CASE-HARDENED

STEELS:

Microstructural & Residual Stress Effects

Edited by Daniel E. Diesburg

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MICROSTRUCTURAL AND RESIDUAL STRESS EFFECTS

A Publication of The Metallurgical Society of AIME
420 Commonwealth Drive
Warrendale, Pennsylvania 15086
(412) 776-9000

Printed in the United States of America.
Library of Congress Card Catalogue Number 83-63326
ISBN Number 0-89520-471-1

Case-Hardened Steels: Microstructural and Residual Stress Effects

Proceedings of the symposium sponsored by the Heat Treatment Committee of The Metallurgical Society of AIME held at the 112th AIME Annual Meeting, Atlanta, Georgia, March 9, 1983.

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A Publication of The Metallurgical Society of AIME

Foreword

Although case-hardened steels have been in use for many years and much research has been conducted, a great deal of speculation still exists regarding what metallurgical features are desirable for enhanced performance. Although some of the confusion comes from not having a precise understanding of the properties required for a given application, more confusion comes from not knowing how to test and evaluate case-hardened specimens.

Recently, several significant advances have been made toward the understanding of the measurement techniques for evaluating the properties of case-hardened steels. These advances have occurred mainly in three areas: (1) x-ray diffraction for measuring residual stress, (2) prediction of micrsostructural gradients in carburized cases, and (3) understanding the importance of non-uniform loading histories on subsequent fatigue performance.

The following collection of papers was presented March 9, 1983, at the Annual Meeting of The Metallurgical Society of AIME in Atlanta, Georgia. The main authors are known for their current interest and understanding of case-hardened steels and were personally invited to make a contribution. This was the first symposium on case-hardened steels since the Cincinnati, Ohio, meeting of AIME in November 1975. The purpose was to update each other on the current understanding so we could benefit from this knowledge in subsequent research activities.

The first three papers discuss, in general, laboratory test results and their possible relationship to field service. The fourth, by Kim, describes a fracture-toughness model for the fracture of case-hardened steels. Once the complexities of testing carburized cases have been discussed, the value of being able to predict both the case microstructure and the corresponding residual stresses becomes apparent, and the papers by Ingham and Clarke and by Ericsson et al. address these subjects thoroughly. Residual stress measurement is covered by Scholtes and Macherauch. The next two papers present specific test data and discuss the results in relationship to residual stress and microstructure. The final paper is an example of how an improved understanding of case-hardened steels can be used by industry to better design steels for carburized components.

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November 1983

Acknowledgments

The editor would like to acknowledge the combined efforts of the Heat Treatment and Book Publishing Committees of The Metallurgical Society of AIME: The Heat Treatment Committee for providing the forum for oral presentation and discussion and the Book Publishing Committee for providing the means to distribute the information to those unable to attend the conference. The following Heat Treatment Committee members are specifically acknowledged for their contribution during committee meetings prior to the conference:

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Contents

PROPERTIES OF CASE-HARDENED COMPONENTS --

BASIC CONSIDERATIONS CONCERNING THE DEFINITION AND

EVALUATION OF TOUGHNESS

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Fracture behavior depends on strength and toughness. Strength of case-hardened steels is a well-known and defined property whereas toughness is not as clearly defined. This paper deals with the problems of defining and evaluating the toughness required for heavily loaded gears.

Introduction

The object of case-hardening steels is to obtain a high-carbon martensitic case with good wear, fatigue and pitting resistance in combination with a tough low-carbon core. Depending on the procedure of heat treatment the properties of case-hardened components are frequently different. The surface carbon concentration, the depth of carburized zone and the hardenability of steel have a considerable influence on the performance of highly stressed parts. Every destruction of gears, e.g. by fracture, by wear or by pitting, begins in the surface or immediately below. Consequently the microstructure of that area has to receive due attention. Obviously the definition of the quality of a case depends on many objective considerations, but also on some subjective experiences. Toughness of case-hardened components is no doubt a controversial subject. The term is interpreted differently, the methods for its determination seem inconsistent, and the evaluation of existing experimental results is non-uniform. Therefore the question "To what extent is toughness a necessary characteristic of structural components in service?" will be discussed.

