Failures due to improper hardening of steel components

S. GHOSH CHOWDHURY

National Metallurgical Laboratory, Jamshedpur - 831 007.

ABSTRACT

Components made up of steel are often quenched, so that they become hard due to the formation of martensite. The quenching rates through out the component, however, changes depending on the section size. Wherever the rate of cooling is greater than the critical cooling rate martensitic microstructure is obtained. In a specified standard quenchant the depth of martensitic case being a characteristic of the steel is known as hardenability. Hardenability is characterized by critical diameter (D_l) or critical plate thickness (L_l) which corresponds to the formation of 50% martensite –50% pearlite at the centre. This, D_p is dependent on the carbon content, austenite grain size and various alloying elements. Presence of alloying elements lead to increase in hardenability by delaying the ferrite pearlite transformation. However, the differential cooling rates encountered by the component produces stresses leading to distortion and cracking. To reduce these stresses, hardened materials are subjected to tempering to make a balance between hardness and toughness required in service. This also determines the conditions of tempering for a given application. Case studies will be presented to show the effect of the quenching response and the subsequent tempering treatment for a component depending on its specific application requirements.

INTRODUCTION

Heat treatment is an operation or combination of operations involving the heating and cooling of a metal or alloy in the solid state for the purpose of obtaining certain desirable properties. The usefulness of steel is due to the relative ease with which its properties may be altered by changes in chemical composition and heat treatment. Steels employed in industry are not only pure iron-iron carbide (Fe_3C) alloys; for special service, it contains as many as five or more elements. Fig. 1 shows a continuous cooling curve superimposed on the isothermal transformation (I-T) diagram for various cooling curves [1]. Cooling curve 3
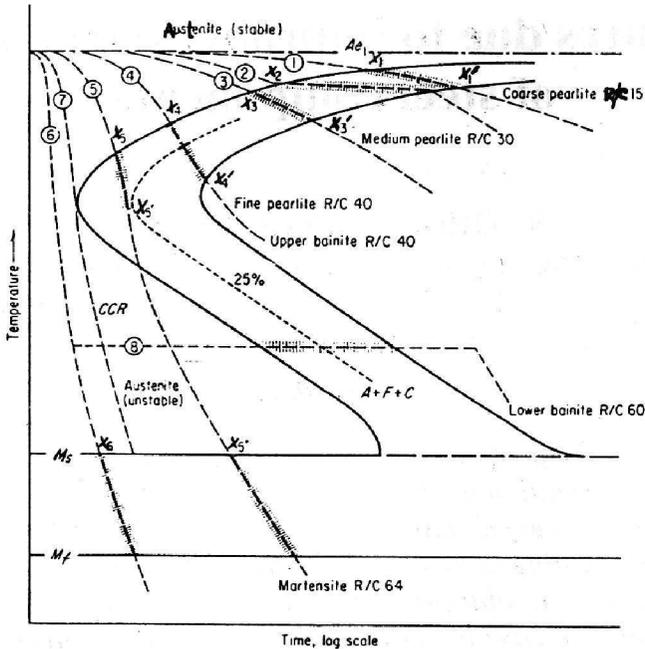
Fig. 1 : Cooling curves superimposed on a
hypothetical I-T diagram for a eutectoid steel

shows a very slow cooling rate typical of conventional annealing. Transformation starts at X_1 and continues until point X_1'. The overall product will be coarse pearlite with low hardness. Cooling curve 2 presents a more uniform microstructure and hardness compared to 3. Curve 3, may be considered as normalizing the microstructure, will be a mixture of medium. Cooling curve 6 is rapid enough to avoid transformation to the nose region. It is apparent that to obtain a fully martensite structure, it is necessary to avoid transformation in the nose region. Therefore cooling rate which is tangent to the nose, would be the approximate critical cooling rate (CCR). Any cooling rate slower than this produce some softer transformation product whereas the cooling rate faster than that will form only martensite.

Machine parts, automobile parts and steels used in different industry have any appreciable size. These are expected to be stronger and tougher by means of heat treatment. Two processes of hardening are common to achieve those properties for the components i.e. (1) Hardening by varying cooling rate and (2) Surface hardening. The need for better control of the properties of through hardened and carburized steels has led to intense interest in quenching and the transformation phenomena which occur during quenching. In the present article, the fundamentals of hardening and the methodology for achieving that have been described. In the latter part, some case studies have been presented to show the

improper application of the methodology which lead to the failure of the components.

HARDENABILITY

In a steel specimen of any appreciable size, the cooling rates at the surface and at the centre are not the same. Thus, at any instance, there will be little difference between the temperature at the surface and at the centre of a bar of some size when it is furnace-cooled. On the other hand, the same bar if quenched in a rapid coolant will produce entirely different microstructures at the surface and at the centre of the bar. Hence, by drastic cooling, (more than critical cooling rate) the steel will have hardened throughout the cross-section. Therefore the hardenability is defined as the ability of the material to harden throughout the cross-section without any distortion or cracking caused by drastic quenching.

