The Calculation of Optimum Surface Carbon Content for Carburized Case Hardened Gears

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Introduction

For high-quality carburized, case hardened gears, close case carbon control is essential.

While tight carbon control is possible, views on what optimum carbon level to target can be wider than the tolerance.

Part 5 of ISO standard 6336 makes an attempt to specify a target and the tolerance for the highest quality grade as eutectoid carbon percentage plus 0.20% or minus 0.10%.

That implies that either a method exists to calculate eutectoid carbon content from alloy content or the values have been determined for a wide range of steels and are widely available. Unfortunately, neither is true. Also implicit is that the eutectoid carbon content is the optimum. But no rationale is given.

A simplistic interpretation is to use the eutectoid carbon content from the iron-carbon phase diagram—see Figure 1. The value is 0.77%, which seems reasonable at first glance. However, experienced heat treaters realize that the higher alloy steels would develop excessive retained austenite if targeting 0.77% with the above tolerance.

In practice, the optimum carbon for a grade of steel is determined by experience and is chosen to minimize the risk of forming undesirable phases, including retained austenite, carbides, bainite and pearlite.

The conclusion is that any calculation of optimum carbon content must reflect the need to minimize such risk.

The objective of this paper is to define a readily available methodology to calculate optimum carbon content from alloy content and austenitizing temperature at the hardening stage.

Continuous Cooling Transformation (CCT) Diagrams

To avoid undesirable transformation products, we turn to the effect that carbon content, alloy content and austenitizing conditions have on the formation of phases during cooling.

CCT diagrams are one of the most effective ways of representing transformation behavior, and more than 1,000 diagrams representing the whole range of carburizing alloys, carbon levels and austenitizing conditions are available in the public domain.

Figure 2 is typical of an experimentally determined CCT diagram with hardnesses and microstructures. Temperature is the vertical linear axis and time is the logarithmic horizontal scale.

More than 600 selected CCT diagrams (Refs. 1–7) have been translated into mathematical form (Refs. 8–9) by multiple linear regression analysis and subsequently became one of the cornerstones of the STAMP and AC3 programs (Refs. 10–11), which have a mature pedigree in calculating CCT diagrams, microstructure and case hardness pro-

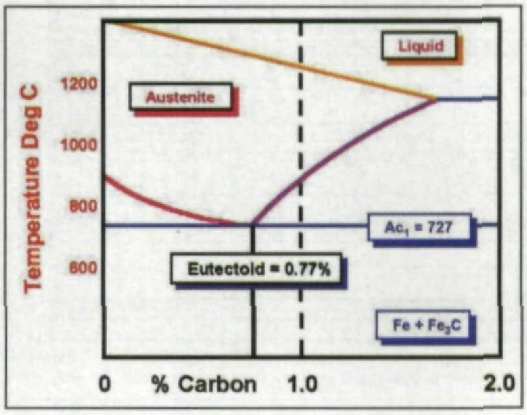

Fig. 1—Iron-carbon phase diagram.

This paper was presented at the 2000 Fall Technical Meeting of the American Gear Manufacturers Association.