Toughness is a very indistinctive and vague term. It is therefore appropriate to select a component for discussion which, in view of its applications, is fairly versatile and permits the observation of "several different kinds of toughness". The gear wheel, which is usually manufactured in a case-hardened version for the purpose of transmitting heavy loads, is a most suitable component in this regard. It is put to versatile use for the construction of machines and vehicles, for which purpose the demands for toughness, particularly with regard to the last-named application, are again and again set especially high for safety reasons, even though no clear statement can be made as to the accurate meaning of the term "toughness".

Any engineer - and not only this one - engaged with the problem of moving a cog railway from place to place is confronted quite impressively with the problems based on the toughness of transmission members! The Swiss Pilatus railway, for example, with a grade of 48 %, is conquering a slope which has not been surpassed by other mountain railways up to now. For this purpose, it is guided by two gear wheels which, among others, are expected to absorb the clearly noticeable, jerky movements of the train In consideration of the fact that this railway has been operating free of problems already for approx. 50 years, the assumption may be permitted that the generation of engineers preceding us must have had at least an excellent feel for problems involving toughness. It is therefore most amazing that today - and even at increased intensity - we are still concerned with unsolved problems with toughness and its definition. This will be better understood after we have come to realize the extent of the different loadings to which such gear wheels are exposed, which is most impressively attained by having a look at all the possible kinds of damage that can occur (Figure 1).

The first frame in Figure 1 is a typical illustration of case-crushing. A type of damage characterized by the fact that the outer layer in range of transition from case-hardened outer zone toward core material is spalling off. The next frame shows the so-called pitting, which occurs mainly in range of tooth flank located between root of tooth and pitch point (range of negative sliding). Another type of damage shown in frame three exemplifies one type of wear. The fourth frame shows the damage occurring in the event of failure caused by an impact overload and should therefore be called an impact fracture. Finally, the last frame shows a fatigue failure, which may be the result of a repeatedly and often occuring slight overloading, closely resembling the fatigue plus overload situation to be discussed in the following paper by Cameron and Diesburg. The location of the individual types of failures is shown in center drawing. A supplementary remark should be that the damage descriped above is

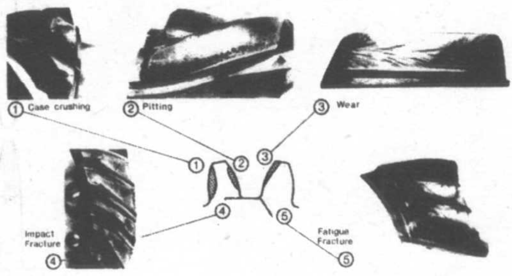

Figure 1 - Possible kinds of damage of overloaded gears

normally not showing up in its purest form, but is frequently superimposed to a certain extent. There is no significance to the fact that examples four and five show fractures at different angles.

Observations concerning Continuum Mechanics

Now, if we want to move from these possible kinds of damage to "toughness", it is quite obvious that a connection between this characteristic and strength must be established, since strength is no doubt the decisive factor which decides essentially about the characteristics prevailing during use and is commonly known best. A known rule is that, with one exception, an increase in strength is always accompanied by a reduction in toughness. (The one exception is that grain refinement increases both strength and toughness). It is still an open question as to what is actually meant by "toughness", but the problem can be approximated by asking the answer to the question: What are we "feeling", whenever we are using the word toughness as intended here? First of all, we are apparently referring to an image of deformation or deformability!

