

ON THE METALLURGICAL DESIGN OF CARBURISED GEARS

S. K. Mandal
TATA STEEL
Jamshedpur 831 001

INTRODUCTION

All automotive power transmission gears, with few exceptions, are carburized and this has become a universal practice today. Carburizing of the gear produces a hard case with relatively tougher core. The common benefits resulting from carburizing are the good wear resistance of the tooth surface and resistance to failure under impact and fatigue load. However, considering the stress systems acting on a gear tooth during its rotation in mesh with another gear, the other properties of a gear that assume importance are:

1. High contact load carrying capacity of the tooth flank surface, i.e., contact fatigue resistance.
2. High bending fatigue resistance arising from the repetitive bending load at the tooth fillet.

The development of each of these properties to a maximum level is not possible, because of the opposing influence of hardness on toughness and increase in contact fatigue resistance on bending fatigue properties. What can be aimed at and achieved, is an optimization of these properties in relation to the type of gear and its applications. For this purpose, however, a careful designing of all metallurgical parameters, including process parameters, are necessary.

In this lecture, the important metallurgical factors that influence the process of optimization have been pointed out, and it has been shown that the development of residual compressive stresses on the surface is the most important single factor that determines the success of

carburizing a gear. The conditions and controls necessary for the ultimate development of residual surface compressive stresses have been discussed, and data on IS-20MnCr1 carburizing steel have been presented as a means for optimizing the desired metallurgical properties in a gear.

STRESSES ON A GEAR : DESIGN CONSIDERATIONS

Functionally, a gear has to rotate in mesh with another gear, ensuring uniformity of motion in both. As a consequence of this constrained rotation, a short duration cantilever loading is imposed on the tooth of each meshing gear, owing to which the stresses on the gear teeth take two principal forms:

1. Contact load over the tooth flank surface.
2. Bending load at the tooth fillet.

These two principal stresses (S_c and S_b) are shown in Fig. 1. The ability of a gear to withstand 'contact', and 'bending' loads are generally evaluated in terms of 'contact fatigue' and 'bending fatigue' resistances, respectively. While the 'contact fatigue' and 'wear resistance' of a gear increases with surface hardness, case depth and core strength, properties like 'bending fatigue' and resistance to 'impact load' are adversely affected by an excessively strong core and high case depth.

Fig. 2 shows the relationship between the tensile strength and the limit of surface contact fatigue. The surface contact fatigue resistance increases as the square of the tensile strength; in other words, a considerable improvement in such resistance may be obtained by increasing the surface hardness of the gear. The relationships between the tensile strength and bending fatigue limit for both 'through hardened' and 'case-carburized' steels are shown in Fig. 3. For through hardened steel, the bending fatigue limit increases linearly up to the tensile range of 60-70 t/in² (95-110 kg/mm²). Beyond this tensile range, there is no increase in bending fatigue limit; rather, a tendency to decrease can be observed. This is believed to be due to the increase in the 'notch sensitivities' in a steel with increasing strength.

For carburized steel, the bending fatigue limit sharply increases by as much as 50% of the value for a through-hardened steel of given tensile strength; but again, the maximum fatigue limit is found to be

associated with a core strength of 70-80 t/in² (110-125 kg/mm²), above which there is a sharp fall in the fatigue strength. This fall in fatigue strength has been attributed to the development of a less favourable residual stress system in the carburized steel by the high transformation volume changes occurring in higher hardenability steels.

A combination study of Figs.2 & 3 indicates that for the optimization of all relevant properties in a gear, the metallurgical design parameters like case depth, core strength, surface hardness, etc., are required to be very carefully assessed and specified. Also, after specifying the desired metallurgical design parameters, the metallurgical processing of the gear, e.g., hardening, quenching, etc., has to be well planned and controlled to make the process most conducive to the development of favourable residual surface compressive stresses. Without the development of favourable residual compressive stresses on the surface, the gear performance would be badly affected, leading to frequent failure of the gear, either by 'contact fatigue' or 'bending fatigue', with consequent loss resulting from the down time of the machine or vehicle.