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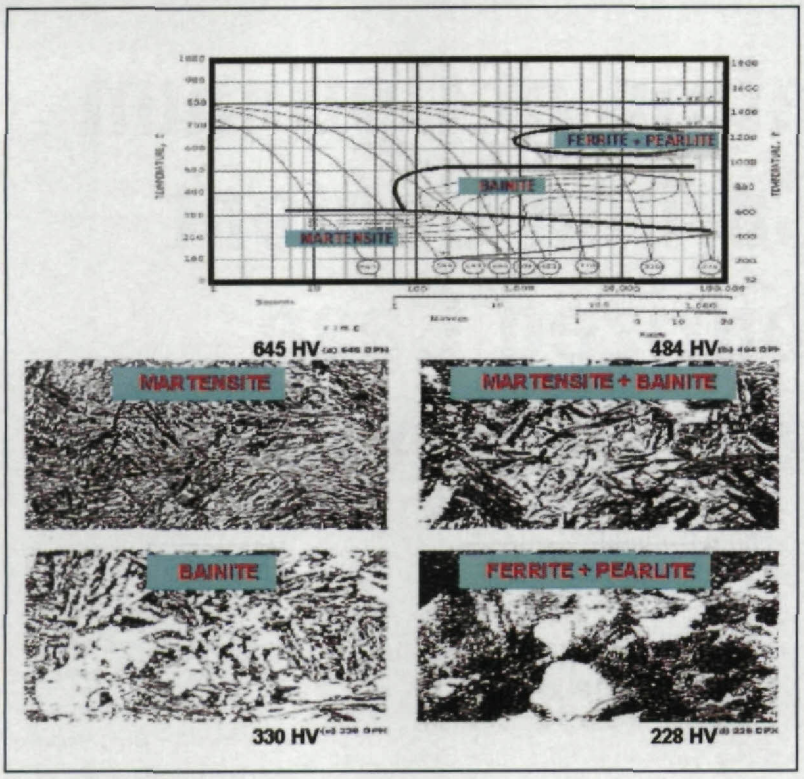

Fig. 2—CCT diagrams, hardnesses and microstructures.

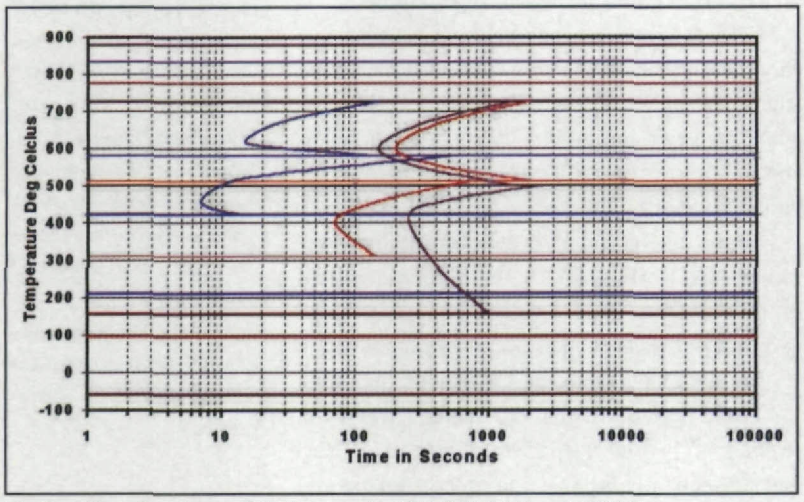

Fig. 3—Effect of carbon on CCT diagrams for 0.2% C, 0.50% C and 0.90% C.

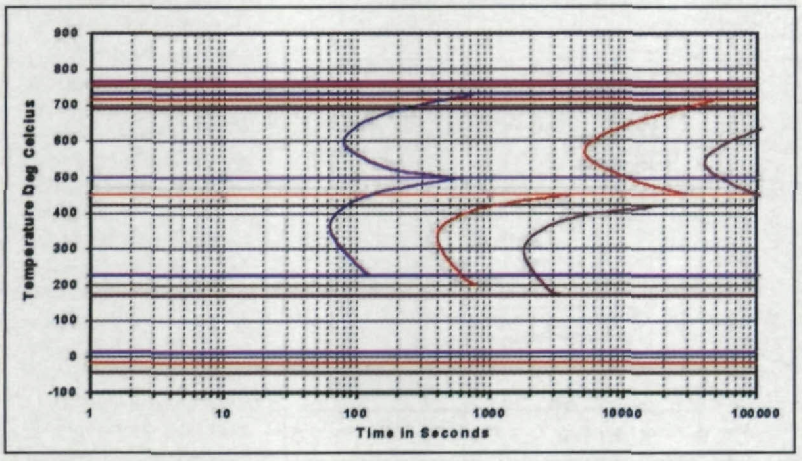

Fig. 4—Effect of nickel on CCT diagrams for 0% Ni, 1.5% Ni and 3.0% Ni at 0.70% Carbon.

files from alloy content, carbon profile, austenitizing conditions, part geometry and cooling media.

The CCT equations create the ability to analyze the effects of carbon and alloy content on transformation products.

