Case Hardenability at High Carbon Levels

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Loss of hardenability in the case was thought to be responsible for a lower than specified hardness found on a large carburized bushing. Pseudo Jominy testing on several high hardenability carburizing grades confirmed that hardenability fade was present at carbon levels above 0.65% and particularly for those steels containing molybdenum. Analysis of previous work provided a formula for calculating Jominy hardenability at various carbon levels. Again the results confirmed that the loss of hardenability was more severe in steels containing molybdenum.

Keywords
carburizing, case hardenability, hardenability

1. Introduction

THERE would seem to be little yet to be learned about the metallurgy of carburizing steels. However, the evolution over many years of the many steel grades suitable for carburizing has occurred more by trial and error than by sound technological principles. The change in the relative cost of individual alloying agents has often been the driving force behind change. For example, new steels have appeared in recent years where molybdenum replaces the high cost nickel as a hardenability agent.

With the ever-increasing size of gears and expected higher design stresses, the hardenability of the base material (core) has been the primary criteria used in selection. Conversely, because it is normally assumed that hardenability increases significantly with increasing carbon levels, little attention has been given to the case hardenability. With even the largest gears, the cross section of individual teeth is still relatively small. Therefore, the influence of cross section on the cooling rate at or near the surface is little affected. Cooling rates of plain surfaces on the other hand are very much dependent on the section size. For example, the cooling rate at 700 °C (1300 °F) at the surface of oil-quenched bars ($H = 0.5$) calculated from such charts as those given in Timken's *Practical Data for Metallurgists* (Ref 1) is decreased approximately tenfold from 170 to 20 °C per second (305 to 33 °F per second) where the diameter of the bar is increased from 12 to 100 mm (½ to 4 in.).

The purpose of this paper is to: (a) highlight an actual problem in the hardening of a carburized plain bushing that was though to be attributable to a loss in case hardenability at high carbon levels; and (b) present a review of subsequent work aimed at better quantifying case hardenability at high carbon levels and identifying the cause for the loss in hardenability.

2. Heat Treatment Problems

After less than 0.5 mm (0.020 in.) was ground from the bore of a large 37.5 mm (1½ in.) cross section gas-carburized and oil-quenched plain bushing, the hardness had decreased below an acceptable level. Cross sections through the bore and outside diameter (OD) surface were prepared for metallographic examination. Microhardness plots (Fig. 1) indicated that the loss in hardness was due to a dip in the hardness profile. The micrographs superimposed on the plot show the usual layer of bainite at the virgin OD surface due to the oxidation of alloys, near 100% martensite to a depth of approximately 25 mm (0.020 in.) and at depths down to approximately 1.25 mm (0.050 in.), and a progressive increase in bainite. Beyond this depth, a fully martensitic structure returned until the normal transition to the core structure. The desirable carbon profile previously obtained from a carbon gradient bar that accompanied the parts was confirmed by further spectrographic analysis of the actual parts.

Deep freezing the samples did not appreciably change the hardness profile. The parts were known to have received a good quench. The bushing had been manufactured from a 0.95% Mn, 0.73% Cr, 0.27% Mo carburizing grade with an inside diameter (ID) of 70 mm (2.79 in.).

Apparently, there was a significant loss in hardenability at high carbon levels. Near the surface and below the oxidized layer, the quench rate was high enough to override the hardenability loss. However, at greater depths where the quench rate was lower, the loss in hardenability became evident. Deeper into the case where the carbon level decreased below 0.6 to 0.7%, the hardenability increased so that 100% martensitic structure returned.

Jatczak (Ref 2) showed a loss in hardenability of alloy steels containing greater than approximately 0.8% C. However, the loss experienced in this particular instance seemed to be more than could be accounted for using his coefficients.

A diagram from the book by Parrish and Harper (Ref 3) illustrates that the hardenability loss for a similar steel at increasing carbon concentration was due to a reversal in the direction of the bainite nose at carbon levels above 0.65% C (Fig. 2).

Because of these findings, it was decided to instigate a program of testing case hardenability in high-alloy carburizing grades, particularly those where molybdenum is being used to replace the more expensive nickel alloying agent.