Looked at macroscopically and considering continuum mechanics, a broken part will show the presence or the absence of deformation characteristics. A tensile test is well suited to show such characteristics and was the first test to be used as an experimental access to the problem. In the tensile test differences in elongation and constriction can cause differences in fracture behavior and appearance. A look at the fractured surfaces under slight magnification shows additional signs of different deformability. Consequently, the known fact is established that at similar stress there are obviously materials with different macroscopic deformation behavior, which seems to be essential for the type of fracture development shown. Based on a technical a priori knowledge we can differentiate between a tough fracture and a brittle fracture. Seen analytically, the type and scope of deformation are determined by the effective state of stress. This again depends entirely on the shape of the stressed body. Smooth samples show, for example, characteristics of deformation, which may be absent on notched samples (Figure 2). According to mechanical laws, this difference is based on a changed state of stress. In the case of single directional multi-axiality there will be a restriction of deformation, which can be described in a first approximation by its representation in a Mohr's circle. The effective maximum shearing stress τ_{max} is reduced, so that macroscopic flow will start at higher forces only, unless the breaking strength is attained

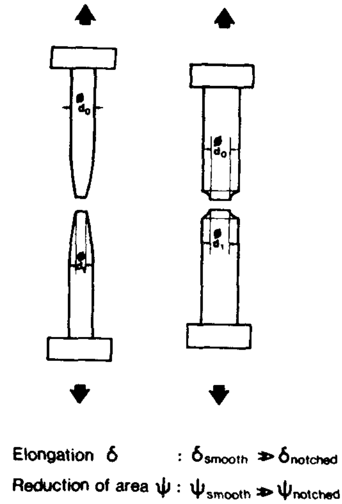

Figure 2 - Characteristics of deformation. The influence of shape of the stressed body

first (Figure 3). What could be responsible for the appearance of a normal stress fracture with low deformation. The more intensive the multi-axiality, the more favorable are therefore the conditions for the appearance of a macroscopically no-deformation fracture.

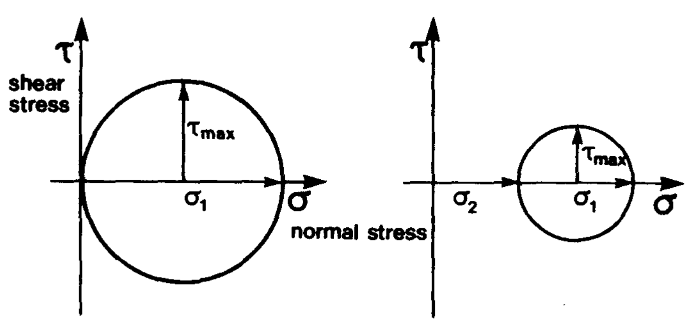

Figure 3 - Representation of the state of stress by Mohr's circle. The maximum shear stress is reduced in the case of multi-axiality

Additional intensifications in the direction of a brittle fracture appear at increased speed of stress of the type occurring, for example, during impact tensile test.

Obviously, the state of stress and its change under influence of time is the determining variable which determines the fracture characteristics when looked at from a point of view involving continuum mechanics.

The embrittling effect of notches can be convincingly demonstrated in a series of tests in which tensile test pieces of ductile non-casehardened steels with notches of different form factors are loaded up to fracture (Figure 4). The sharper the notch, the higher the appearance of fracture toward higher stresses, the higher the maximum rupture load, but the lesser the elongation and constriction. In this connection, we are talking about a reduction of the working capacity, which is often a considerable quantity influencing structural design.

Observations concerning Structure Mechanics

In contrast with observations concerning continuum mechanics, microstructural investigations provide information concerning interrelations between possible fracture behavior and the structure of the materials. It is important to state at this time that a total identity between macroscopic fracture characteristics and microscopic fracture characteristics does not exist. Even brittle macrofracture shapes show areas with some plastic deformations in micro range. The characteristic sign in this regard are the dimples shown in Figure 5. On the other hand, characteristics for brittle fractures are, for example, the microfractures (Figure 5) called "quasi-cleavage fracture". However, the proportion of microscopic brittle fracture characteristics will always increase with the increasing formation of macroscopic brittle fracture.

