Influence of Alloying Elements on the Annealability of Carburizing Steels

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SUMMARY

The effects of manganese (0.6-1.0 wt.%), nickel (0-1.8%), chromium (0.5-1.0%), and molybdenum (0.2-0.7%) on annealability of 0.2% C carburizing steels were determined and the results have been expressed in a regression equation. Annealability was defined as the time required to reach a hardness of 200 HV10 during isothermal transformation studies. The regression equation relating annealing time to hardenability and composition showed that substitution of the ferrite-stabilizing elements Cr and Mo for the austenite-stabilizing elements Mn and Ni is generally an effective means of reducing the annealing time while maintaining constant hardenability. These results can best be utilized when designing high-hardenability steels. Examples are given of steels having hardenabilities with D_I values in the range of 130-155 mm (5-6 in.) having annealing times ranging from 1.5 to 12 h.

INTRODUCTION

Carburizing steels are typically softened by annealing to enhance their formability and machinability prior to carburizing. Often the steels will be annealed more than once between forming operations. Shortening the annealing time required to soften the steel can lead to significant cost savings. The ease of achieving the required softness, i.e., the time required, is generally referred to as annealability. Of course, the benefits gained by achieving shorter annealing times can best be realized when the annealing times required far exceed that minimum time required to heat a furnace and load of parts. For example, decreasing annealing time by 30 min compared to steels that already soften in 1 h is of little practical importance if the annealing operation itself already requires 2 h. On the other hand, decreasing the annealing time from 6 to 2 h would be considered very significant.

An inverse relationship between hardenability and annealability is usually anticipated, i.e., a steel with high hardenability normally has poor annealability. However, steels with different alloy compositions but equal hardenabilities may have different annealabilities. The present study was conducted to evaluate the relative effects of manganese, nickel, chromium, and molybdenum on annealability and develop a regression equation relating annealing time to hardenability and composition. Each of the four elements was first investigated at each of two levels as follows: 0.6 and 1% Mn; 0.95 and 1.8% Ni; 0.55 and 1% Cr; and 0.2 and 0.4% Mo. In addition to the 16 heats that covered all combinations of the above dual levels, eight steels with no nickel and/or molybdenum and seven steels with either higher molybdenum or other differences in alloy content were included. Since 200 HV10 (approximately 91.5 HRB)[1] is a suitable hardness for machining and the minimum isothermal transformation time required to reach 200 HV10 (t_{200}) corresponded well to the minimum time for the completion of transformation to pearlite, t_{200} was chosen as the index of annealability.

EXPERIMENTAL PROCEDURES

Materials

The chemical compositions of the test steels are shown in Table I. The first 24 steels were prepared by induction melting of 10 heats in a vacuum furnace backfilled with argon. Each of these 23-27 kg (50-60 lb) heats was cast into 90-mm (3.5-in.) diameter ingot molds with ladle additions of alloy between ingot casts to obtain the 24 chemistries desired. Ingots of Steels 1 through 24 were forged into 30-mm (1.25-in.) diameter and 20-mm (0.8-in.) diameter bars. Steels 25 through 31 were induction melted in air and aluminum deoxidized. Each of these 23 kg (50 lb) heats was forged into 30-mm (1.25-in.) square bar stock. All the bars were normalized at 925°C (1700°F).

End-Quench Hardenability

Jominy hardenability test specimens were machined from normalized 30-mm (1.25-in.) diameter bars. The Jominy specimens were austenitized for 30 min before end-quenching in accordance with ASTM Standard A255. The austenitizing temperature was 900°C (1650°F) for the vacuum/argon-melted steels 1-24, and 925°C (1700°F) for the air-melted steels 26-31. Two parallel flats were ground on each bar and Rockwell C hardness determined as a function of the distance from the quenched end.

