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Determination of Decarburization in Steel

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A computer program has been written that optimizes the fit between the microhardness numbers determined in a cross section traverse and the diffusion equation corresponding to Fick's second law of diffusion. Using an iterative procedure, the program minimizes the RMS error between the microhardness numbers and three constants corresponding to (1) the product of diffusivity and time, (2) surface hardness, and (3) core hardness. The type of decarburization, as described in SAE J419, "Methods of Measuring Decarburization," may also be evaluated by determining the base carbon concentration and the near-surface carbon concentration from the same sample. Test samples of 5160H and 6150H steel were decarburized and evaluated using this procedure.

Keywords:
decarburization, heat treating, steel

1. Introduction

AUTOMOTIVE suspension springs typically are manufactured from alloy steels containing chromium such as 5160H or 6150H. These steels have nominal carbon contents of up to 0.6%, and high strength levels are achieved by the processes of austenitizing and quenching and tempering heat treatments. Because diffusion of carbon is significant at elevated temperatures, the steel carbon chemistry may change if the furnace atmosphere is not sufficiently controlled to prevent chemical reactions at the surface. These reactions result in an addition or depletion of carbon at the steel surface. When the carbon content is altered in this way, the heat treatment response will also change, and this in turn results in a corresponding variation in the local strength level. Although the amount of near-surface material that is altered is normally relatively small, there may be a significant detrimental effect with regards to fatigue crack initiation if carbon is depleted from the surface. The applied loads in machine components are often cyclic, and the surface condition of a material plays a critical role in its ability to resist initiation of fatigue cracks.

Decarburization, in a heat treated steel part, is normally revealed optically with a metallographic sample. This entails micropolishing, etching with 3% nital (nitric acid and ethanol), and evaluation with a metallurgical microscope. When the depth of decarburization is required, a cross section microhardness traverse is normally performed, which reveals the variation in hardness from the near-surface region to the core region, at which location the hardness is expected to stabilize.

A microhardness measurement is an indication of the carbon content and is directly related to the local strength level. The Society of Automotive Engineers has published a recommended practice for determining decarburization, which helps to define this condition, "Methods of Measuring Decarburization," SAE J419.[1] This specification refers to three basic types of decarburization (Type 1, Type 2, and Type 3), in which the actual carbon content on the surface is compared to the base carbon content. Type 1 exhibits a carbon-depleted layer; Type 2 exhibits a carbon content varying between 0 and 50% of the base carbon; and Type 3 defines the condition in which the carbon content is above 50% of the base carbon at the surface. An accurate microhardness traverse will generally suffice for determining the existence of decarburization. However, it is unclear how to verify the type of decarburization based only on a cross section microhardness traverse if the surface carbon concentration has not been determined. The following procedure was developed to present a viable method for making this determination based on a microhardness traverse and carbon determinations at the core, as well as at a location near the surface.

2. Analysis

The hardness of tempered martensite, in iron-carbon alloys, is an approximately linear function of carbon content for any given alloy system in the range of 0.2 to 0.6% carbon.[2,3] Decarburization is brought about by surface reactions and carbon diffusion. The formal diffusion equation provides a physically accurate mathematical model to fit the cross section microhardness traverse data, and this procedure should provide an improved means for the determination of decarburization depth. Decarburization obeys Fick's second law of diffusion and the working form of the equation is:[4]

$$(C_x - C_s) = (C_o = C_s)\,\mathrm{erf}\left[\frac{x}{2(Dt)^{1/2}}\right] \qquad [1]$$

where C_x is the carbon concentration at position x; C_s is the carbon concentration at the surface; C_o is the carbon concentration at the core; erf is the error function; x is the distance from the surface; D is the diffusivity of carbon in the alloy; and t is the diffusion time.