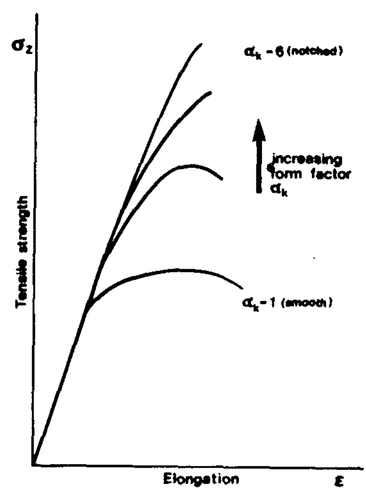

Figure 4 - Tensile test with notched samples of different form factors α_k. The higher α_k, the higher the ultimate tensile strength

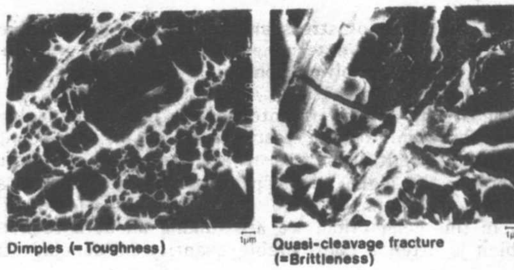

Figure 5 - Characteristic sign of microfracture

An investigation as to the type of microscopic fracture formation shows first the significance of transformation structures. Consequently, martensite is first in place for case-hardened steels. In an ideal case it will be a homogenous structure, comprising a tetragonally distorted crystal lattice which is oversaturated with carbon. According to latest investigations (1), the designation martensite does require an addition to indicate the difference between the various types of martensite. In dependence of the carbon content, there is therefore a difference between lath martensite with low C content and plate martensite with a high C content (Figure 6). A transitory range shows a mixture of both types. An investigation can be made microscopically only and the identifying characteristic is the layout and the shape of the martensite crystallites. Lath martensite is described best by thinking of a fine crystalline martensite, which has also been known by the name of "Hardenit". On the other hand, plate martensite is more coarse-needle shaped and is in most cases surrounded by clearly recognizable residual austenite. Practical experience

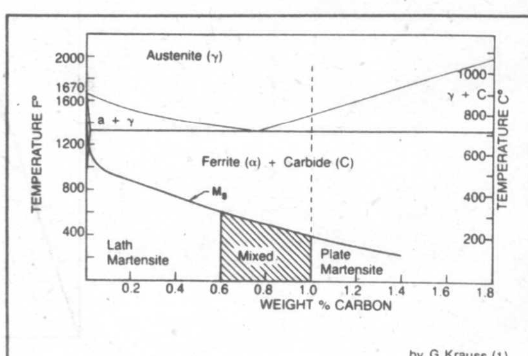

Figure 6 - Different types of martensite in dependence of carbon content

already shows that the martensite with a low C content is the tougher variant. Thorough investigations on lath martensite with a low C content provided information about possible types of fractures and their causes. The package-like arrangement of lath martensite is indicated by the hatched lines within a former austenite grain (Figure 7). Investigations by means of Auger-spectroscopy have confirmed the coverage of former austenite grain boundaries with P and C (2). These "intercrystalline" precipitations may provoke an intercrystalline fracture in the event of overloading, since they will considerably reduce the cohesive strength at ambient temperature. Cleaner (low in phosphorus) steels have a tendency towards transgranular fracture formation. Two different possibilities prevail: Even at low C contents, residual austenite, though a very low one, cannot be avoided during martensitic conversion. This austenite, which is located in parallel with laths, can convert to martensite under stress coupled with a simultaneous precipitation of carbide. This formation of carbide and martensite weakens the grain by bursting due to increase of volume and favors a transcrystalline fracture running in parallel with laths (packages). Coarser carbides, which may also be located between the laths, may be the cause for a transcrystalline transverse fracture, as shown diagrammatically in Figure 7.

The effect of the P content cited above (2) on toughness is shown quantitatively in Figure 8. Simultaneously, the influence of temperature can be seen. There is also the fact that the negative effect of phosphorus, as shown in detail by the results of the investigations, occurs only in the presence of a carbide precipitation at the former austenite grain boundaries.

