



ACADEMIC STUDY

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Decarburization: The Silent Enemy

INTRODUCTION

A large proportion of metallic engineering components are made from carbon steels. These components may encounter high temperatures during furnace heat treatment and/or hot working. High strengths combined with adequate ductility are achieved by heat-treating carbon steels. This involves heating to a high temperature followed by quenching and then tempering. Hot working includes processes such as rolling and forging. It is at high temperatures in air that “The Silent Enemy” (decarburization) can strike. Carbon can be sucked out of the component, resulting in a severely weakened surface layer. The surface layer is just where we need the component to be at its strongest. Maximum applied stresses and defects acting as stress-raisers occur at the surface. Shot peening is much less effective if applied to a decarburized component. Decarburization would not be a problem, however, if post heat-treatment machining was applied to all sensitive areas.

High-strength carbon steel typically contains about 0.8% of carbon. That does not sound like very much but carbon atoms are much lighter than iron atoms with atomic weights of 12 and 58.8 respectively. If we express carbon content in terms of proportion of atoms, we find that the carbon content is about 4%. In other words, about one in every twenty-five atoms is a carbon atom.

Decarburization occurs if carbon atoms in the heated steel component have both (a) a mechanism for migrating and (b) a desire to migrate to the surface. If decarburization is occurring, then a continuous surface layer of soft ferrite is being produced together with ferrite formation around austenite grains further away from the surface.

This article considers the migration mechanism and migration desire involved in decarburization together with property effects and methods of detection. The description of the migration mechanism uses an analogue involving shot particles. Overall the article is meant to be complementary to standard specifications such as ASTM 1077-14.

A proposed rapid-test technique for decarburization is based on the ratio of drop height to rebound height for an indenter given a range of energies.

MIGRATION MECHANISM

Imagine four large identical spherical shot particles arranged

in a square formation as shown in fig.1. These four enclose a four-pointed hole that scientists call an “interstice.” A smaller shot particle could rest neatly in the hole provided that it was of the required diameter. The square arrangement of spheres replicates the cubic nature of steel crystals.

Carbon steel at a high temperature has a closely packed face-centered-cubic (f.c.c.) structure. Carbon atoms in f.c.c. austenite grains are then too large to fit into the hole shown in fig.1. In order to be accommodated, a carbon atom has to push four iron atoms slightly apart as shown in the scale drawing fig.2. The ratio of diameters is 52 for the hole of fig.1 to 80 for the enlarged hole of fig.2 (page 28). Pushing the iron atoms slightly apart generates possible escape routes for the carbon atom. These routes are, however, too narrow for escape to occur.

The iron atoms in steel are actually positively charged ions. They therefore repel one another just as the positive ends of two bar magnets tend to push on each other. What holds the lattice together is the so-called “electron cloud”—vast numbers of negatively charged electrons whizzing

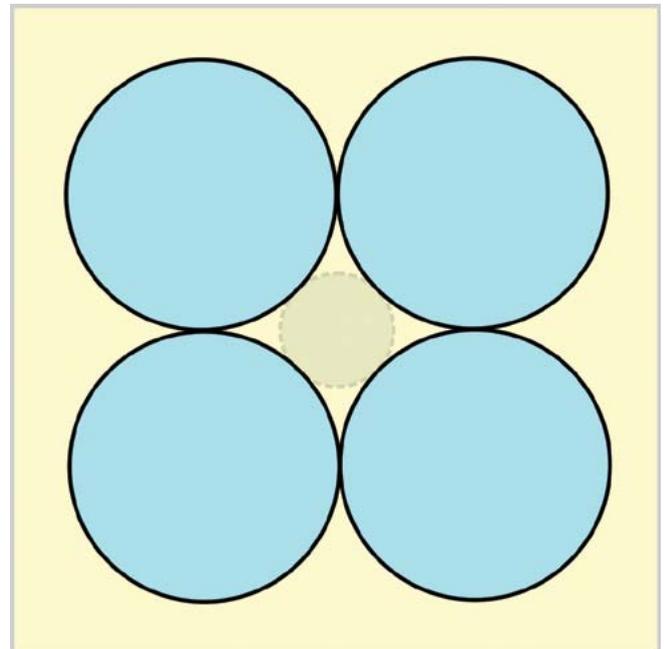


Fig.1. Square arrangement of spheres enclosing an interstice.