DEVELOPMENT OF RESIDUAL SURFACE STRESSES

Work at the Max-Planck Institute by Rose et. al. has established that for producing residual compressive stresses in the surface layer, the material must follow a definite 'transformation sequence' during the hardening of the carburized part. Studies in this field indicate that the nature and magnitude of the residual stresses after case-hardening are largely determined by:

1. The rate of cooling of the job from the hardening temperature. This produces thermal stresses in the job owing to differential contraction during cooling under a thermal gradient.
2. The transformation characteristics and transformation sequence of the case and core volume during cooling.
3. The geometry of the job.

The influence of the transformation characteristics of the core volume on residual stresses imposes the condition of selecting a suitable grade of steel for a known gear application; but for a given grade of steel and gear design, the control of the surface carbon, the depth of the carbon rich case and the efficiency of the cooling during hardening determine the final state of residual stresses.

Fig. 4 shows the various stages in the development of residual stresses in a steel which has been quenched to produce a shallow outer hardened layer or case, a situation which is comparable to a case hardened part.

In Stage I, the difference in the cooling rate between the surface and the core, leads to a differential thermal contraction in the job and tensile stress on the surface and compressive stress in the core.

In Stage II, when the temperature in the core reaches its transformation temperature (which is essentially the upper transformation product), the core undergoes a volume change due to transformation. This adds further to the tensile stress on the surface and compression in the core.

In Stage III, the hot plastic deformation of the core occurs as a consequence of the stress build up in Stages I and II. The hot plastic deformation of the core is possible due to the build up of stresses during cooling and transformation to a level exceeding the hot elastic limit of the relatively hot core. For a low carbon core, the hot elastic limit will be lower and the resultant deformation due to stress build up will also be easier. Due to this deformation, the stress level - both at the core and the surface - will get considerably relaxed and, as a result, the stress pattern in the surface and the core will be 'reversed'. This is shown in Fig. 4.

This 'stress reversal' creates a condition in the surface and the core, such that even by following the normal course of cooling with ultimate temperature equalization in the surface and core, the surface is left with some compressive stress and the core tensile. However, due to the delayed transformation of the high carbon case, which results in the transformation volume expansion of the case layer, further compressive stresses are generated at the surface (Stage IV), and, finally, the job is left with:

1. A compressive stress on the surface.
2. And equal amount of tensile stress in the core.

Since the volume of the core is a few times the volume of the case, the level of tensile stress per unit area in the core will be much lower than the level of compressive stress per unit area in the case.

DATA ON IS-20MnCr1 STEEL

The stages of stress development show that for the generation of maximum surface compressive stresses, the following conditions must be fulfilled.

1. The transformation in the core has to be completed before that of the case. ⑨
2. The time and temperature of the transformation of basic steel have to be such that the transformation of the core is complete prior to the so-called 'stress reversal' during cooling. A shorter time and higher temperature for the transformation of the core will favour an easy 'stress reversal'.

Fig. 5 depicts the continuous cooling transformation diagrams of IS-20MnCr1 steel, with super-imposed Ms temperatures for carbon levels of 0.4, 0.6, 0.8 and 0.9 per cent. Such a graph helps to deduce whether the steel is at all suitable for successful carburizing, and also indicates the conditions and controls to be exercised for successfully case-hardening a job made from that particular steel. An analysis of Fig. 5 shows that in a case containing a minimum carbon of 0.6%, the transformation starts at a depth of about 3 mm with 0.6% carbon (corresponding to point A in Fig. 5) after about 100 sec. from the start of quenching, and then gradually proceeds towards the surface containing higher carbon per cent. On the other hand, the core transformation to bainite starts as early as 11 sec. after the start of quenching where the composition corresponds to 0.2% carbon (point B in Fig. 5), and then gradually proceeds towards the centre, and by the time the case starts transforming, the core transformation is almost complete. It would, however, be obvious from Fig. 5 that while a steel, such as 20MnCr1 in this case, can fulfil the theoretical conditions for successful carburizing, certain controls in practice are also required. There are:

1. The control on the hardenability of the core. This should not be too high to cause excessive delay in core transformation, and also not too low to produce a core strength level below 95 kg/mm².
2. The surface carbon has to be controlled at a level where the case should transform to 100% high carbon martensite and the Ms temperature has to be low enough to delay the transformation. This has been found to be 0.8% carbon (max.) for 20MnCr1 attaining a surface hardness of 810 VPN.