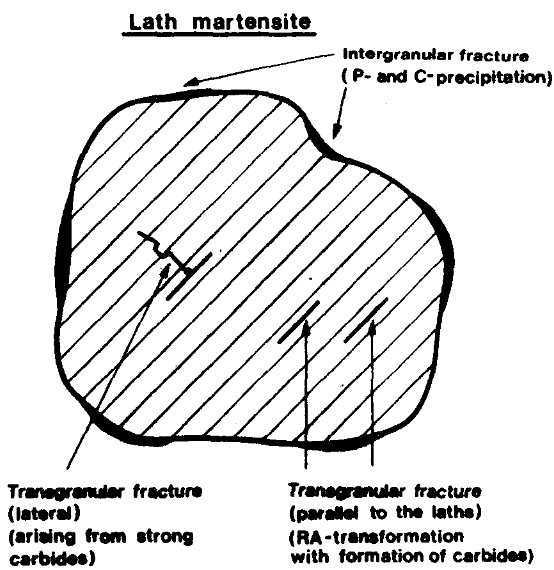

Figure 7 - Different types of fracture in lath martensite

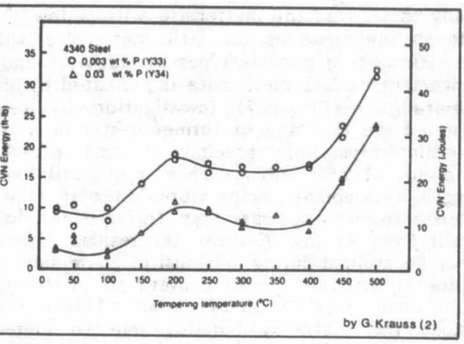

Figure 8 – Effect of P content on toughness depending on temperature

In addition to the martensite structure which has been considered nearly homogenous with restrictions up to now, the heterogenous transformation structures, in which, for example, a larger amount of residual austenite occurs in addition to martensite, are of special significance when seen from technical points of view. The appearance of larger quantities of residual austenite is connected with a coarsening of the martensite (Figure 9). This in turn is theoretically derivable and results in a reduction of ductility. Likewise, the effect is certainly a reduction in toughness which may be caused by the overcarburizing due to carbide networks (Figure 10) and is therefore critical in the event of impact stresses. The shape of the carbide network has an additional influence and the assumption is that closed networks will behave particularly unfavorable in the event of overstressing. Uniformly distributed rounded carbides appear to have no influence on ductility as compared with homogenous martensite.

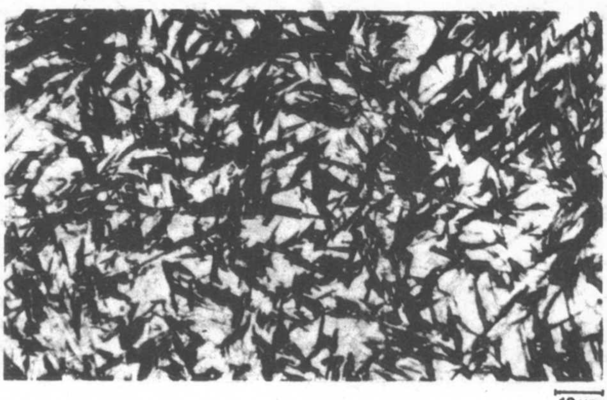

Figure 9 – Typical retained austenite with coarse martensite

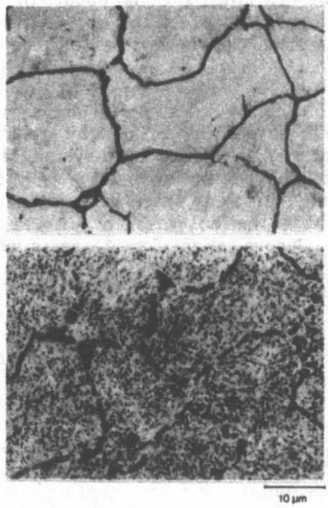

Figure 10 - Different carbide network in different steels. 3,5 % Ni-Cr-steel (at the top) and 1,2 % Cr-Mn-steel (at the bottom)