The initial step in the hardening of steel is the formation of austenite i.e. austenitizing and it depends on temperature and time. When other elements such as Cr, Mn and Mo are added to steels, the boundaries of the phase field changes to a degree that depends on the amounts of the alloying additions and on the carbon content [2]. The eutectoid temperature as well as the eutectoid carbon content vary with the concentration of alloying elements present in the steel [2]. The rate of austenite formation increases rapidly with temperature. However, the time for complete homogenization is much longer than for the formation of 99% of austenite. In alloy steels, alloy carbides dissolve much more slowly than cementite and the dissolution temperature is dependent on the stability of carbides. The dissolution temperature of V-carbide is 1050°C whereas for Nb-carbide, it is 1150°C. Even after the carbides have dissolved, the homogenization of austenite is a slow process, because of slow diffusion of alloying elements. Hence, if the material was kept at high temperature for longer time, there would be austenite grain growth and results in poor impact properties of the heat treated steel. Therefore, controlled rapid heating to high austenitizing temperature can minimize the required holding time for austenitizing.

After austenitizing, steel parts can be hardened to various degrees by controlling the cooling rate and the temperature at which the steel is held below Ae_1 temperature for a given period of time prior to further cooling. The rate of cooling tends to decrease with increase in depth. The structure, hardness and strength resulting from a heat treating operation are determined by the actual cooling rating obtained by the quenching process. If the actual cooling rate exceeds the critical cooling rate, only martensite will result whereas the part will not completely harden if the rate is less than the above. The greater the difference between the two cooling rates, the softer will be the transformation prod-
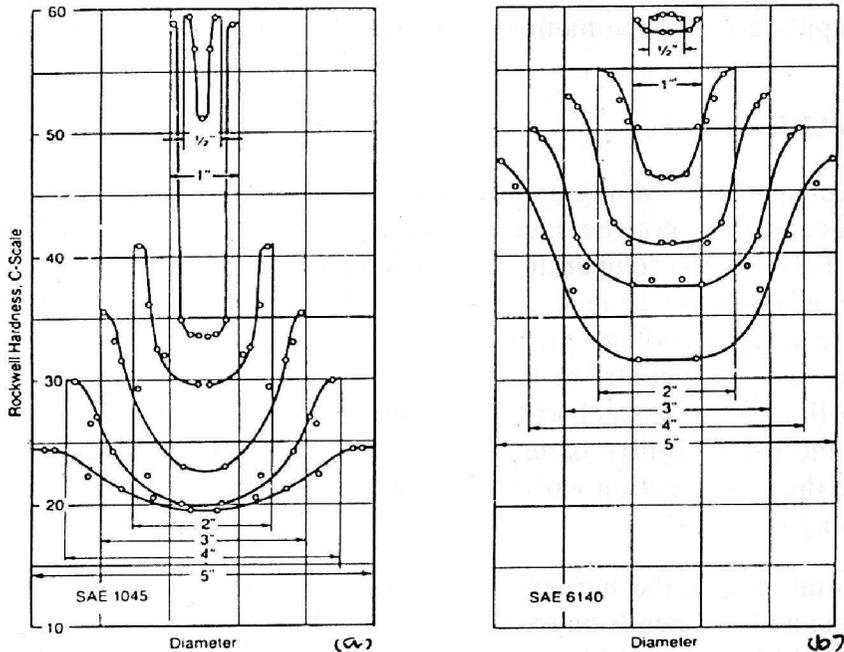
Fig. 2 : Hardness distribution in water-quenched bars of SAE 1045 and SAE 6140 steel

ucts and the hardness will be low. Fig. 2(a) and (b) show the effects of bar diameter on hardness distribution of water-quenched rounds [3]. Comparison of Fig. 2 indicate that SAE 6140 is much more hardenable than the plain carbon SAE 1045 steel. SAE 6140 is, therefore, said to have a higher hardenability than the SAE 1045 steel. The chemical compositions have been given in Table 1. The alloying elements in SAE 6140 steel increase the time required for austenite to decompose to ferrite and/or ferrite-cementite mixtures and thereby make it possible to form martensite at lower cooling rates. It should also be noted that the plain carbon steel can be hardened but only in small sections and/or with very severe quenchs. Therefore, the characteristic that is used to quantify the ability to form martensite in steel parts of various section sizes is called 'Hardenability'. It depends mainly on two factors :

1. quenching ability of the quenchant, and
2. hardening characteristics (i.e. critical cooling rate) of the steel.

Table 1 : Composition of steels used in bar quenching

Steel	C	Mn	P	S	Si	Cr	V
SAE 1045	0.48	0.60	0.022	0.016	0.17	-	-
SAE 6140	0.42	0.73	0.027	0.023	0.25	0.94	0.17

QUENCHING ABILITY OF A QUENCHANT

The quenching ability of a quenchant is specified by its quenching severity, H, which is defined as the rate of removal of heat by the quenching medium from the object [4].

$$H = \frac{\text{heat transfer coefficient between steel and medium}}{\text{thermal conductivity of the steel}}$$

The transfer of heat at the interface of a steel part and a quenching medium is a complex process that depends on the emmissivity of the steel and convection currents within the quenching medium that remove heat from the interface.