Figure 3 is a calculated example of the effect of carbon on those transformations. Increasing the carbon content pushes the boundaries of the undesirable products—bainite, ferrite and pearlite—to the right, increasing hardenability.

The martensite transformation temperatures are lowered, increasing the amount of retained austenite at ambient temperatures.

Figure 4 is a calculated example of the effect of nickel on the CCT diagram at a carbon level of 0.70%. The effects of nickel are similar but less pronounced compared with carbon.

The key to defining the optimum carbon level is to examine how certain features vary with carbon content. The features chosen by the method described later are those that exhibit the greatest sensitivity to carbon content and have a large influence on case hardenability.

Those are:

- Bainite nose time,
- Pearlite nose time,
- Cementite nose time, and
- Martensite start temperature.

The nose times are the lowest values on the start of transformation curves. For example, the bainite nose time for 0.20% carbon in Figure 3 is 7 seconds, and the pearlite nose time at 1.5% nickel in Figure 4 is 5,000 seconds.

Multiple Linear Regression Equations

The bainite, pearlite and cementite nose times and the martensite start temperature can be calculated from the equations in the shaded area on page 55.

The effects of carbon content, austenitizing temperature and alloy content calculated using those regression equations are illustrated in Figures 5–7.

Characteristic features of Figure 5 include:

- The bainite nose time and hardenability peaks close to 0.80%.
- The pearlite nose time and hardenability decreases with carbon and drops below the bainite line at 0.64%.
- Cementite only forms when the nose time is less than the pearlite nose time, which occurs at 1.02%.

If a tolerance band of –0.1% to +0.2% is applied, then the permitted carbon levels are 0.56% to 0.86%. That band is described as the car-

bon hardenability window.

The ISO 6336 standard implies a target carbon of 0.66% for that window, which would be considered too low in practice.

The effect of carbon on the martensite start temperature for austenitizing temperatures typical of direct and reheat quench case hardening cycles is shown in Figure 6.

Also included on Figure 6 is the martensite start temperature of 147°C calculated from the Koistinen and Marburger equation (Ref. 13), which results in 25% retained austenite on quenching to an ambient temperature of 30°C. That demonstrates that while all carbon levels for reheat quenching are acceptable, the carbon level for direct quenching would need to be restricted to less than 0.88%.

Carbon Hardenability Windows

The effect of chromium on carbon hardenability is illustrated by Figure 7. Characteristic features include:

- For 0% chromium, the upper limit is set by the bainite nose time.
- For 2% chromium, the upper limit is set by the *pearlite nose time.*
- Increasing the chromium content moves the window to lower carbon levels.
- Increasing the chromium content reduces the carbon content at which cementite can form from 1.00% to 0.87%—quite close to the upper limit (0.83%) of the window.

Those features demonstrate the affinity of chromium for carbon and promotion of carbide formation.

Defining the Method of Calculating Optimum Carbon Content

The Criteria. The criteria chosen to define the method for the avoidance of undesirable transformation products are:

1. Cementite

If the cementite nose time is less than both the pearlite and bainite nose times at 0.85% C, then use the cementite nose time to replace the bainite nose time in criterion 3.

2. Pearlite

If the pearlite nose time is less than the bainite nose time at 0.5% C, then use the pearlite nose time to replace the bainite nose time in criterion 3.

If the pearlite nose time is less than the bainite nose time at 0.85% C, then use the pearlite nose time to replace the bainite nose time in criterion 3.

3. Bainite

To minimize bainite, calculate the carbon content corresponding to maximum hardenability

MULTIPLE LINEAR REGRESSION EQUATIONS

T = Austenitizing temperature, in degrees Celsius and
t = Austenitizing soak time, in minutes.