The linear relationship between microhardness and carbon content[2,3] can be described by the following equation:

$$H = m \cdot C + a \qquad [2]$$

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where H is the hardness, *e.g.*, Knoop hardness number (HK); m is the slope of the linear relationship; c is percent carbon concentration; and a is the intercept of the linear relationship.

Substituting the expression for C into Eq 1 (with the appropriate subscripts for C and H values) and letting erf $\{x/[2(Dt)^{1/2}]\}$ be expressed by ϕ results in:

$$(H_x - a)/m - (H_s - a)/m = [(H_o - a)/m - (H_s - a)/m] \cdot \phi \qquad [3]$$

Equation 3 then simplifies to the following:

$$H_x = (H_o - H_s) \cdot \phi + H_s \qquad [4]$$

H_x is the experimentally determined Knoop microhardness value at various depths, X, and H_s and H_o refer to the estimated true surface and core microhardness values. A typical cross section microhardness traverse will generate several hardness values as a function of distance from the surface. The computer program estimates a beginning value for the product Dt, H_s, and H_o and then iterates Dt, H_s, and H_o sequentially using a procedure that minimizes the RMS error between the measured microhardness data points and Eq 4. All of the experimentally measured hardness numbers are therefore used in the iterations, and the derived H_s and H_o values reflect the best estimates for the surface hardness and core hardness that satisfied Fick's second law of diffusion.

The depth of decarburization is defined as the distance from the surface where the base carbon concentration is reached. Because the "best fit" equation that relates hardness to distance has been determined, the distance x that satisfies Eq 4 for a hardness that is sufficiently close to the core hardness determines the depth of decarburization. The value of 0.99 H_o has been chosen arbitrarily to represent the position of base alloy carbon content.

The microhardness data will reveal whether decarburization is present, but they do not provide information concerning the carbon content at the surface. A second chemical analysis performed near the surface will give a second data point from which the linear relationship between hardness and carbon content can be determined and therefore can provide a procedure for using microhardness measurements to effectively determine the carbon concentration ratio at the surface, C_s / C_o. This method enables identification of the type of decarburization. The relationship between carbon content and hardness from Eq 1 takes the following form:

$$C_s / C_o = (H_s - a)/(H_o - a) \qquad [5]$$

Equation 5, with the application of Eq 2 for the core condition, reduces to the following:

$$C_s / C_o = (H_s - a)/(m \cdot C_o) \qquad [6]$$

The slope, m, and intercept, a, of the linear relationship between microhardness and carbon content can be evaluated experimentally. The surface carbon content is then calculated based on the extrapolated hardness value for the surface.

3. Experimental Procedure

Samples of 5160H and 6150H steel were cut from commercial truck leaf springs and ground to prepare a surface on each sample that was free of any chemical variations such as decarburization from prior surface chemical reaction histories. The alloy chemistries were determined with an ARL 3460 optical emission spectrometer and are shown in Table 1; both alloys conform to standard grades of 5160H and 6150H spring steels.

The ground steel samples were intentionally decarburized by austenitizing in an air atmosphere furnace for 4 h at 900 °C and then quenching in water. Metallographic samples were prepared using standard laboratory practice, and a series of cross section microhardness traverses was made on the as-pol-

Table 1 Chemical Composition of 5160H and 6150H Alloy Steels

	Composition, %									
Alloy	C	Mn	Si	Cr	P	S	Ni	Mo	Cu	V
5160H............	0.586	0.85	0.19	0.769	0.013	0.022	0.07	0.017	0.132	0.067
6150H............	0.543	0.81	0.20	0.926	0.012	0.019	0.07	0.019	0.134	0.157

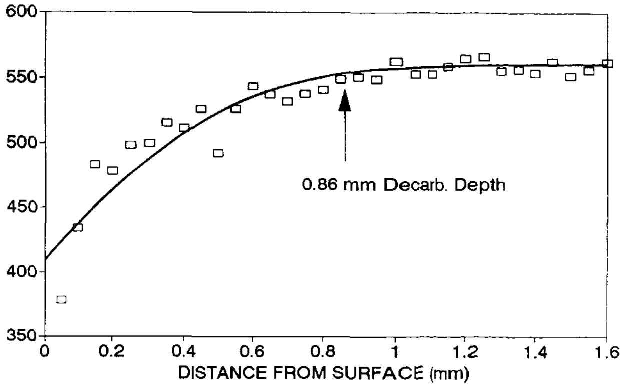

Fig. 1 Decarburization of 5160H alloy steel, 4 h at 900 °C in air.