3. Procedure Used for Measuring Case Hardenability

Because only comparative results were needed, the heat treat department marquench salt bath was used as the end quench media (immediate surface wetting and relatively fast

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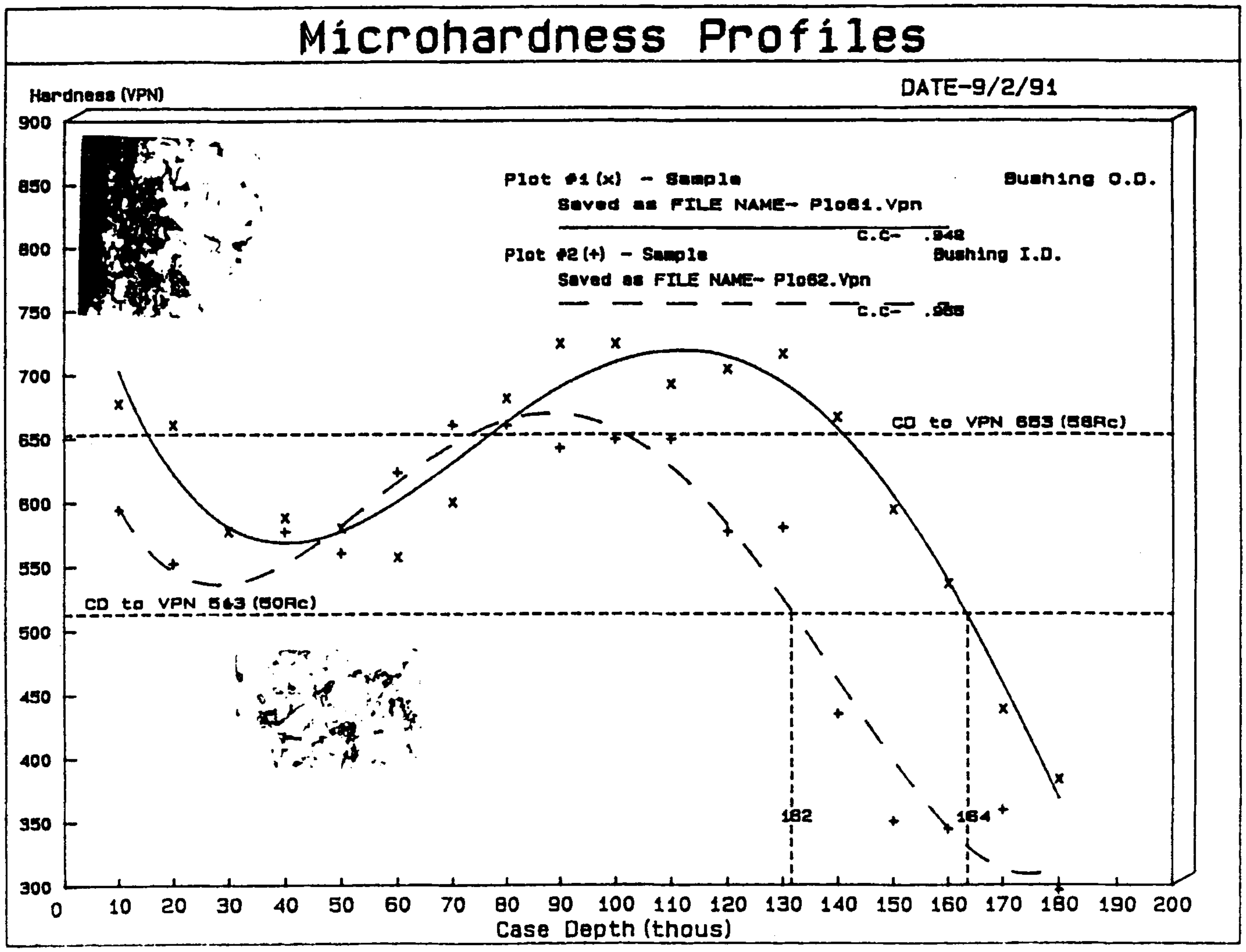

Fig. 1 Microhardness plots taken through the case at the ground ID and nonground OD bushing surface