3. The case depth and carbon gradient.
4. The method and rate of cooling. Cooling has to be such that its rate is faster at the temperature above the Ms or core steel, but slower below this temperature, i.e., where the case transforms.

The significance of the control of case depth is illustrated in Fig. 6, which shows the relationship between the bending (reverse) fatigue strength and case depth in the same IS 20MnCr1 carburized steel. The bending fatigue strength is found here to be reaching a maxima at a case depth of 0.6 mm in a 18 mm dia. specimen, and then sharply falling with increased case depth to a level even below the fatigue strength of the material without carburizing, i.e., the base fatigue level. This fall of bending fatigue strength even below the base fatigue strength cannot be explained by considering the development of the less favourable residual stresses alone. It is, therefore, likely that at an increased level of case depth, the weakening effect of 'notch sensitivity' of the high carbon case becomes significant, and this weakening effect cannot any more be fully compensated by the beneficial effect of residual compressive stresses on the surface.

CONCLUSIONS

1. All the desired metallurgical properties for a case-hardened gear cannot be fully achieved simultaneously. An optimization of the required properties would be necessary and accordingly, the gear designer should specify the properties, depending upon the applications in view.
2. The general metallurgical properties of a case-hardening gear can be specified in terms of surface hardness, case depth and core strength, but the full benefit of case-hardening (carburized) is not achieved, until the development of residual compressive stresses in the surface layer is maximized.
3. To develop residual compressive stresses on the surface, the following care and control become necessary:
 - a) the steel should be selected such that the hardenability of the core is adequate to meet the specified core strength, but not too high to cause undue delay in transformation;
 - b) the surface carbon level after carburizing and cooling during hardening should be such that the case transforms to 100%

martensite and the transformation of the case occurs at a time later than that of the core.

The specification of the case depth for a gear requires careful assessment, because there appears to be a definite range of case depth or case-to-core ratio, above which the bending fatigue strength sharply falls even below the base fatigue strength of the material with no carburizing.

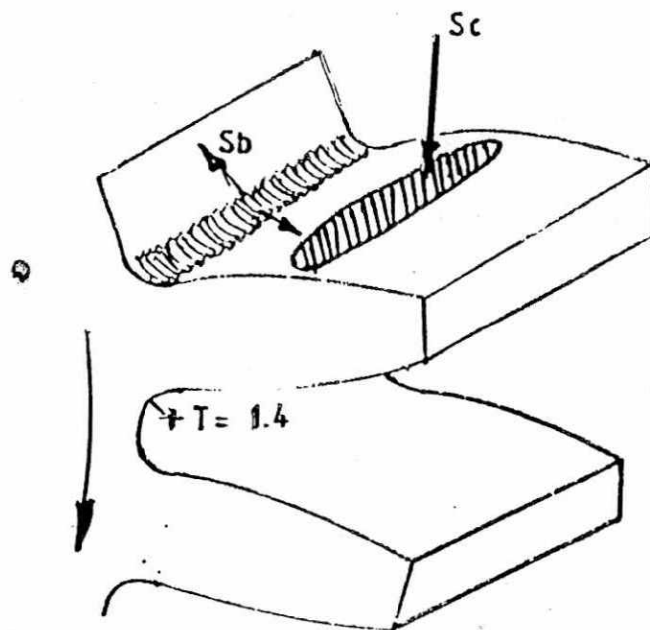


FIG: 1 SHOWING CONTACT AND BENDING STRESSES
ON A GEAR TOOTH .