BAINITE NOSE TIME (BTAU IN SECONDS)

(1) $C \leq 0.50\%$

$$\text{Log}_{10}(\text{BTAU}) = -3.79 + 8.68 \cdot C - 5.35 \cdot C^2 - 1.70 \cdot Mn \cdot C + 1.56 \cdot Mn + 0.79 \cdot Cr + 0.92 \cdot Mo + 0.41 \cdot Ni + 0.32 \cdot Mo \cdot Ni + 0.0058 \cdot T + 0.00021 \cdot T \cdot \text{log}_{10}(t)$$

(2) $0.50\% \leq C \leq 0.80\%$

$$\text{Log}_{10}(\text{BTAU}) = \mathbf{a} + \mathbf{d} \cdot (C - 0.8)^2$$

Where:

a equals the lower of:

$\log_{10}(t_2) - g_2/40$

or

$\log_{10}(t_1) + 0.50$

and

$\mathbf{d} = (\log_{10}(t_1) - \mathbf{a})/0.09$

t_1 = BTAU at C = 0.50% from Eq. 1

t_2 = BTAU at C = 0.85% from Eq. 4

g_2 = is the gradient of the curve BTAU vs. C at 0.85% from Eq. 4.

(3) $0.80\% < C < 0.85\%$

$$\text{Log}_{10}(\text{BTAU}) = \mathbf{a} + \mathbf{b} \cdot (C - 0.8)^2$$

Where:

$\mathbf{b} = 400 \cdot (\log_{10}(t_2) - \mathbf{a})$

and **a**, t_2 are as defined previously in Eq. 2.

(4) $C \geq 0.85\%$

$$\text{Log}_{10}(\text{BTAU}) = -7.30 + (1.69 - 0.36 \cdot Ni)/C + 0.57 \cdot Mn + 0.57 \cdot Cr + 1.81 \cdot Mo + 0.93 \cdot Ni + 0.0065 \cdot T$$

PEARLITE NOSE TIME (PTAU IN SECONDS)

(5) $C \leq 0.60\%$

$$\text{Log}_{10}(\text{PTAU}) = -3.45 + 2.77 \cdot C + 2.67 \cdot Mo \cdot C - 0.75 \cdot Ni \cdot C - 3.00 \cdot C^2 + 1.26 \cdot Mn + 1.52 \cdot Cr + 4.54 \cdot Mo + 0.98 \cdot Ni - 0.30 \cdot Cr^2 - 1.45 \cdot Mo \cdot Cr + 0.00233 \cdot T$$

(6) $0.60\% < C < 0.80\%$

$$\text{Log}_{10}(\text{PTAU}) = \text{Log}_{10}(t_1) + 5 \cdot (C - 0.6) \cdot \text{Log}_{10}(t_2/t_1)$$

Where:

t_1 = PTAU at C = 0.60% from Eq. 5

t_2 = PTAU at C = 0.80% from Eq. 7

(7) $C \geq 0.80\%$

$$\text{Log}_{10}(\text{PTAU}) = -3.96 + 0.95/C + 0.73 \cdot Mn + 0.54 \cdot Cr + 3.33 \cdot Mo + 0.65 \cdot Ni + 0.00340 \cdot T$$

CEMENTITE NOSE TIME (CTAU IN SECONDS)

$$\text{Log}_{10}(\text{CTAU}) = -1.24 + (-6.76 - 0.11 \cdot Mn - 0.16 \cdot Cr + 1.69 \cdot Mo - 0.06 \cdot Ni + 0.00602 \cdot T)/C + 3.42 \cdot C^2 + 0.00047 \cdot T \cdot \text{Log}_{10}(t)/C^2$$

MARTENSITE START TEMPERATURE (MS IN °C)

(8) $C \leq 0.50\%$

(Andrew's Formula, Ref. 12)

$$MS = 512 - 453 \cdot C - 71.5 \cdot Mn \cdot C - 67.6 \cdot Cr \cdot C + 217 \cdot C^2 + 15 \cdot Cr - 9.5 \cdot Mo - 16.9 \cdot Ni$$

(9) $0.50\% < C < 1.10\%$

$$MS = T_2 + (T_1 - T_2) \cdot (C - 1.1)^2/0.36$$

Where:

T_1 = MS at C = 0.50% from Eq. 8

T_2 = MS at C = 1.10% from Eq. 10

(10) $C \geq 1.10\%$

$$MS = 436 + 40 \cdot Cr - 5 \cdot Mo - 7 \cdot Ni - 0.339 \cdot T - 0.023 \cdot (Mn + Ni \cdot Cr) \cdot T$$