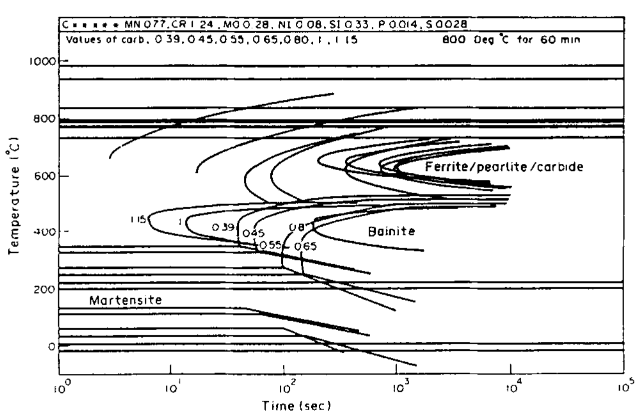

Fig. 2 Transformation behavior of case elements of a carburized Cr-Mo steel

quench). A small, removable fixture was positioned on the side of the bath. Carburized and spheroidized annealed, 1-in.-square, 6-in.-long bars were austenitized at 845 °C (1550 °F) in the high-temperature salt bath and transferred to the quenching jig (Fig. 3).

All bars were deep frozen in liquid nitrogen before testing. Spectrographic analysis and microhardness traverses were performed on the quenched bars. Figure 4 shows the data from a test on one of the carburized bars. While the hardenability is increasing up to a carbon level of 0.65% C, there clearly is a rapid decrease above this level.

Further bars from several steel grades were carburized together for testing in a similar manner. Figure 5 compares the measured hardenabilities at 1.00% C.

4. Calculated Case Hardenability

A further literature search revealed the work done by Rose and Hougardy at the Max Planck Institute of Research (Ref 4). Their data on eight steels showed the similar reductions in hardenability at high carbon levels (Fig. 6). The lower line represents the critical time to reach 500 °C (932 °F), which is

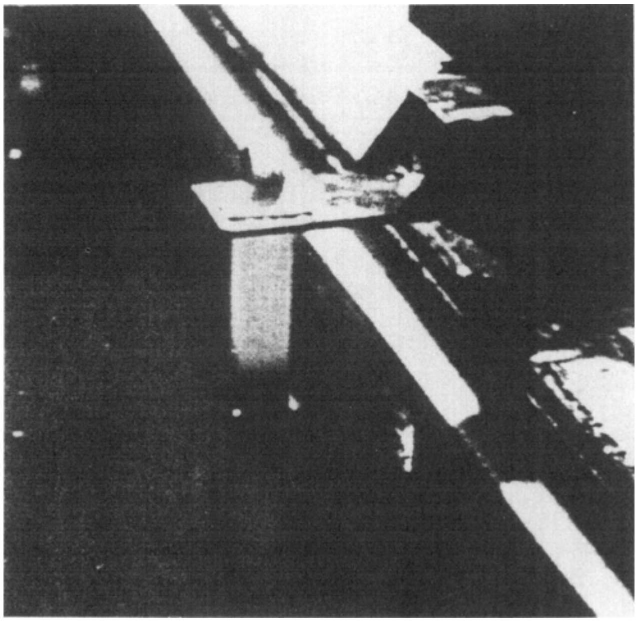

Fig. 3 End quenching 1-in.-square bar in 230 °C (450 °F) salt

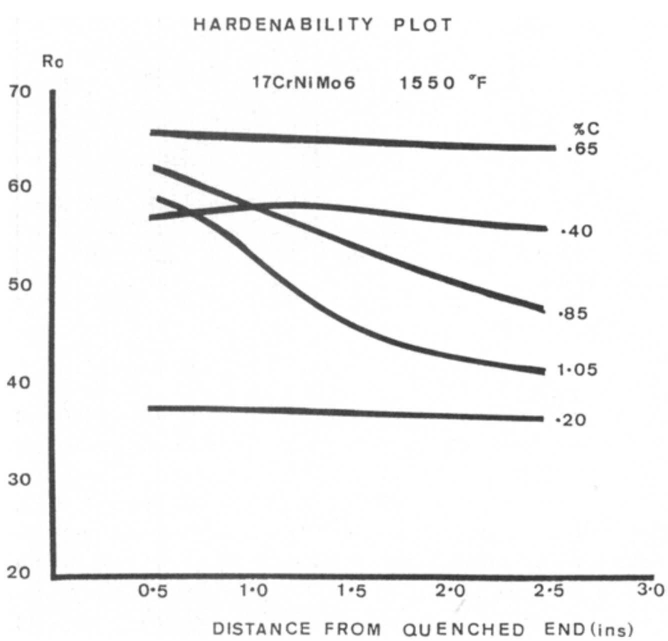

Fig. 4 Hardness plots along the length of the 17CrNiMo6 bar at various carbon levels. (17CrNiMo6 is a high hardenability steel favored by large gear manufacturers.)