Understanding of the cooling process has important practical consequences. For example, if the low cooling rate of the first stage results in ferrite or pearlite, the cooling rate may be improved and the temperature of the medium kept constant by circulation of the medium and agitation of the piece. This effectively wipes off the vapour film as quickly as it forms, reducing the length of the vapour-blanket stage and results in faster cooling [5]. It is worthy to be mentioned that workers should be advised not to wash their hands in the quenching water because that leads to decrease in the H values of the water by the addition of soap, oil and grease.

The ability of a steel to transfer heat is characterized by its thermal diffusivity. For a given quenching medium, the thermal diffusivity determines the temperature distribution as a function of position at any given time in the quenching process [3]. Practically, there is little control of thermal properties possible in steels and the most important control of cooling rates is performed by proper selection of quenching media. The H values for different quenching media are listed in Table 2. Knowing H, the cooling rates in the interior of a round of steel of diameter D can be calculated. The result of such calculations are presented as plots of (D_U/D) against log (DxH) (Fig. 3) [4]. D_U represents the diameter of the circular area in the centre of the round where the cooling rates are less than an arbitrarily specified cooling rate. The curves in Fig. 3 correspond to many possible values of H and specified cooling rates.

For the determination of H of a coolant, rounds of a low alloy steel of various diameters are quenched in it. The rounds normally have a soft core and a hard case. The soft core containing less than 50% martensite is the criterion for the critical diameter [3]. Etching differences between the hardened surface of a bar and the unhardened centre are most clearly developed close to the 50% pearlite – 50% martensite zone in a bar. The diameter of the soft core represents

Table 2 : Severity of quench (H) for various quenching media [3]

Agitation	Air	Oil	Water	Brine
No	0.02	0.25 – 0.30	0.9 – 1.0	2
Mild	–	0.30 – 0.35	1.0 – 1.1	2 – 2.2
Good	–	0.4 – 0.5	1.4 – 1.5	–
Strong	0.05	0.5 – 0.8	1.6 – 2.0	–
Violent	–	0.8 – 1.1	4	5
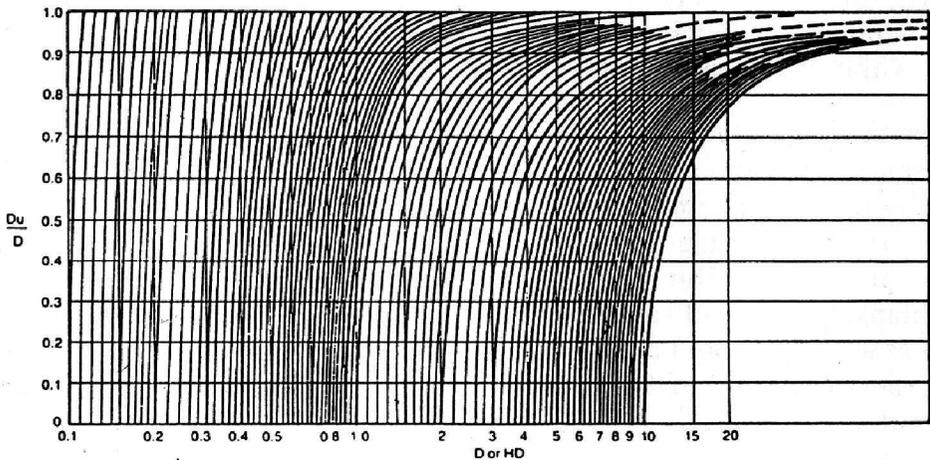
Fig. 3 : Curves of D_U/D vs HxD for estimating severity of quench (H) for quenching baths

D_u. Experimental values of D_u/D are plotted against log D on a transparent paper in the same scale is shown in Fig. 3. The experimental curve is compared with the theoretical curves and the best matching theoretical curve is determined. The coordinate of any point in the theoretical curve on the X-axis gives (HxD). Since, D is known, H can be calculated. Usually an average value of H is obtained after considering a large number of points on the curve.

The quenchant with H = ∝ is some times taken as the standard quenchant. When H = ∝, the surface of the object cools instantaneously to the temperature of the medium and heat is extracted from the surface as rapidly as it is conducted to the surface. This is therefore called 'Ideal Quenchant'.

HARDENING CHARACTERISTICS OF STEEL

D_I, the ideal critical diameter of a steel is the diameter of a infinitely long cylinder of that steel which when quenched in the ideal quenchant would have 50% martensite in its centre. Fig. 4 shows that rods of different diameters harden to a different depth on quenching in the same medium [2]. The largest

diameter rod 4 has only fine peartite at the centre. The hardness changes more rapidly at a value of R_c 54, corresponding to a microstructure of 50% martensite - 50% pearlite. Rod 3 has hardness of R_c 54 at the centre. Hence, this is the critical diameter (D_C).
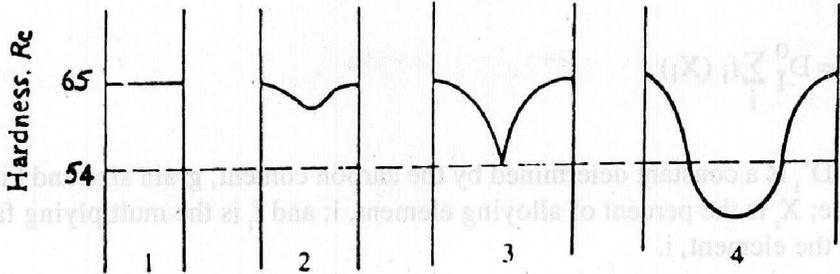