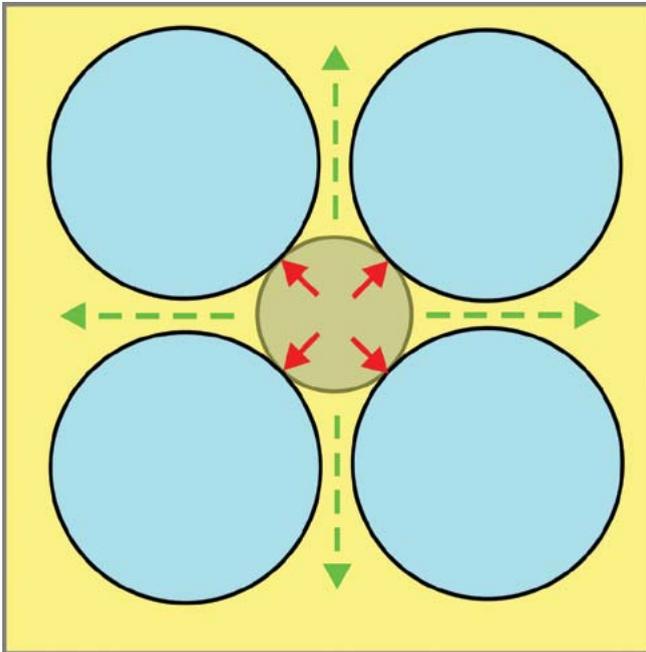


Fig.2. Scale drawing of a carbon atom pushing apart four iron atoms thus generating possible escape routes.

around. Apart from holding the lattice together, the electron cloud is responsible for steel's ability to conduct electricity.

At room temperature, the iron atoms are effectively static in terms of position. However, if the temperature is increased, the amplitude of vibration is also increased. At temperatures in the region of 1000°C, the amplitude of vibration becomes sufficient to create escape routes that carbon atoms can get through. This effect is the mechanism that allows carbon atoms to move through the lattice and to a component's surface if decarburization is occurring. Fig.3 is an attempt to represent the vibration of an atom at high temperatures. The frequency of vibration is about 10 trillion per second!

The vibration of atoms at high temperatures is sufficient to generate usable escape routes for the otherwise captive carbon atoms. This is represented schematically in fig.4. At some instant in time, atoms have moved apart sufficiently to allow a carbon atom to jump into a neighboring interstice. This confluence is aided by the enormous rate of atomic vibration.

MIGRATION DESIRE

Having established an escape mechanism, carbon atoms will only migrate if there is a desire to migrate—a situation analogous to that of prisoners in jail! The surface of a component represents the only means of permanent escape. If carbon atoms in sufficient numbers do escape from the surface, we then have decarburization.

Surface Escape of Carbon Atoms

(a) Hot-Working

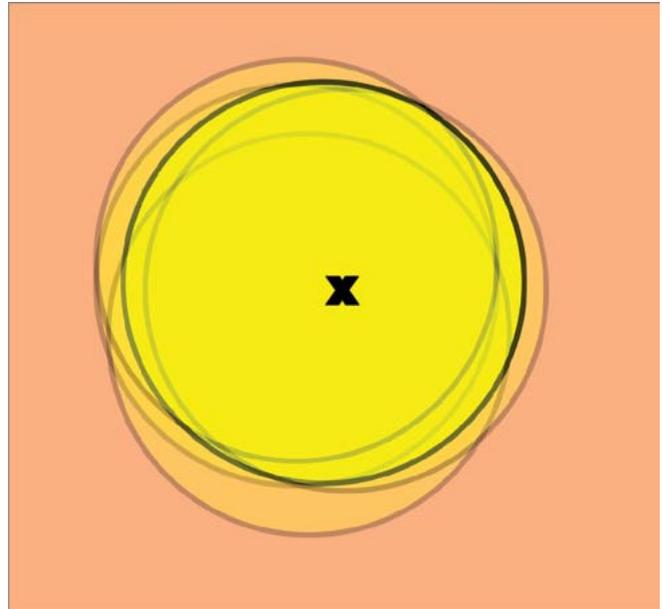


Fig.3. Schematic representation of atomic vibration at high temperatures.