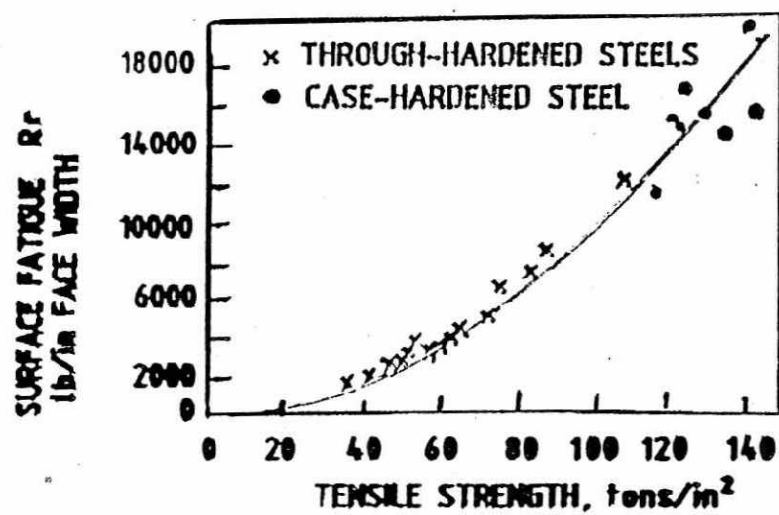


FIG. 2 RELATIONSHIP BETWEEN TENSILE STRENGTH AND SURFACE FATIGUE STRENGTH .

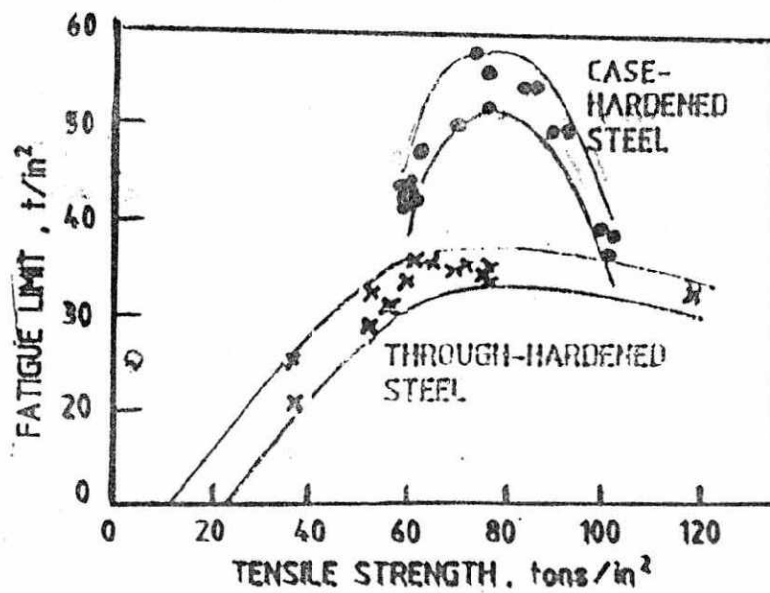


FIG. 3

RELATIONSHIP BETWEEN TENSILE STRENGTH AND BENDING FATIGUE STRENGTH.