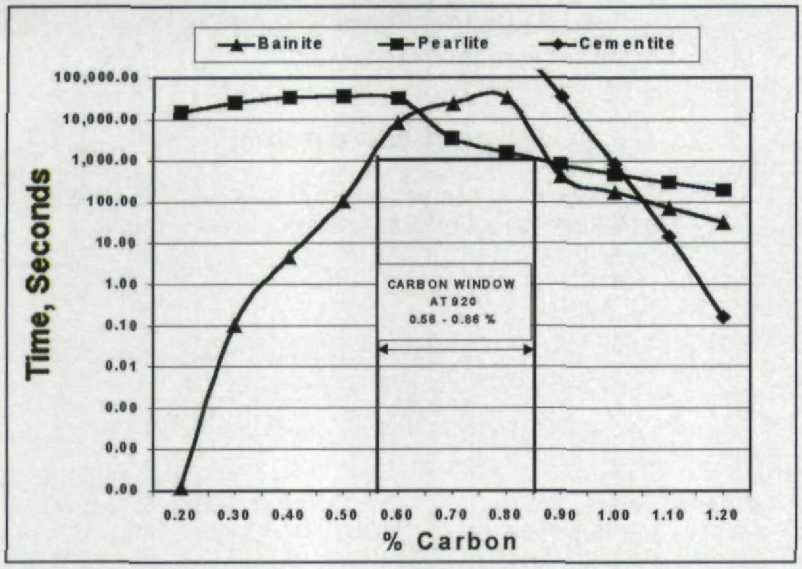

Fig. 5—Effect of carbon on nose times for SAE 8620 at 920°C.

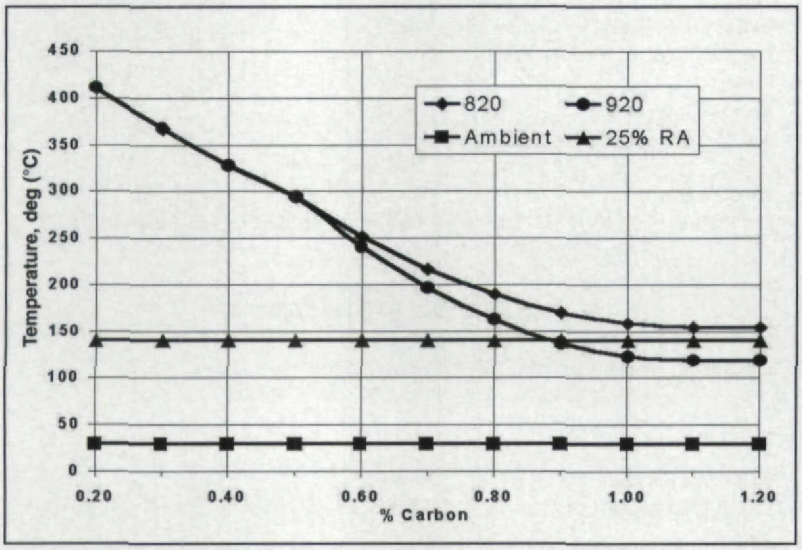

Fig. 6—Effect of carbon on martensite start temperature for SAE 8620 austenitized at 820°C and 920°C.

on the bainite nose time versus carbon curve between 0.50% and 0.85%.

4. Excessive Retained Austenite

The upper carbon limit must be more than 0.10% below the carbon level calculated to leave 25% retained austenite measured optically after quenching and tempering.

Procedure. The principle is to calculate the carbon content within the carbon hardenability window, which minimizes the risks of transformation to non-martensitic products—in particular bainite, pearlite and carbide—while avoiding excessive retained austenite.

The procedure is based on the variations of bainite, pearlite and cementite nose times and on the carbon content corresponding to 25% retained austenite.