Structural faults, which include segregations, microcracks or porosity, boundary oxidation, non-metallic inclusions and grain boundary deposits (for example oxidation products) and excessive hydrogen content, are surely having negative effects most of the time. Of these, only the effect of grain boundary oxidation has been thoroughly investigated by now. Of the others, it is only known that (for example microcracks, micro porosity, oxide inclusions) they may be areas of preferred crack formation or the cause (for example H_2) of spontaneous fractures. The effect of hydrogen is particularly remarkable. It seems to be clearly reversible, but to a certain extent. On the other hand, the number of investigations performed at the moment is not large enough to pronounce a final evaluation concerning the influence on case-hardened steel. The hydrogen input during gas carburization in usual atmospheres is definitely unavoidable and not without significance for the properties of components.

As the result of the observations concerning structure mechanics there is the conclusion that the ductility of a technical material obviously depends on a multitude of influences. Their complete consideration is problematic and the performance of experimental investigations can hardly be designed in such a manner that transferability to other materials systems and conditions in the meaning of generalization will be possible.

Residual Stresses

Components hardened at their outer layers are considerably affected with residual stress. Their effect on the behavior of case-hardened components has been thoroughly investigated with regard to their strength characteristics.

However, investigations about the influence on toughness have not yet been explicitly described and can therefore be derived only indirectly from available structure conditions. To facilitate estimates, a few basic facts, based on the versatile results of investigations of the recent past will be shown.

While in a single-phase, purely martensitic structure of case-hardened steels a description of the residual stress condition is non-problematic, its discussion in a two-phase system, for example in the presence of martensite and residual austenite will be more difficult, because then a difference has to be made between phase-homogenous, aligned macro parts in martensite and identical macro parts in residual austenite (σ_EMa) (Figure 11) and phase-homogenous, aligned micro parts which are, however, different in martensite and in residual austenite (σ_EMi). In addition, there are still unaligned residual stresses in submicroscopic range of both phases (σ_EMi*). (σ_EMa + σ_EMi) can be evaluated by x-ray analysis. The variation of residual stresses of the micro part measured on martensite is congruent with the macro part of $\sigma_{röE}$ of the residual stresses (Figure 12) determind by x-ray analysis. These facts are of significance for an analysis of the fracture characteristics of statically stressed samples and components. The nature of the residual stresses which are characterized simultaneously by macro and micro effects, results both in an influence on the macroscopic stress condition, as well as in a reaction on the micro-structural fractural behavior. There is therefore an interaction between the structure and the macro characteristics. This will simultaneously also make clear that the strength characteristics of case-hardened components can then no longer be explained alone by a superposition of load and residual stresses, if the stryucture composition is multi-phase. In the case of a residual austenite--containing case-hardening layer, for example, the strength characteristics are very heavily determined by the residual tensile micro stresses in the austenite phase. They are, among others, responsible for the unfavorable fatigue characteristics of deep cooled, case-hardened components containing residual austenite.

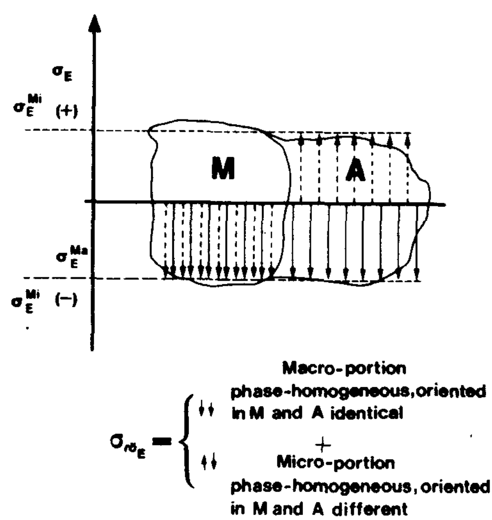

Figure 11 - Various types of residual stresses