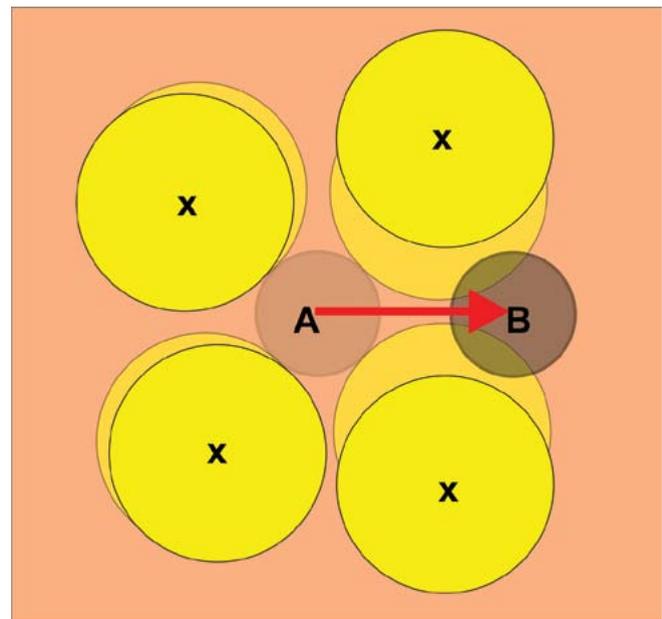


Fig.4. Schematic representation of atomic vibration of iron atoms generating an escape route AB for a carbon atom.

During a hot-working operation, such as hot-rolling, exposure to oxygen in the air is unavoidable. Mill scale forms on the steel surface which is basically solid iron oxide. At high temperatures, the oxygen atoms in mill scale are itching to grab carbon atoms from the component's surface. A typical chemical reaction would be:



(b) Furnace Heat-Treatment

The atmosphere in a heat-treatment furnace inevitably contains oxygen molecules (O₂). These are pairs of oxygen atoms bonded together. The oxygen molecules fly about at high speed and often collide with the component's surface. At the temperatures involved, about 1000°C, the colliding molecules react with surface carbon atoms. The commonest chemical reactions are:



Vast numbers of carbon atoms can be removed from the component's surface using these reactions to produce a decarburized surface layer.

The rate of carbon removal depends on the furnace temperature and atmosphere. The higher the temperature, the faster is the rate of carbon removal. Plain air furnace atmospheres give the fastest rate of carbon removal at a given temperature. Vacuum and neutral gas furnaces give the lowest rate.

Carbon Gradient

When decarburization is occurring, carbon atoms are being leached out of the component's surface. This gives rise to a carbon gradient with, say, 0.8% away from the surface falling to almost 0% at the surface (for a plain air furnace). The crystal structure near the surface changes from f.c.c. austenite to the less closely packed body-centered-cubic (b.c.c.) structure of ferrite. In effect the surface region is converted into mild steel. Fig.5 is a schematic representation of carbon being leached out from a single austenite grain. Real carbon-steel components when heated to high temperatures contain, however, vast numbers of austenite grains.

The carbon content variation for a multi-grain situation is much more complicated than that shown in fig.5. Atoms in grain boundaries are much more disorganized than those inside a grain. As a consequence, carbon atoms can move much more quickly along grain boundaries than they can within a grain. The carbon content falls sufficiently to allow ferrite formation at grain boundaries. Ferrite has much larger interstices than does austenite. Carbon migration along these

newly created ferritic grain boundaries is relatively very rapid. In a sense we can regard hot ferritic grain boundaries as "super highways" for carbon migration.