Fig. 4 : Schematic diagram showing the determination of critical diameter

D_I values can be determined by the following method. Rods of the steel whose D_I value is to be determined are quenched in a quenchant of known H. The rounds are sectioned, etched and the diameters of the cores containing less than 50% martensite are measured. Thus, D_U/D values can be plotted against D. The value of D corresponding to $D_U/D = 0$ is determined and is designated as critical diameter D_C. As it is possible to calculate the cooling rate at the centre of any round with a known value of H, the diameter of the round which when quenched in the ideal quenchant would have a cooling rate at its centre same as that of D_C can be calculated. Here, the calculated D will be D_I. Calculated values of D_I corresponding to many possible combination of H x D_C are shown in Fig. 5 [3]. Each point on the curves in this figure correspond to set of values of D_I, D_C and H.
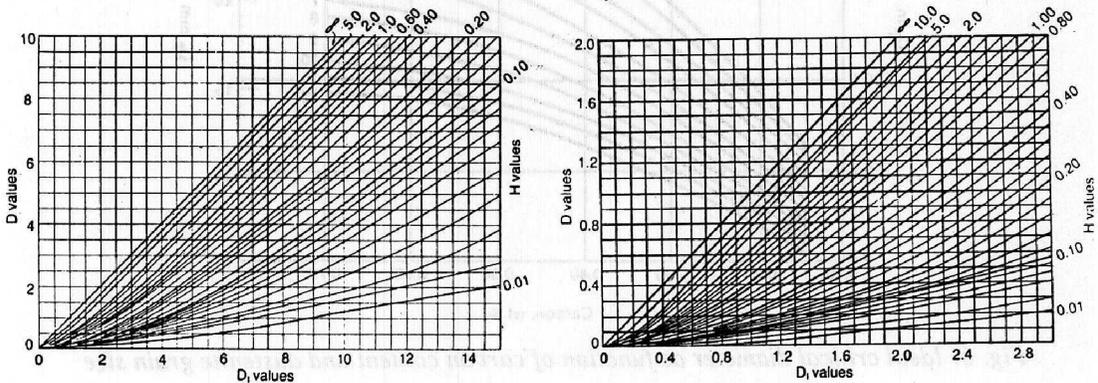

Fig. 5 : Correlation between critical diameter, D_C
and ideal critical diameter, D_I for various quenching media.

Similar curves between critical plate thickness, ideal plate thickness and quench severity have also been developed [3]. The relationship between D_I and L_I

(critical plate thickness) is $D_I = 1.377 \, L_I$.

The ideal diameter can be used to compare the hardening response of different steels to the same quenching medium. D_I can be represented by the following analytical equation [6]

$$D_I = D_I^0 \sum_i f_i \, (X_i)$$

where D_I° is a constant determined by the carbon content, grain size and killing practice; X_i is the percent of alloying element, i; and f_i is the multiplying factor due to the element, i.

Fig. 6 shows the relationship of hardenability in terms of D_I for a carbon steel to carbon content and grain size [7]. D_I decreases with decreasing carbon and decreasing grain size. It is worthy to be mentioned that the nose of the C-curve shifts to the left and the hardenability decreases due to lower carbon content than the eutectoid value as well as fine grain size. It should also be noted that D_I value decrease when the carbon content is increased beyond 0.8%.
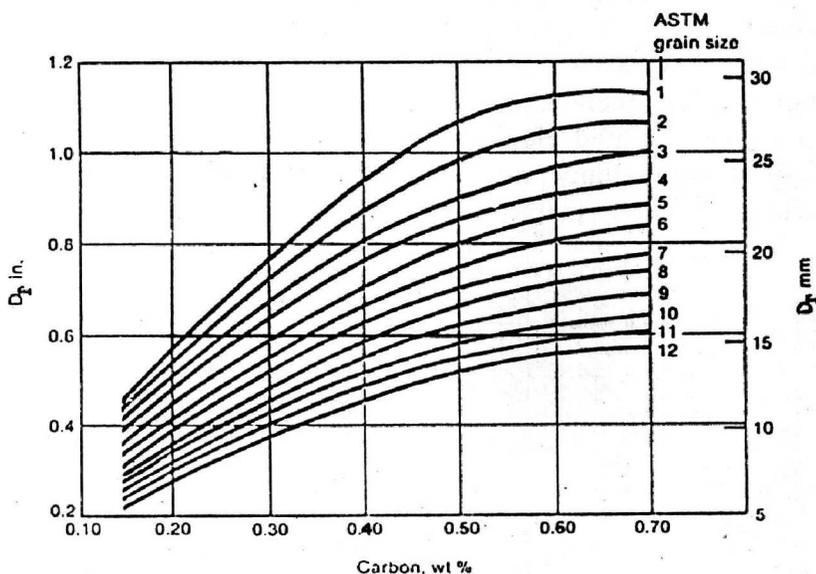