necessary to obtain 100% martensite when quenching from 830 °C (1525 °F). These data were used to obtain multiregression equations that could be used to calculate the Jominy hardenability (in 1/16 in.) for discrete carbon levels from 0.6% to 1.10%. These equations are given in Table 1 together with standard errors and correlation coefficients.

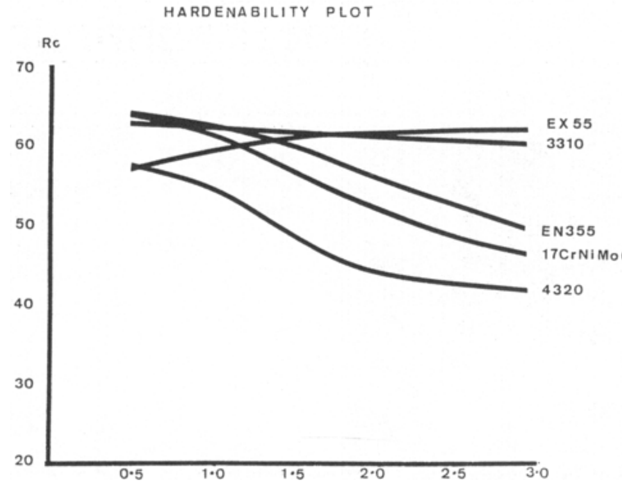

Fig. 5 Comparison of case hardenability at 1.00% carbon for various steels

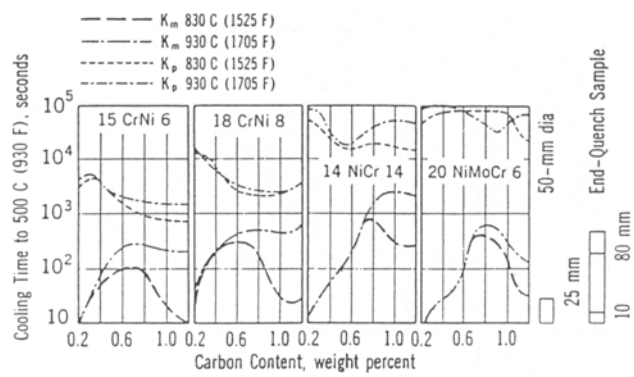

Fig. 6 Critical cooling times of four carburized steels as a function of carbon content. In each diagram, the lower plot represents the critical time to obtain 100% martensite when quenching from 830 °C (1525 °F).

It was possible to compare the case hardenability of several carburizing steels using these equations (Table 2). Results based on equations derived from the Jatczak data (Ref 2) are included for comparison. These data illustrate the significant loss in hardenability at high carbon levels, particularly when molybdenum is present.

5. Discussion

The calculations presented in Table 2 from the Jatczak (Ref 2) and Rose (Ref 4) data are reasonably close for the lower carbon levels. However for the molybdenum steels, there is a divergence at levels of >0.90% C. The percentage of decline in hardenability from the maximum to the value at 1.10% C averages 37% for the first three high nickel steels whereas in the last three steels, where molybdenum is a major alloying agent, the hardenability loss averages 76%. This suggests that a high nickel content is essential to avoid an unacceptable hardenability "fade" when carburizing to carbon levels in excess of 0.80% and where delays in the transfer of large components to the quench may occur (for example during fixture quenching). Although the hardenability fade is 98% in the EX55 steel, the level of hardenability at high carbon levels may still be considered adequate. However the cost per pound of EX55 is close to that for the high nickel steels.