It is not possible to obtain a micrograph of decarburizing austenite grains because decarburizing only occurs at high temperatures in furnaces. We have to deduce what has happened from micrographs taken when the steel has subsequently cooled down. A set of such micrographs appears in the excellent article "Decarburization of Steel" by R. Cornell and H.K.D.H. Bhadeshia. It is available at www.phase-trans.msm.cam.ac.uk/abstracts/M0.html.

Fig.6 uses one of their micrographs to illustrate carbon migration. At high temperatures the austenite grains gradually become smaller as the grain boundaries lose enough carbon to transform into ferrite. These grain boundaries become thicker the closer they are to the component's surface.

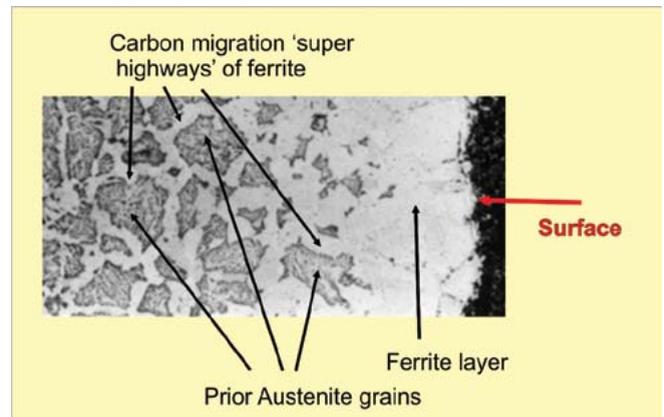


Fig.6. Room temperature micrograph of decarburized steel.

DEFINITION AND DEPTH OF DECARBURIZED SURFACE LAYER

Looking again at fig.6 we can pose the question "How thick is a decarburized surface layer?" We first have to define the end-point of decarburization. One definition could be "the depth at which the ferrite layer ceases to be continuous." Another definition could be "the depth below which no grain boundary ferrite occurs." Using the first definition, the depth corresponds to about a quarter of the width of the micrograph. Using the second definition, on the other hand, puts the depth as being much greater than the total width of the fig.6 micrograph.

Fig.7 (page 32) is a schematic interpretation of the variation in average carbon content associated with the structure shown in fig.6. The indicated depth, D1, would correspond to the first definition of the previous paragraph and is readily detectable. Applying the second definition is relatively difficult.

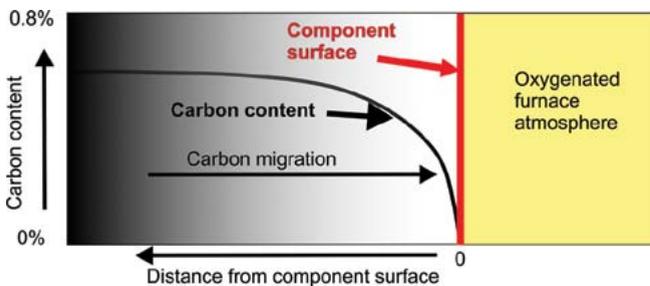


Fig.5. Schematic representation of decarburization from a single austenite grain.

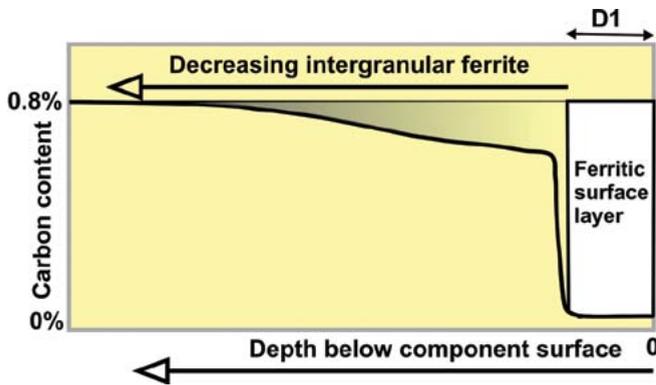


Fig.7. Variation of carbon content with depth below the surface after decarburization.

CONVENTIONAL DETECTION OF DECARBURIZED SURFACE LAYER DEPTH

The ferrite in the surface of a decarburized steel etches differently from carburized steel as evidenced by fig.6. It is also much softer. Chemical analysis of carbon content variation is rarely used. There are, however, two well-established methods for the detection of decarburized surface depth:

- (1) Metallography and
- (2) Micro-hardness testing.