To calculate the optimum carbon from alloy content and austenitizing conditions:

1. Calculate the bainite and pearlite nose times at 0.50% C.
2. Calculate the bainite, pearlite and cementite nose times at 0.85% C.
3. Find the lowest nose times at 0.50% C and 0.85% C.
4. Use the lowest nose times to calculate the optimum carbon for case hardenability by log linear interpolation.
5. Calculate the carbon content equivalent to 25% retained austenite from the Koistinen and Marburger equation (Ref. 13).
6. Calculate the final optimum carbon by averaging the carbon content from step 4 and the carbon content from step 5 minus 0.10%.

The formulas. The formulas, derived from the multiple linear regression equations, are:

At 0.5% Carbon

Bainite: $10^{(-0.79 + 2.41 \cdot Mn + 0.79 \cdot Cr + 0.92 \cdot Mo + 0.41 \cdot Ni + 0.32 \cdot Mo \cdot Ni + 0.001 \cdot T)}$

Pearlite: $10^{(-2.82 + 1.26 \cdot Mn + 1.52 \cdot Cr + 5.85 \cdot Mo + 0.60 \cdot Ni - 0.30 \cdot Cr \cdot Cr - 1.45 \cdot Mo \cdot Cr + 0.00233 \cdot T)}$

At 0.85% Carbon

Bainite: $10^{(-5.31 + 0.57 \cdot Mn + 0.57 \cdot Cr + 1.81 \cdot Mo + 0.51 \cdot Ni + 0.0065 \cdot T)}$

Pearlite: $10^{(-2.84 + 0.73 \cdot Mn + 0.54 \cdot Cr + 3.33 \cdot Mo + 0.65 \cdot Ni + 0.0034 \cdot T)}$

Cementite: $10^{(-4.46 - 0.13 \cdot Mn - 0.19 \cdot Cr + 1.99 \cdot Mo - 0.07 \cdot Ni + 0.0084 \cdot T)}$

Calculation of Optimum Carbon, C_H, for Case Hardenability by Log Linear Interpolation:

$$C_H = 0.65 + IF(LOG_{10}(N_{0.85}/N_{0.5}) > 1, 0.2, IF(LOG_{10}(N_{0.85}/N_{0.5}) < -2, 0, 0.2 \cdot (LOG_{10}(N_{0.85}/N_{0.5}) + 2)/3)$$

Where:

$N_{0.5}$ = lowest nose time at 0.50%

$N_{0.85}$ = lowest nose time at 0.85%

Carbon equivalent, C_M, to 25% Retained Austenite at an Ambient Temperature of 30°C:

$$C_M = 1.1 - \sqrt{(0.36 \cdot (117 - MS_{1.1})/(MS_{1.1} - MS_{0.5})}$$

Where:

$$MS_{0.5} = 339.75 - 35.75 \cdot Mn - 18.8 \cdot Cr - 9.5 \cdot Mo - 16.9 \cdot Ni$$

and

$$MS_{1.1} = 436 + 40 \cdot Cr - 5 \cdot Mo - 7 \cdot Ni - 0.339 \cdot T - 0.023 \cdot (Mn + Ni \cdot Cr) \cdot T$$

Calculation of Final Optimum Carbon:

$$C = (C_H + (C_M - 0.1))/2$$

Results

The formulas have been used to form the basis of a spreadsheet. Examples for selected steels are tabulated in Appendix 1.

Points to emerge from Appendix 1 include:

- For direct quenching, the retained austenite carbon tends to dominate the final optimum carbon.

• For reheat quenching, the nose time equations tend to dominate.

• The highest nickel steels have the lowest optimum carbons.

Conclusions

1. A definitive method to calculate optimum carbon levels for carburized case hardened gears has been described.

2. The optimum carbon level minimizes the risk of forming undesirable transformation products, including retained austenite, carbide, bainite and pearlite.

3. The method uses multiple linear regression equations, derived from more than 600 published CCT diagrams, to calculate key points on the CCT diagrams.

