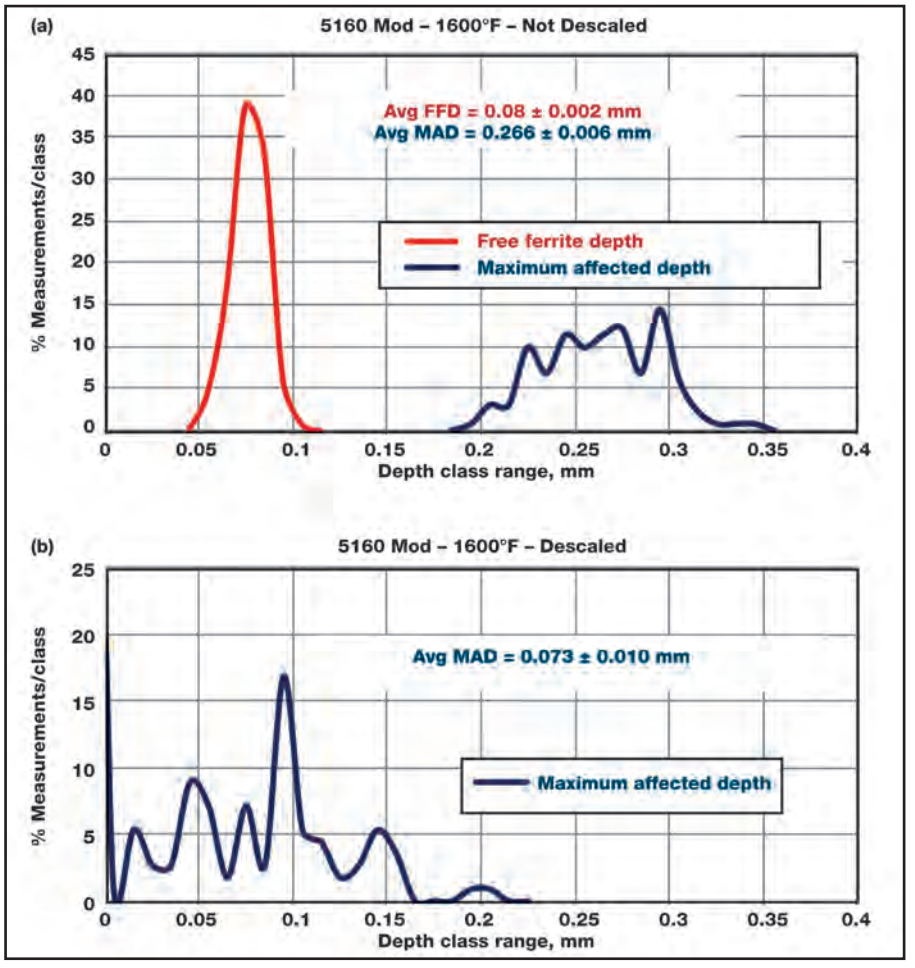

Fig. 4 — Frequency histograms of decarburization measurements made around the periphery of 5160 modified bars after heat treatment. a) 1600°F specimen with a mill scaled surface has an average FFD of 0.08 mm and average MAD of 0.266 mm for 132 measurements. Note the narrow, peaked distribution of the FFD measurements and broad distribution of MAD measurements. b) 1600°F specimen with a descaled surface does not exhibit any free ferrite. No decarburization was observed for almost 19.5% of the measurements and distribution of MAD values is broad.

SiC abrasive paper can be used for grinding, resin-bonded diamond discs such as MD-Piano provide excellent flatness and long life. Napless cloths are used for diamond polishing while low-nap clothes are used to polish with alumina or colloidal silica abrasives. In most cases, a reticule is used to make the measurement. Alternatively, many image-capture software programs allow operators to make point-to-point distance measurements. However, these systems must be properly calibrated.

Hot working temperatures can produce ferrite at the surface with the amount and size of the ferrite grains growing as carbon loss increases at the surface. The upper critical temperature, Ac_3, of these grains could be above 1600°F, as alloy composition and residual elements influence the Ac_3 of the steel grade. Spring steels are used as an example. If a decarburized specimen is induction hardened, the heating rate to the austenitization temperature is extremely fast. To put all of the carbon in solution (assuming that the steel has a carbon content of 0.60-0.65%), it is heated to roughly 1700°-1750°F. As the holding time is short, perhaps no more than 10 s, there is little time for appreciable carbon diffusion and the decarburization depth after heat treatment is a function of the as-rolled mill decarburization depth.