(1) Metallography

Fine polishing and etching (usually employing Nital) is the standard metallographic technique used on carbon steels. Cutting a test specimen out of a component and mounting it in, say, Bakelite is very inconvenient. Examining Almen strip surfaces for decarburization does not necessitate cutting. The specified heat-treatment for Almen strips includes heating to austenitizing temperatures prior to quenching. They therefore run the risk of decarburization.

The author's preferred metallographic technique for detecting decarburization is to use "taper polishing" as illustrated by Fig.8. A taper-polished surface presents a range of depths with a maximum of AB, tapering to zero at C. The range of depths can easily be measured using an accurate dial gauge. Etching of a taper-polished decarburized surface will reveal the range of microstructures shown in fig.6.

Taper polishing is not restricted to a flat surface. Components normally have regions that will subsequently be machined. Such regions can be tested for decarburization in situ using localized polishing and etching, together with photography.

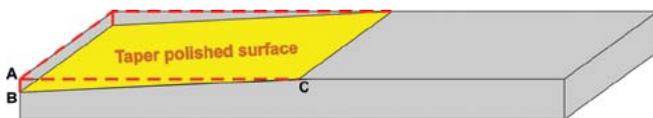


Fig.8. Taper polishing of a rectangular test specimen.

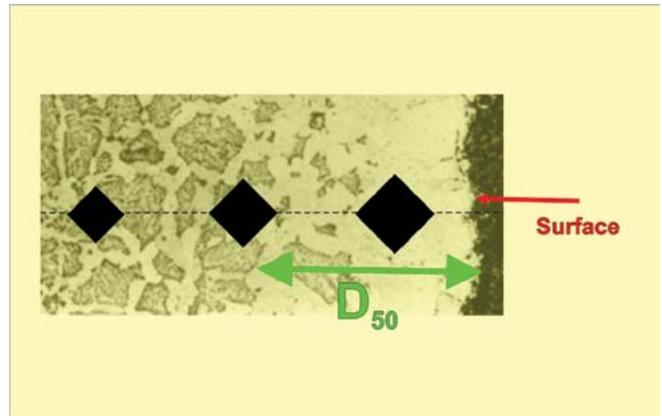


Fig.9. Micro-hardness variation below decarburized surface.

(2) Micro-Hardness Testing

The thickness of the continuous ferrite layer depends on the severity of the decarburization. Discontinuous ferrite normally extends to about ten times the thickness of the continuous ferrite layer. Fig.9 illustrates the application of micro-hardness testing to examine hardness variation in a decarburized steel surface. The black diamonds have been superimposed to represent hypothetical micro-hardness indentations. Indentations become progressively smaller as the hardness increases. The smaller indentations shown in fig.9 average the hardness of ferritic and pearlitic regions.

Micro-hardness testing of mounted cross-section specimens requires that the indentations are spaced both from each other and from the component's surface. Testing of a taper-polished specimen is much less restrictive.

RAPID TESTING FOR DECARBURIZED SURFACE LAYER DEPTH

There is an obvious need for a technique that can rapidly detect the presence and depth of a decarburized surface layer. This section proposes techniques that are based on the energy loss that occurs when impacting objects rebound from the component's surface. The softer the surface, the greater the energy loss. Established rebound hardness test methods include the Shore Scleroscope and the Leeb rebound tester. These methods are, however, designed solely to measure surface hardness rather than decarburized surface layer depth.