4. The accuracy of the coefficient,

$\alpha = -1.1 \times 10^{-2}$ in the Koistinen and Marburger equation:

$V\gamma = e^{\alpha \times (MS-Tq)}$

Where:

$V\gamma$= % retained austenite,

MS = martensite start temperature,

Tq = ambient temperature,

needs to be re-evaluated because it was based on light microscopy measurements of retained austenite, and more accurate methods of measuring retained austenite by X-ray diffraction and electron microscopy are available and have demonstrated that light microscopy can give seriously misleading results.

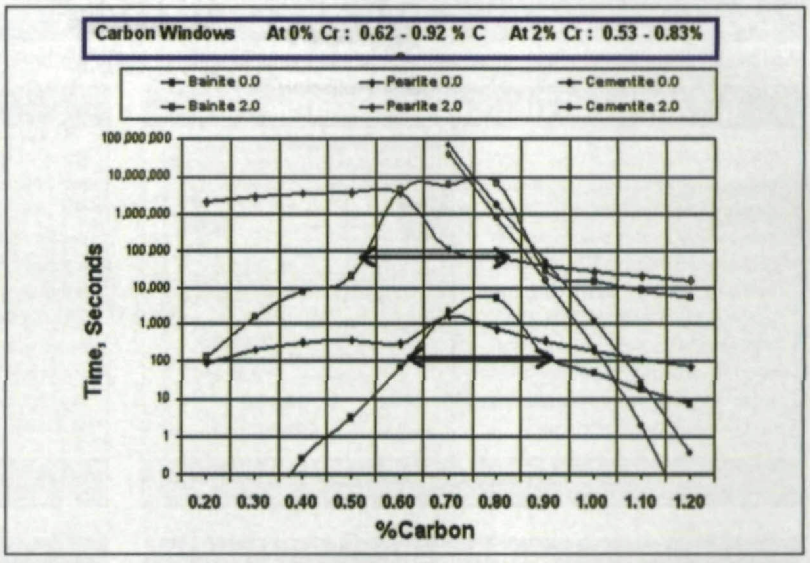

Fig. 7—Effect of chromium on carbon hardenability windows at an austenitizing temperature of 920°C.

Appendix 1 —Results of Sample Calculations

Grade	Base Composition %Mn	%Cr	%Mo	%Ni	Aust Temp. (°C)	% Optimum Carbon
16MnCr5	**1.00**	**1.00**	**0.00**	**0.00**	**820**	**0.70**
655M13	0.45	0.82	0.11	3.20	930	0.62
17CrNiMo6	0.48	1.62	0.29	1.52	930	0.73
8620	0.74	0.47	0.19	0.47	930	0.77
4320	0.52	0.47	0.24	1.73	930	0.71
8822	0.84	0.47	0.34	0.51	930	0.75
655M13	0.45	0.82	0.11	3.20	820	0.72
17CrNiMo6	0.48	1.62	0.29	1.52	820	0.76
8620	0.74	0.47	0.19	0.47	820	0.78
4320	0.52	0.47	0.24	1.73	820	0.79
8822	0.84	0.47	0.34	0.51	820	0.79

Appendix 1 —Supplementary Calculations

Grade	Pearlite 0.5% C	Pearlite 0.85%C	Bainite 0.5% C	Bainite 0.85% C	Cementite at 0.85%C	% Carbon for 25% Ret Aust.	MS deg C at 0.5%C	MS deg C at 1.1%C
16MnCr5	**91**	**7**	**71**	**4**	**1,733**	**1.10**	**285**	**179**
655M13	201,210	308,704	16,176	142,786	91,002	0.72	253	65
17CrNiMo6	321,558	276,565	29,007	121,691	240,623	0.83	264	111
8620	2,554	1,338	37	1,049	285,216	0.87	295	115
4320	46,420	39,135	779	14,564	319,331	0.81	281	98
8822	86,492	17,254	187	5,217	618,630	0.85	289	111
655M13	91,698	101,056	10,561	12,181	2,762	0.82	253	110
17CrNiMo6	152,126	89,359	19,412	9,924	10,681	1.10	264	155
8620	736	179	17	13	13,463	1.10	295	154
4320	18,577	9,733	435	591	15,689	1.02	281	138
8822	36,669	3,775	95	140	37,969	1.10	289	151

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