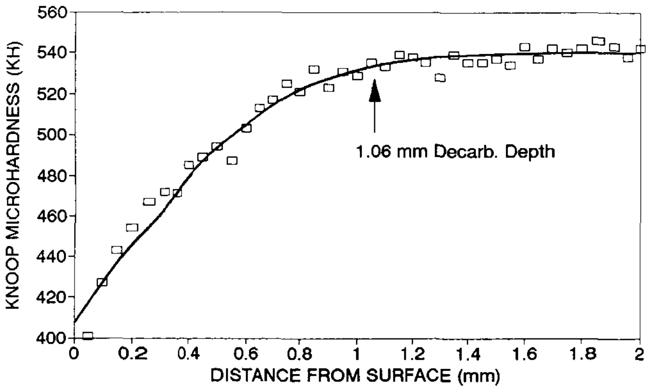

Fig. 2 Decarburization of 6150H alloy steel, 4 h at 900 °C in air.

ished samples. A Leco M400 microhardness tester equipped with a Knoop diamond indenter was used, and the readings were taken in a normal direction from the surface. Three indentations were made at each depth, and the microhardness numbers were averaged. This resulted in a series of microhardness numbers that varied from the near-surface location to the core and whose values were dependent on the carbon concentration at each location. The Knoop microhardness numbers are plotted as a function of distance from the surface, and the optimum fit of the data, according to the diffusion equation, is shown for both alloys in Fig. 1 and 2.

A near-surface chemical analysis for carbon content was obtained by grinding the surface to remove the oxidized scale prior to performing the chemical analysis. The depth of the ground surface was determined by measuring the before and after ground thickness with a micrometer. The ground depth was normally within the first 0.2 mm of the surface. The slope, m, was then determined from the relationship between the measured values for carbon content and the best fit equation for the microhardness at the distance corresponding to the chemical analysis. The experimental values for 5160H and 6150H alloy steels are listed in Table 2.

All of the microhardness values were then normalized with respect to the surface carbon ratio, C_s / C_o, and a graph was made showing how the carbon content, C_x / C_o, varies as a function of distance from the surface. The data from Fig. 1 and 2 are replotted in Fig. 3 and 4 using this procedure.

4. Discussion of Results

The slope and intercept of the linear relationship depends on factors such as grain size, alloy chemistry variations, and previous thermal history. A value for this slope can be reasonably approximated using hardenability data for a particular series of alloy steels, providing carbon content is the primary variable. Published hardenability data may be used by plotting the maximum and minimum hardness values for a specific Jominy distance for each alloy. Figure 5 shows a plot for eight 51XX steels having nominal carbon contents ranging from 0.2 to 0.6%. The maximum and minimum hardness values at a constant Jominy distance of 16 mm ($^{10}/_{16}$ in.) were selected for each alloy and plotted.[5] This particular Jominy distance was chosen because the maximum and minimum hardness numbers are equivalent to a typical spring specification hardness range. The microstructure achieved by a cooling rate corresponding to this Jominy distance was approximately equivalent to the quench and tempered 5160H steel. The normal hardness values are given in Rockwell C units, and these have been converted to Knoop hardness numbers for direct comparison with the measured microhardness numbers. The accompanying graph shows that the slope varies from approximately 351 HK/%C to 1271.7 HK/%C. The experimentally determined slope for the 5160H data is also plotted to show that the value for decarburized 5160H falls within the expected slopes for Jominy hardenability data.