Fig.10 (page 34) illustrates the principle of rebound hardness testers. Imagine a small ball bearing is dropped from a height H1 onto the surface of a component. The ball bearing loses some of its kinetic energy as it indents the surface and rebounds to a height H2. (H1 - H2) is the measure used for Scleroscope hardness testing and is a direct measure of the loss of kinetic energy. **The softer the surface material the greater is (H1 - H2).** The Leeb method uses the ratio $V2/V1$

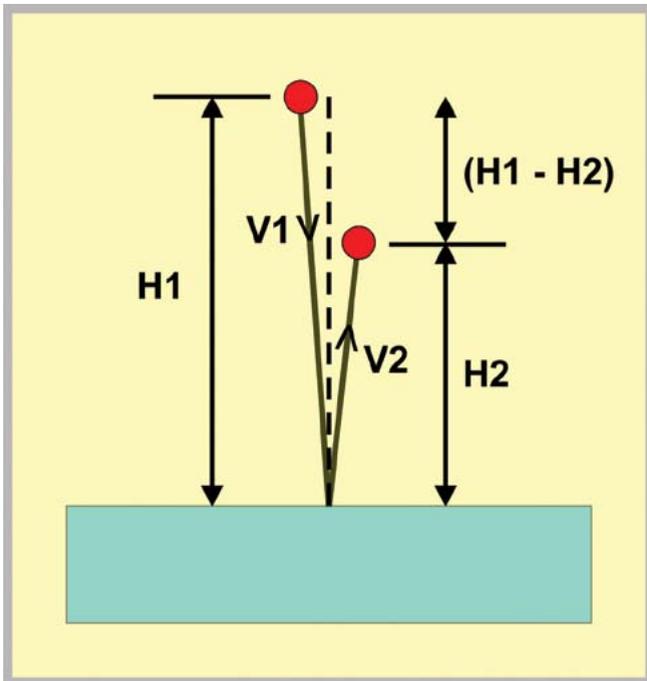


Fig.10. Principles of rebound hardness testing.

$V1$ as a measure of hardness and again is a measure of kinetic energy loss.

Fig.11 illustrates the nature of our problem when examining decarburized steel components. At the extreme surface there is a thin (hopefully) continuous layer of soft ferrite—shown in red. Below that layer the structure progressively contains less and less soft ferrite. Eventually the structure becomes free of decarburization.

1. Rapid Detection Test

A simple method for detecting the presence of decarburization is to drop a small ball bearing from a known height $H1$ down a clear, ruled, tube and measure the rebound height $H2$. Height measurements are best made by using video. If $(H1 - H2)$ is much less than it should be for a normally hard component then we have a problem! Either the surface is decarburized or the entire component has not been heat-treated properly.

1.2 Reference Specimens

Reference specimens allow us to differentiate between decarburization and faulty heat-treatment. They also allow us to quickly estimate the depth of a decarburized layer. Appropriate reference specimens are rectangular blocks that have been heat-treated correctly except for employing an air-rich austenitizing furnace that induces surface decarburization. The heat-treated block is then taper-polished as shown in fig.8 together with grinding-off decarburization from the opposite face. This yields a reference specimen ABCDE as indicated in fig.11 by dashed lines. Heating to

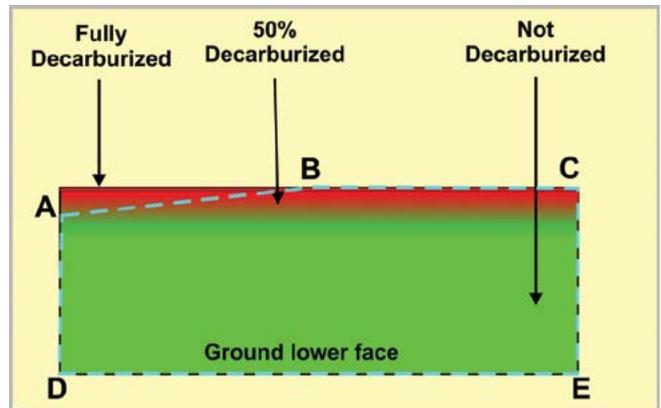


Fig.11. Decarburized layer thickness variation.

different austenitizing temperatures would produce different thicknesses of decarburized surface layer.

2. Decarburization Depth detection

A small-diameter, low kinetic energy, indenter impacting on face BC will confine deformation to the soft decarburized surface layer. This will result in high values for both $(H1 - H2)$ and $V2/V1$. Turning the sample over and impacting on face DE will give low values for both $(H1 - H2)$ and $V2/V1$, assuming that the specimen's core has been correctly heat-treated to high hardness. This will confirm that there is a soft surface layer rather than a completely soft component.