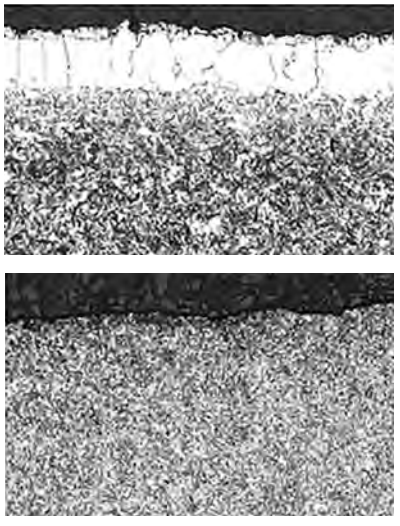

Fig. 5 — Decarburized surfaces of 5160 Mod austenitized at 1600°F for 80 min. and oil quenched. Free ferrite on the scale covered specimen, top. No free ferrite present on the specimen that was descaled before being austenitized (2% nital, 200×), bottom.

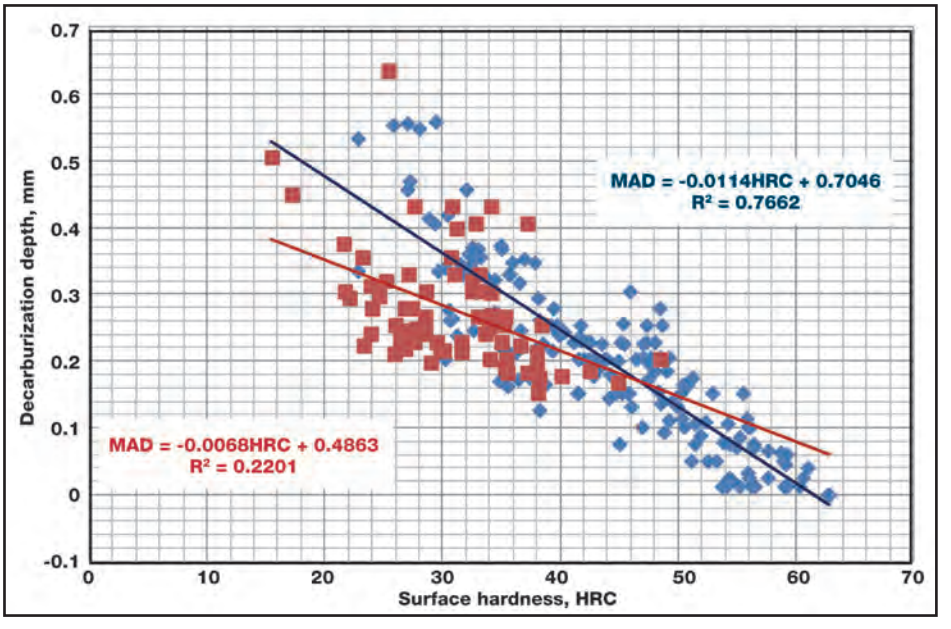

Fig. 6 — Rockwell C hardness tests on the surface of 5160H, 5160M, and 9260M (after glass bead blasting) is a simple screening test to determine if the surface is decarburized or free of decarburization. The correlation is much better when there are no free-ferrite grains at the surface (blue data points) than when free ferrite (red data points) is present.

EXPERIMENTAL DATA

If spring steels (typically ~0.6% carbon) are heat treated in gas-fired furnaces, operating conditions can either increase or decrease the as-rolled depth of decarburization after heat treatment, relative to the starting point. Austenitizing of these grades is typically performed in the 1600°-1650°F range and holding times, which depend upon bar diameter, are usually at least 20 minutes. In many cases, a protective atmosphere is not employed.

An experiment was conducted using round bars of 5160 modified spring steel. Specimens were austenitized either with the as-rolled mill scale present or removed by sand blasting. Specimens were austenitized at 1600°F (871°C) for 80 minutes, then oil quenched. Part of each bar was incrementally machined (after scale removal by glass-bead blasting) and the carbon content was determined. Surface hardness readings were also recorded and results are shown in Fig. 3. Note that the specimen austenitized at 1600°F exhibits a large difference between surface carbon content and surface hardness, compared to the bar covered with mill scale to the descaled one.