A copy of the computer program along with the data files is available on request to the authors. The program was written in Turbo Pascal language; an executable version is available for IBM compatible computers using the DOS-based operating system.

5. Conclusions

A computer program and procedure has been developed that permits an accurate determination of the depth of decarburization. The method accurately determined the decarburization depth profile of two medium-carbon alloy steels, 5160H and 6150H. The type of decarburization was also evaluated by de-

Table 2 Experimentally Determined Decarburization Constants

	H_o	H_s	C_o	C_s	m	a	C_s / C_o
5160H	560.6	409.5	0.586	0.283	497.7	268.9	0.482
6150H	540.1	407.4	0.543	0.170	356.6	346.7	0.314

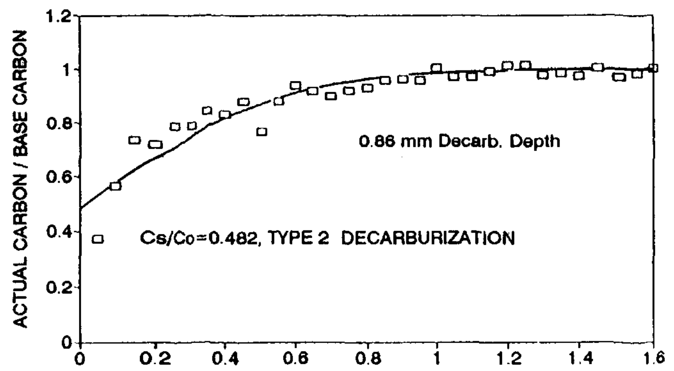

Fig. 3 Variation of carbon ratio in 5160H alloy steel with decarburization depth.

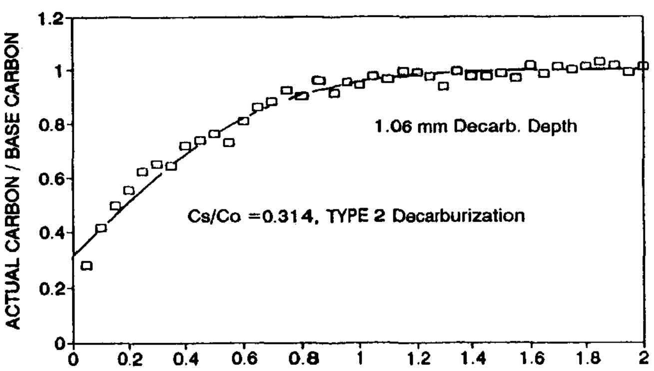

Fig. 4 Variation of carbon ratio in 6150H alloy steel with decarburization depth.

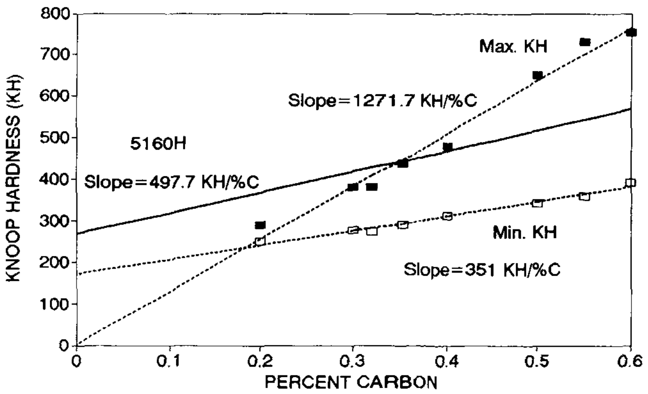

Fig. 5 Variation of Jominy hardness at 16 mm with carbon content in 51XX alloy steels.

termining the linear relationship between hardness and carbon content based on two carbon analyses. A near-surface carbon content and the core carbon content was determined, which defined the slope and intercept of the linear relationship.

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