Fig. 6: Ideal critical diameter as function of carbon content and austenite grain size

The base hardenability is then multiplied by factors as given in Fig. 7, for different alloying elements [8]. Each and every one of the chemical elements in steel has an influence on its hardenability. Of all the alloying elements in steel, Co, is the only one that decreases hardenability. The presence of Co in steel

increases both the nucleation and growth of pearlite. Alloying elements, increase hardenability by delaying diffusion-controlled transformation and form martensite with slower rates of cooling. Higher hardness persists to greater distances from the quenched end in the more hardenable steels. For any grade of steel, a hardenability band develops because of the small variations in composition allowable in the grade. The SAE/AISI steels designated by the letter H are guaranteed to meet established hardenabilities.
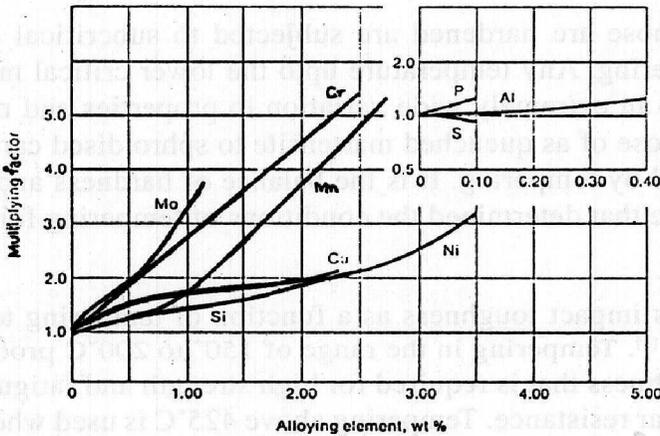

Fig. 7: Multiplying factors for various alloying elements

PROBLEMS ASSOCIATED WITH QUENCHING

The differential cooling rates encountred by the heat treatment parts produces stresses that may lead to distortion and even cracking. During cooling two processes take place : (a) volume expansion due to martensite formation and (b) thermal contraction during cooling. Residual stresses and distortion arise because cooling rate is a function of section size or position in a part and therefore, the volume change occur at different times in different locations during the cooling process. The stresses produced by the different rates of cooling throughout a part produce distortion if the stresses generated are high enough to produce nonuniform yielding or plastic deformation on cooling. Even, stresses upto the yield point may be present at room temperature and such stresses will be superimposed on the applied stresses in service unless tempering or stress-relief treatments are performed. Residual compressive stresses at the surface are desirable. However, residual tensile stresses add to the applied tensile stresses and lowers the strength and fatigue resistance in service.

Surface tensile stresses developed due to severe quenching lead to cause quench cracking rather than yielding. The tendency to distortion, quench cracking and/or residual stress formation during heat treatment may be reduced by

any change in processing that lowers the differences in the rates of cooling be-tween the surface and the interior of the part. This can be done by using moder-ate quenching for hardening. The effectiveness of a less severe quench in hard-ening require the use of a more hardenable steel and the matching of steel com-positions, section size and cooling rates are an important application of hardenability.

TEMPERING

All steels those are hardened are subjected to subcritical heat treatment known as tempering. Any temperature upto the lower critical may be used for tempering, thus an extremely wide variation in properties and microstructures ranging from those of as quenched martensite to sphroidised carbides in ferrite can be produced by tempering. It is the balance of hardness and toughness re-quired in service that determined the conditions of tempering for a given appli-cation.

Fig. 8 shows impact toughness as a function of tempering temperature for hardened steels [3]. Tempering in the range of 150° to 200°C produces a modest increase in toughness that is required for high strength and fatigue resistance as well as good wear resistance. Tempering above 425°C is used where high tough-ness is of major requirement and strength is of secondary concern.

SUMMARY

Selection of steel to meet a minimum hardness at a given location in a quenched part under certain conditions should be governed by the cooling rate at that location. Alloy steels that can be hardened by moderate quenching may
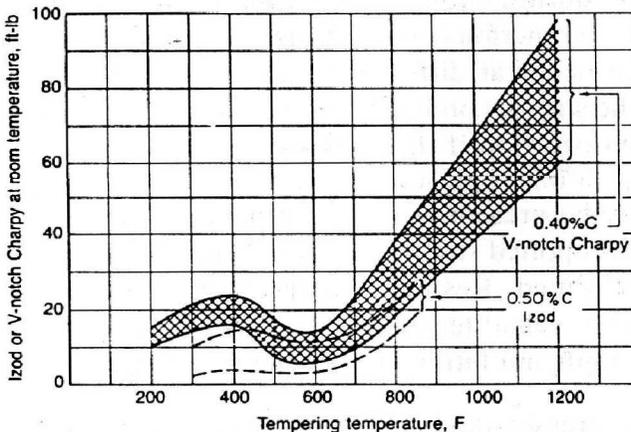

Fig. 8: Impact toughness as a function of tempering temperature of low alloy steels

be selected to replace leaner steels in which the severe quenching required to obtain high hardness causes quench cracking.