Figure 4 shows results of quantitative FFD and MAD measurements for the two specimens austenitized at 1600°F—including 132 measurements around the periphery of the scaled bar and 113 measurements for the descaled sample. The scaled bar austenitized at 1600°F exhibits a consistent free-ferrite layer around its periphery with an average depth of 0.08 ± 0.002 mm (95% confidence interval). Note that FFD measurement distribution is very narrow, or *peaked*. The MAD, however, shows an average depth of 0.266 ± 0.006 mm and distribution is broad. In contrast, for the descaled bar, no free ferrite was seen and 19.47% of the 113 measurements indicate no decarburization was present. The remaining measurements exhibit an average depth of 0.073 ± 0.010 mm, slightly lower than the scaled bar's average FFD. The MAD distribution curve appears to be bimodal. Figure 5 shows typical microstructures observed at the specimens' two surfaces.

Visual estimates of the maximum affected depth of decarburization generally produce more conservative estimates than the incremental carbon analysis procedure or microindentation hardness traverses. This is because it is difficult to detect the final minor loss in carbon as the unaffected core is reached. Color etchants are likely to perform better for this purpose than black and white etchants such as nital or picral, but comparative tests have not been performed. For annealed microstructures, the visual estimate of the average MAD is generally about 50-70% of the MAD determined by incremental carbon analysis or microindentation tests. This depth, however, can be considered an effective depth where carbon content is usually within about 10-25% of the matrix carbon content and responds reasonably well to heat treatment. If the maximum observed MAD is used as criteria for stock removal, the surface's carbon content will be close to the matrix carbon content after machining.