The novel part of the proposed technique is to impose a range of impact intensities.

If we increase the indenter's impact intensity, the induced dent will become larger. The plastic deformation zone under the dent will become correspondingly deeper. As the deformation zone becomes deeper, more and more of it represents the hardness below any decarburized surface layer.

Variation of indenter impact intensity can readily be achieved by dropping a weighted carbide ball from different heights, $H1$. If we do this for the ground lower face of a reference specimen, the ratio $H2/H1$ will remain reasonably constant. If, however, we do it for a decarburized face (BC in fig.11) the ratio will not be constant. For small values of $H1$, the rebound height $H2$ will be lower than for larger values of $H1$ because deformation is being confined to the soft, fully decarburized surface layer. This means that a plot of $H2/H1$ against $H1$ will reflect the hardness variation below the surface. The polished and etched face (AB in fig.11) will reveal how decarburization varies quantitatively with depth below the extreme surface. This can then be used to allow a plot of $H2/H1$ against $H1$ to indicate depth of decarburization.

Fig.12 (page 36) is a schematic representation of how $H2/H1$ would be expected to vary with $H1$ for different thicknesses of decarburized surface layer. Published work

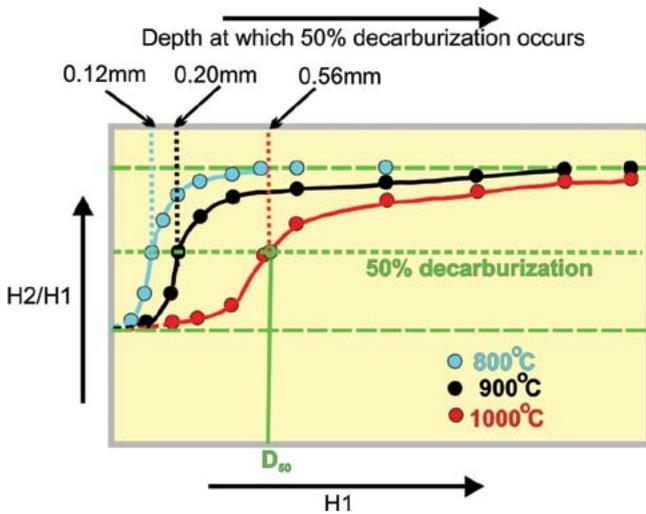


Fig.12. Effect of decarburization depth on H2/H1.

indicates that austenitizing at 800, 900 and 1000°C would produce a useful range of decarburization layer thicknesses in reference specimens.

Imagine, as an example, metallography on the taper-ground face of a reference specimen treated at 1000°C

revealed that 50% decarburization has occurred at 0.56mm. 50% decarburization must also coincide with being halfway between the maximum and minimum H2/H1 ratios as shown in fig.12. This gives us one point for a secondary axis converting H1 values to depth at which 50% decarburization occurs. See the upper axis in fig.12. Repeating the procedure on specimens treated at 800 and 900°C would give us two further points for the upper axis. This secondary axis allows rebound tests on components to indicate the depth of 50% decarburization.

DISCUSSION

This article is largely intended to be educational. The migration mechanism and migration desire involved in decarburization have been outlined together with property effects and methods of detection.

A novel rapid test technique has been proposed. The technique is based on rebound testing using a range of impact intensities. At this stage it is purely a theoretical concept, utilizing the author’s previous experience of rebound testing to predict dent diameters.

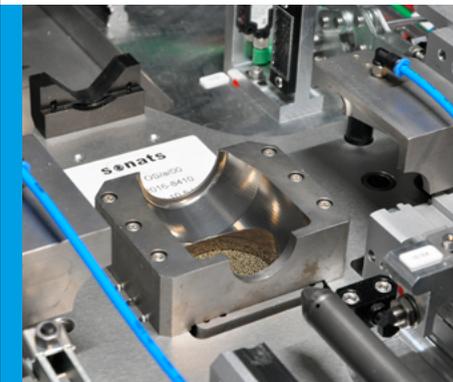
It is hoped, however, that the concept will be taken on board as a project by one or more interested organizations. ●



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