It is also of great importance to calculate the cooling curve correctly because cooling rate will govern the hardness distribution by controlling the phase transformation. As heat conductivity as well as the specific heat changes is a function of temperature and cooling rate, the calculation are difficult. Therefore, when a steel is purchased on the basis of a hardenability specification, the purchaser is certain that he will obtain the desired mechanical properties after heat treatment. This results in fewer rejections in retreatments and greater economy.

For better toughness and wear resistance, the components are hardened by quenching. This requires that the materials is to be heated above the austenitizing temperature for some time and then quenching is carried out by water, oil or air depending upon the size, section, steel composition and the application requirements. Quenching and the heat transfer at the quenchant-workpiece interface establishes the cooling rates within the work piece, which together with the austenitic structure and composition of steel, controls the transformation of austenite to mixtures of ferrite-cementite or martensite. The generated microstructure ultimately controls the final mechanical properties of the components. However, the temperature and transformation gradients established during quenching influence the development of residual stress, distortion and cracking. Thus the understanding of quenching and associated phenomena is essential not only for the production of steel parts with desirable mechanical properties but also to minimize manufacturing difficulties associated with quench products which leads to higher rate of production.

CASE STUDIES

I. FAILURE ANALYSIS OF BOW SHACKLES AND CHAIN LINKS [9]

Fig. 9 shows typical deformation pattern at the inner side of the crown of both the components. One side has worn out less than the other side. Such features of damage are generally attributed to the exposure at high temperature. However, no high temperature phenomena is present. The deformation features on the surfaces indicate that the hardness is not sufficient to take care of wear. The composition of the steel is given in Table 3.

Table 3 : Chemical composition

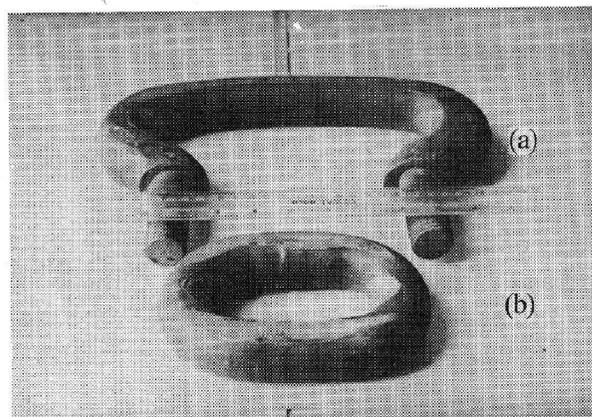| Material	C	Mn	P	S	Si	Al
Bow shackle	0.32	0.67	0.02	0.01	0.19	–
Chain link	0.18	1.4	0.022	0.006	0.2	0.008

Fig. 9 : Worn out portions of (a) Bow Shackles and (b) Chain links

(a)   *Bow shackle :* The material was used in quenched and tempered condi-
tion. The microstructure on either side of the component show mostly similar
features. The structure is essentially ferrite-pearlite with a hardness of R_c20
The ferrites have widmanstatten morphology and the amount of windmanstatter
is more in the outer side (Fig. 10). Limited amount of spheroidisation was also
observed which is typically soft but with high toughness. This is indicated by
the material flow marks on the worn out surface without any crack. The above
observations indicate that the material is not hardened properly. The analysis is
given below.

From Fig. 6, $D^°_I$ for 0.32%C and grain size of ASTM No. 12, will be 0.38. As
per the chemical composition in Table 3, f_{Mn} = 1.35, f_{Si} = 1.2, f_p = 1.1, f_s = 1
Therefore, D_I = 0.38 x 1.35 x 1.2 x 1.1 x 1 =0.68 inch. Comparing with Fig. 5
for H = 1.0, D_c is 0.22 inch and D_c is 0.1 inch for H = 0.35. Therefore, due to this
low severity of quench, this low C-content material will form widmanstatter
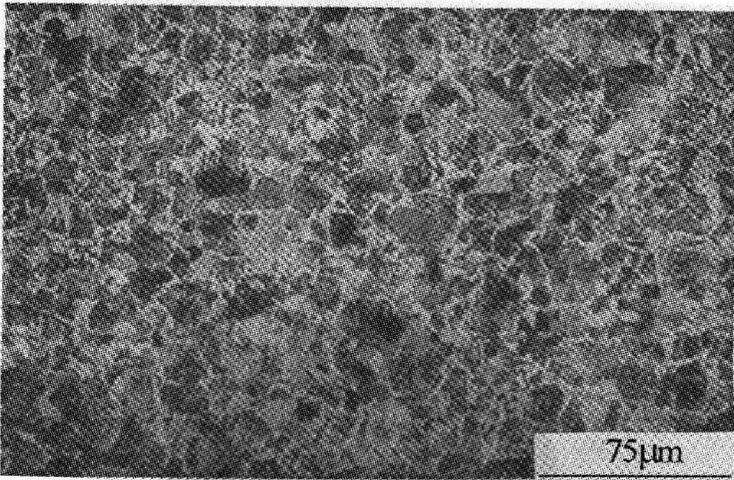kind of structure. Later, during tempering, the widmanstatten structure changes