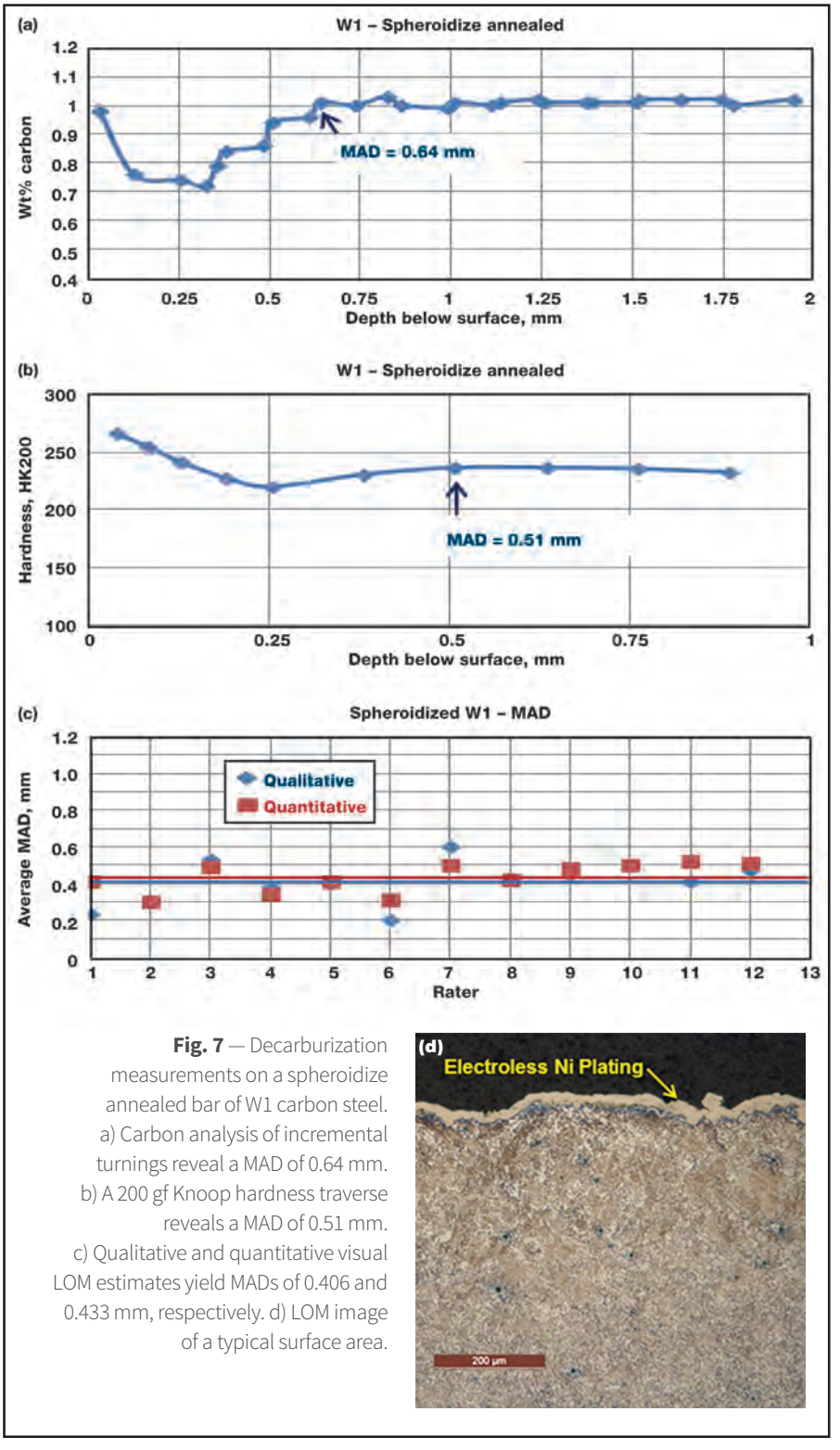

Fig. 7 — Decarburization measurements on a spheroidize annealed bar of W1 carbon steel. a) Carbon analysis of incremental turnings reveal a MAD of 0.64 mm. b) A 200 gf Knoop hardness traverse reveals a MAD of 0.51 mm. c) Qualitative and quantitative visual LOM estimates yield MADs of 0.406 and 0.433 mm, respectively. d) LOM image of a typical surface area.

Additionally, a simple screening test was used to detect decarburized specimens of 5160H, 5160M, and 9260M spring steel lots used for front wheel drive automobile springs. As the design loads on these springs increased throughout the 1970s, no free ferrite and almost no MAD could be permitted or spring life would be reduced. Mill processing helped minimize the MAD to less than the amount removed in the final processing step of turning and burnishing. Figure 6 shows data for a number of specimens where the surface scan was removed by glass-bead blasting after hardening and bulk Rockwell C tests were made on the OD surfaces at a number of locations and averaged. Bars were sectioned, metallographically prepared, and rated for maximum free-ferrite depth (when present) and maximum affected depth of decarburization. The plot shows a much better correlation between HRC and MAD when free ferrite was not present versus when it was present.

Examples of the variation in decarburization ratings by three methods—carbon analysis of incremental turnings, microindentation hardness traverses, and visual qualitative or quantitative estimates by light microscopy—are shown in Fig. 7. The spheroidize annealed microstructure of W1 carbon tool steel (~1% C), a typical specimen rated by mill metallurgists in plants that make tool steel, is shown in Fig. 7d at 100×. The carbide in the decarburized surface zone exhibits a significantly lower volume fraction than the interior. At the extreme surface, individual carbides can be seen. Note the seemingly unusual carbon distribution at the surface in Fig. 7a. The lowest carbon content is only to about 0.7%, roughly a 30% loss. So, free ferrite is not present. Examination at 1000× shows that the cementite in the decarburized zone is not well spheroidized but tends to be lamellar. This is because the annealing cycle cannot spheroidize cementite in the lower carbon surface area compared to the bulk carbon content. Note that the hardness at the surface of the decarburized zone is actually greater than in the core, a result that may seem counterintuitive. However, as some tool steel metallurgists are aware, coarse lamellar carbide structure—even with a lower volume fraction than the spheroidized core—is harder and less ductile.

Carbon analysis of the incremental turnings provides the best estimate of the maximum affected depth. The MAD estimate is more accurate using the Knoop traverses than LOM measurements, but is still rather conservative compared to the MAD from actual carbon analysis. However, this is not a major problem because the hardness became essentially constant at a shallower depth than shown by the incremental carbon analysis. The qualitative estimates, based on a simple visual estimate going around the bar's periphery, are slightly lower than the

quantitative average, which was based on 25 random measurements around the periphery. If it was assumed that the visual estimate of the greatest MAD around the bar periphery would be deeper than the mean MAD of 25 randomly chosen locations, then the actual result would be rather surprising.

CONCLUSIONS

Decarburization of steel parts is a serious problem as the weaker surface layer reduces wear resistance, enabling fatigue failures to occur more easily. A simple screening test was discussed, which can be used for certain shapes and high production runs. If the surface hardness is below some predetermined limit, which varies with grade, then a microstructural examination is required. Chemical analysis of carbon on incremental turnings (or millings) can be performed, although this is more applicable to research than production. Metallographic rating of decarburization depth requires properly prepared specimens with good edge retention. This can easily be achieved with modern equipment and is reasonably fast. Qualitative measurements of the free-ferrite depth (when present) and the maximum affected depth of decarburization are usually adequate. But such measurements are subject to bias and the reproducibility is not as good as when quantitative measurements are made using at least 25 randomly selected locations around the bar periphery. Microindentation hardness traverses are excellent for defining the MAD. The FFD is easily observed by light microscopy and adequate inspection of the periphery is needed to detect the deepest amount present. ~AM&P

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