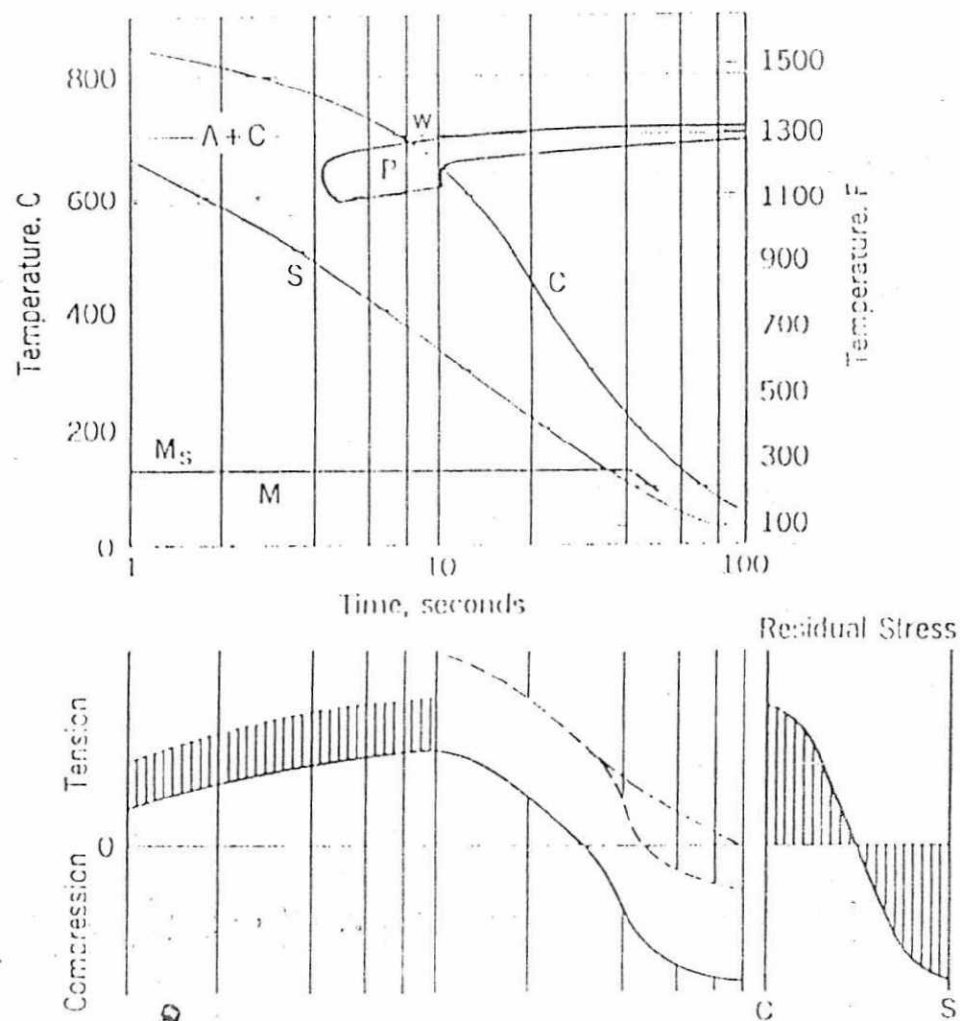
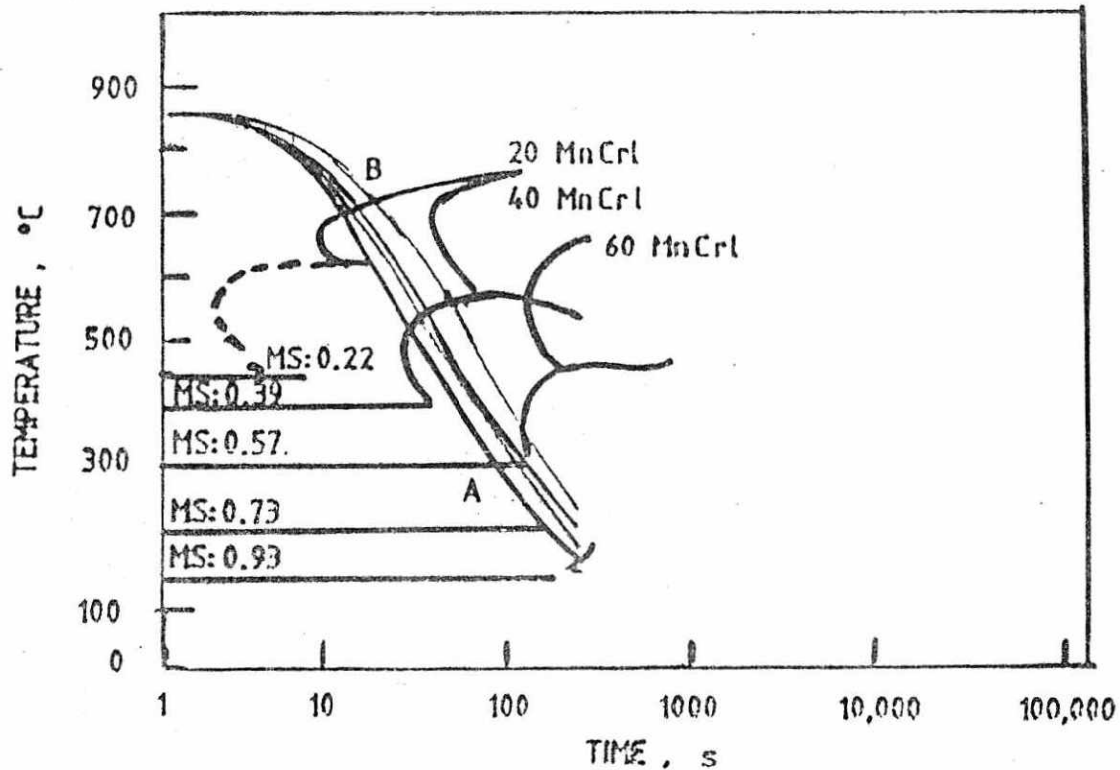