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Fig. 10 : Microstructure of the bow shackle showing ferrite-pearlitic structure

to equiaxed and the carbides (Fe_3C) will form globules. This softens the structure and it is known that spheroidization of this low carbon structure leads to a 'gummy' structure. However, if the material is hardened by water quenching (H=1.5 to 2.0) followed by tempering at 150°C leads to hardness of R_C= 40 which is known to have good wear resistance. The corresponding microstructure is shown in Fig. 11.
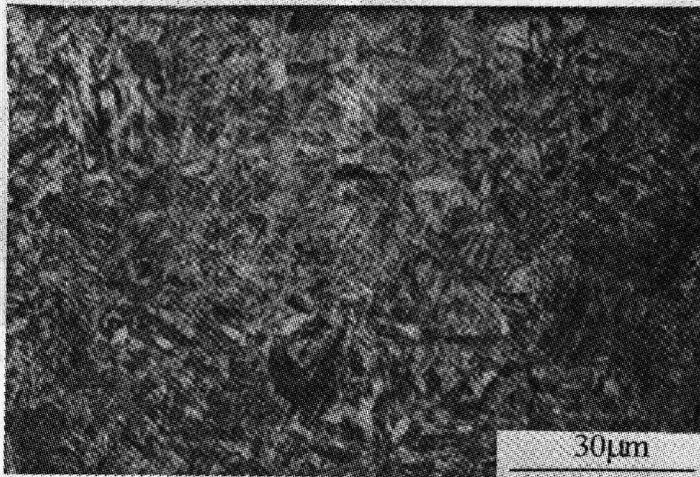

Fig. 11 : Optimum microstructure after proper quenching and tempering

(b) *Chain link :* The material was carburized, then quenched and tempered. The case depth was found to be 2.5 mm (Fig. 12). The microstructure shows spheroidized structure in the case and simple ferrite-pearlite structure in the core (Fig. 12). By similar procedures, D_I is found to be 0.9 inch. Therefore, for H = 0.35, D_c is 0.15 inch and D_c will be 0.35 inch for H = 1.5. Therefore, the

process of quenching has not been done according to proper methodology. After light quenching, the material had ferrite pearlite microstructures. Later during tempering, the lamellar carbides changed to globules, as the carbon content is more in the cases the degree of spheroidization is high there (Fig. 12b). The microstructure after proper quenching and tempering is shown in Fig. 13. The quenching is done in water with agitation and then tempering has been performed at 150°C. The hardness is R_c 30 at the core and R_c 55 at the case.
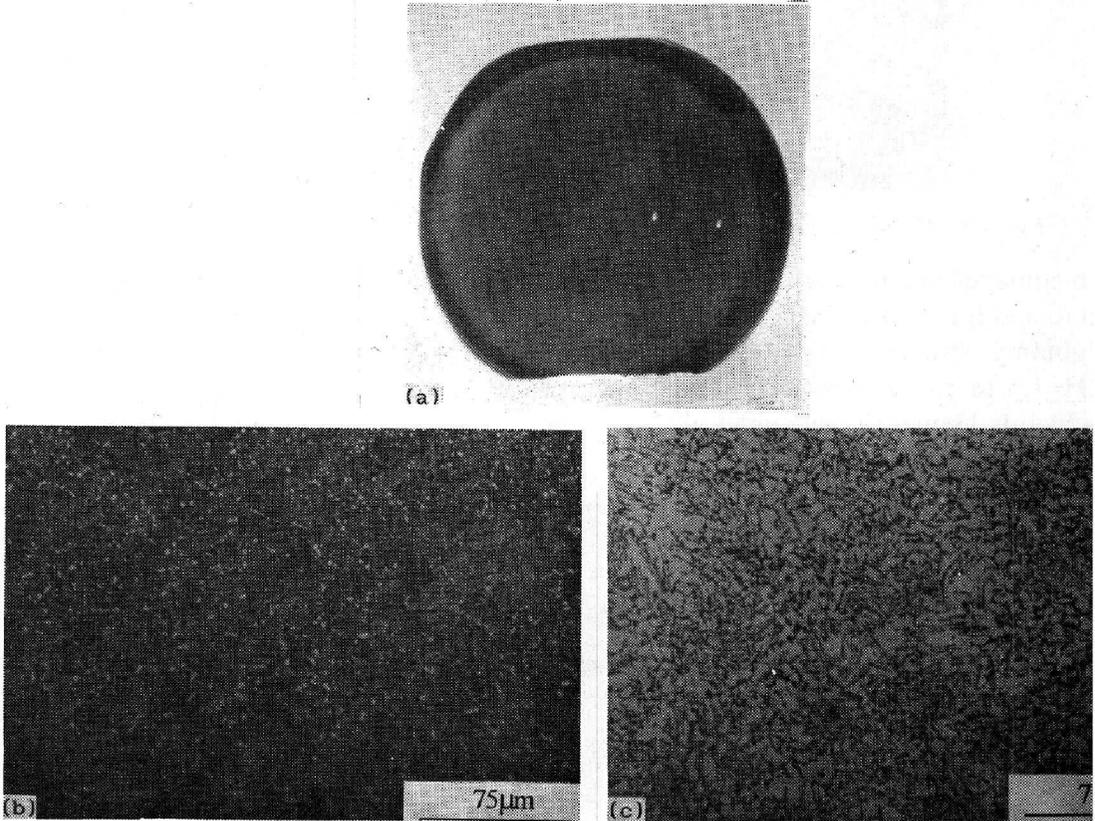