Sponzilli et al. (Ref 5) determined that the loss in case hardenability in a carburized 94B17 steel was due to the formation of very fine network carbides that not only depleted the surrounding matrix of alloys and carbon but acted as nucleation sites for the formation of bainite. The presence of "massive" carbides also had been a factor. In the present work, microexamination revealed that some "massive" carbides, or "super case" as it is sometimes known, only occasionally appeared at sharp corners.

Having a high affinity for carbon, molybdenum should readily form carbides, particularly at high carbon levels. Note that low hardenability was experienced in a heat of 52100 Grade 4 (Ref 6) through hardening steel containing 0.55% Mo and 1.08% C.

Table 1 Results from multiple regression analysis of the data presented by Rose and Hougardy (Ref 3)

At 1.10% C

$J(1/16\ in.) = 8.9Mn + 3.7Ni^2 - 6.3Cr + 0.9$

Standard error = 2.1; correlation coefficient = 0.991

At 1.00% C

$J(1/16\ in.) = 19.9Mn + 17.0Ni + 24.9Mo^2 - 15.5Cr - 5.0$

Standard error = 1.4; correlation coefficient = 0.998

At 0.90% C

$J(1/16\ in.) = 21.4Mn + 20.2Ni + 66.1Mo^2 - 13.8Cr - 7.5$

Standard error = 4.1; correlation coefficient = 0.986

At 0.80% C

$J(1/16\ in.) = 18.4Mn + 23.2Ni + Mo(689.1Mo - 296.3) - 5.5$

Standard error = 2.96; correlation coefficient = 0.995

At 0.70% C

$J(1/16\ in.) = 18.5Mn + 7.0Cr^2 + Mo(974.9Mo - 422.9) - 2.7$

Standard error = 1.75; correlation coefficient = 0.998

At 0.60% C

$J(1/16\ in.) = 12.2Cr^2 + 3.9Ni^2 + Mo(606.8Mo - 264.9) - 0.10$

Standard error = 2.26; correlation coefficient = 0.995

6. Conclusions

As shown, when selecting carburizing steels for large cross section plane surface components, due regard must be given to

Table 2 Compilation of calculated case hardenability for various high hardenability carburizing steels

Reference	Carbon, % 0.60	0.70	0.80	0.90	1.00	1.10
Steel: 3311 **Chemistry: 0.40% Mn, 1.45% Cr, 3.50% Ni, 0.10% Mo** **Hardenability: J (1/16 in.)**						
Jatczak (Ref 2)	...	...	70	59	43	36
Rose et al. (Ref 4)	53	50	60	52	40	41
Steel: 9310 **Chemistry: 0.55% Mn, 1.20% Cr, 3.25% Ni, 0.05% Mo** **Hardenability: J (1/16 in.)**						
Jatczak (Ref 2)	...	...	50	43	31	26
Rose et al. (Ref 4)	47	54	67	54	43	38
Steel: 14NiCr14 **Chemistry: 0.46% Mn, 0.78% Cr, 3.69% Ni, 0.04% Mo** **Hardenability: J (1/16 in.)**						
Jatczak (Ref 2)	...	...	85	72	52	44
Rose et al. (Ref 4)	51	60	78	66	55	51
Steel: 17CrNiMo6 **Chemistry: 0.50% Mn, 1.65% Cr, 1.55% Ni, 0.30% Mo** **Hardenability: J (1/16 in.)**						
Jatczak (Ref 2)	...	...	21	18	13	11
Rose et al. (Ref 4)	18	11	13	18	8	4
Steel: EN355 **Chemistry: 0.55% Mn, 1.55% Cr, 2.00% Ni, 0.20% Mo** **Hardenability: J (1/16 in.)**						
Jatczak (Ref 2)	...	...	39	33	24	20
Rose et al. (Ref 4)	16	11	19	26	17	11
Steel: EX55 **Chemistry: 0.86% Mn, 0.50% Cr, 1.81% Ni, 0.73% Mo** **Hardenability: J (1/16 in.)**						
Jatczak (Ref 2)	...	...	127	108	78	65
Rose et al. (Ref 4)	146	249	203	76	48	18

the case hardenability, particularly at high carbon levels. Molybdenum is a primary contributor to the hardenability fade at carbon levels above 0.65%.

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