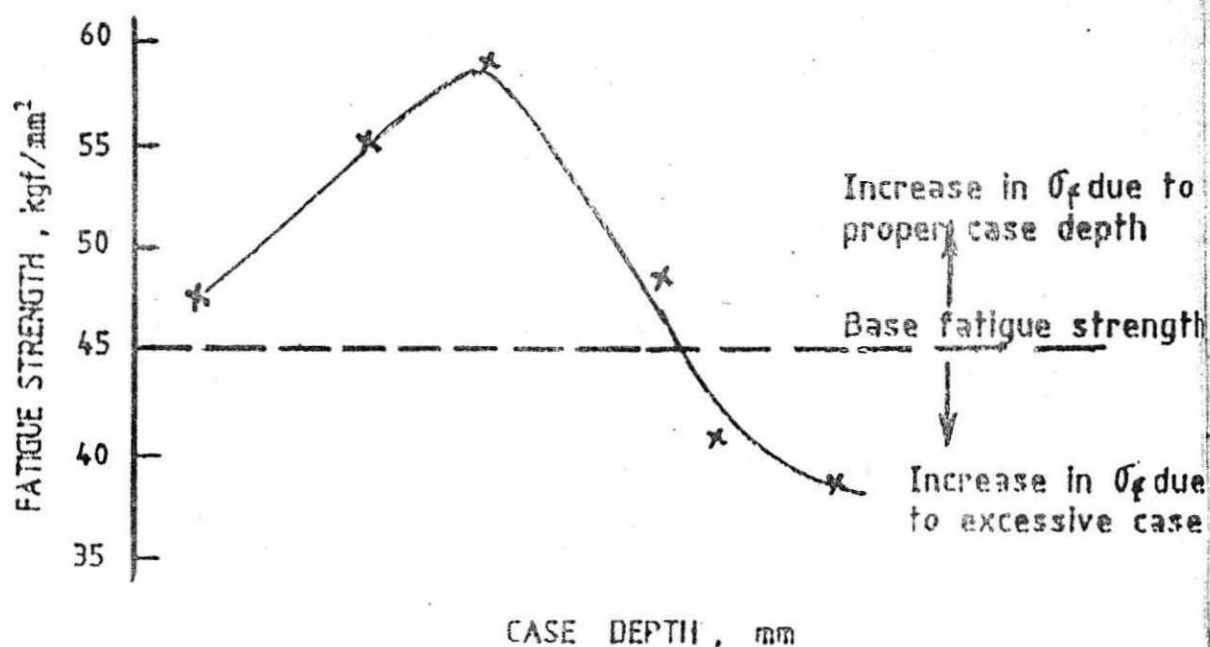
FIGURE 1. Formation of residual stresses in a 28-mm-dia bar of a 1.3% C steel, water quenched to give a shallow outer hardened layer

FIG: 5



SHOWING SUPERIMPOSED CONTINUOUS COOLING DIAGRAMS FOR 20 MnCr1, 40 MnCr1, 60 MnCr1 TOGETHER WITH M_s TEMPERATURE FOR THE HIGH CARBON CASE. COOLING RATES AT VARIOUS DISTANCES FROM THE SURFACE OF AN OIL QUENCHED 50 mm DIAMETER BAR HAVE BEEN SUPERIMPOSED.

FIG. 6



RELATIONSHIP BETWEEN BENDING (REVERSE) FATIGUE STRENGTH AND CASE DEPTH IN IS20 MnCr1 CARBURIZING STEEL .