Fig. 12 : (a) Case depth of the chain link; (b) microstructure showing spheroidization in case (c) microstructure in the core

II. FAILURE ANALYSIS OF LEAF SPRINGS [10]

The material for leaf spring is AISI 5160H with nominal composition of 0.5(C, 0.28 Si, 0.84 Mn, 0.91 Cr, 0.006 S and 0.014 P. In this case, with ASTM grair size of 12, D_I is found to be 3.43 inch i.e., L_I is 2.57 inch. For, H = 1.5, th critical plate thickness will be 2 inch. However, the thickness of the leaf i within 0.34 inch. Therefore, the material gets thoroughly hardened by wate quenching. Even for oil quenching (H = 0.4), L_I is 1.2 inch which exceeds th
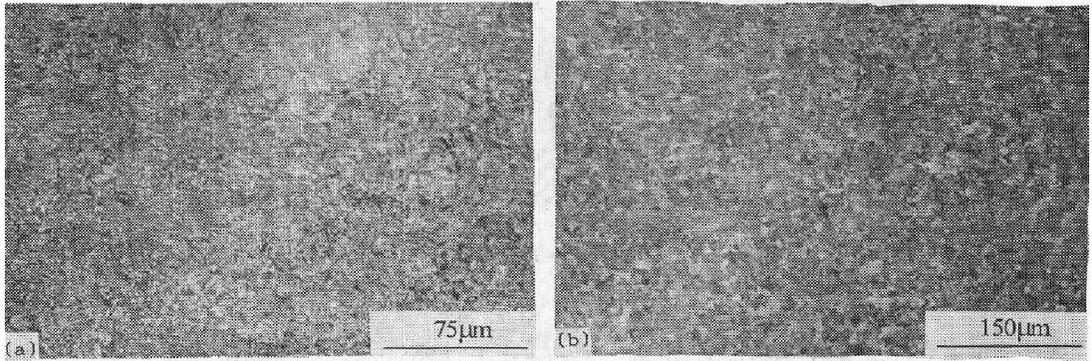
Fig. 13 : Optimum microstructure after proper hardening (a) case and (b) core

leaf thickness. As the actual thickness is smaller than the calculated one, the queching severity increases by many fold and that leads to the formation of residual tensile stresses. This tensile stresses at the surface is relaxed by quench cracking (Fig. 14). The quench cracks are preferentially found to propagate along the prior austenite grain boundaries. Therefore, as mentioned in section 5, this leads to reduction of fatigue strength and ultimately failure occurs prematurely.
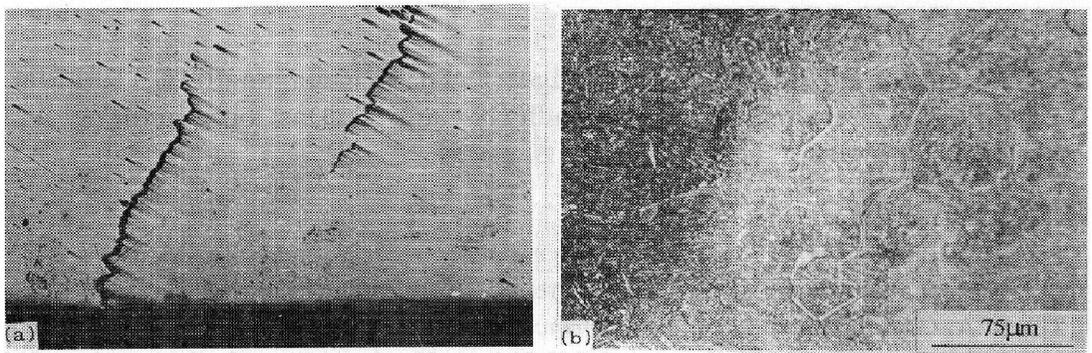

Fig. 14 : (a)Formation of quench cracks; (b) cracks along the prior austenite grain boundary

III. FAILURE ANALYSIS OF COAL PULVERISER MILL SHAFT [11]

The material used was EN 25 grade of steel with composition of C:0.32, Si:0.27, Mn:0.57, Ni:2.45, Cr:0.57, Mo:0.5, P:0.02 and S:0.006. These steels are used in the quenched and tempered condition (Fig. 15). The hardness is found to be about $R_c 30$. The impact energy value is 27 J and 9J along the longitudinal and transverse direction, respectively. However, according to the litera-

Fig. 15 : Microstructure of the shaft material

ture it should be 65 J by optimum heat treatment. Hence, the material was no properly heat treated. Therefore, it can be seen from Fig. 8 that although the hardness may be same but after tempering at about 500°C leads to higher tough ness value. Therefore, although the quenching treatment was done in prope way; wrong choice of tempering temperature imparts poor toughness and lead to premature failure of the component.

ACKNOWLEDGEMENT

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