The ideal critical diameter (D_I) was determined from the Jominy curve by relating the quenched-end hardness (99% martensite) to the expected hardness at 50% martensite,[2] locating the position on the Jominy curve (distance from the quenched end) corresponding to this expected hardness, and correlating this distance to the diameter (D_I) of a cylinder whose center would experience the same cooling rate when subjected to an ideal quench.[3] The ideal critical diameter was also calculated using known multiplying factors for the various alloying elements.[4]

Isothermal Transformation

Wafers were cut from the normalized 20-mm (0.8-in.) diameter and 30-mm (1.25-in.) square bar stock and ground to a thickness of 3-mm (0.125-in.), austenitized in a lead bath for 30 min at 900°C (1650°F), and transferred to another lead bath stabilized at selected temperatures between 600 and 725°C (1110 and 1340°F). After holding at the isothermal transformation temperature for a selected period of time between 0.25 and 32 h, the wafers were water quenched.

Table I: Chemical Compositions of the Test Steels

Steel	C	Si	Mn	Ni	Cr	Mo	P	S	Al	N
	Element, wt.%									
1	0.20	0.26	0.60	0.96	0.53	0.20	0.017	0.017	0.022	0.0067
2	(0.20)**	0.26	1.00	0.95	0.53	0.20	(0.017)	(0.017)	(0.022)	(0.0067)
3	0.20	0.26	1.00	1.70	0.53	0.20	(0.017)	(0.017)	(0.022)	(0.0067)
4	0.20	0.27	0.60	1.80	0.53	0.40	0.017	0.016	0.023	0.0045
5	(0.20)	0.27	1.01	1.78	0.53	0.39	(0.017)	(0.016)	(0.023)	(0.0045)
6	0.21	0.27	1.02	1.78	1.01	0.39	(0.017)	(0.016)	(0.023)	(0.0045)
7	0.20	0.27	0.61	1.76	0.53	0.20	0.018	0.016	0.019	0.0041
8	(0.20)	0.27	0.60	1.76	1.00	0.20	(0.018)	(0.016)	(0.019)	(0.0041)
9	0.21	0.27	1.00	1.73	1.00	0.20	(0.018)	(0.016)	(0.019)	(0.0041)
10	0.21	0.27	0.60	0.95	0.99	0.20	0.017	0.015	0.017	0.0044
11	(0.21)	0.27	1.00	0.94	0.99	0.20	(0.017)	(0.015)	(0.017)	(0.0044)
12	0.21	0.27	1.00	0.94	0.99	0.39	(0.017)	(0.015)	(0.017)	(0.0044)
13	0.21	0.28	0.60	0.95	0.55	0.40	0.019	0.015	0.036	0.0039
14	0.21	0.28	0.99	0.95	0.55	0.40	(0.019)	(0.015)	(0.036)	(0.0039)
15	0.21	0.27	0.60	0.94	1.01	0.40	0.019	0.015	0.031	0.0040
16	0.21	0.27	0.60	1.71	1.00	0.40	(0.019)	(0.015)	(0.031)	(0.0040)
17	0.20	0.31	0.63	0	0.54	0.21	0.021	0.020	0.032	0.0033
18	(0.20)	(0.31)	(0.63)	0	(0.54)	0.42	(0.021)	(0.020)	0.027	(0.0033)
19	0.20	0.29	0.62	0	0.98	0.21	0.021	0.019	0.041	0.0049
20	(0.20)	(0.29)	(0.62)	0	(0.98)	0.40	(0.021)	(0.019)	0.039	(0.0049)
21	0.20	0.28	0.62	0	0.54	0	0.020	0.019	0.038	0.0037
22	(0.20)	(0.28)	0.97	0	(0.54)	0	(0.020)	(0.019)	0.035	(0.0037)
23	0.20	0.28	0.62	0	1.00	0	0.021	0.019	0.024	0.0039
24	(0.20)	(0.28)	0.94	0	(1.00)	0	(0.021)	(0.019)	0.015	(0.0039)
25	0.20	0.32	0.68	1.59	0.51	0.45	ND*	ND	ND	ND
26	0.20	0.57	0.59	1.61	0.73	0.37	ND	ND	ND	ND
27	0.20	0.61	0.60	1.13	0.70	0.47	ND	ND	ND	ND
28	0.20	0.31	0.57	1.11	0.68	0.47	ND	ND	ND	ND
29	0.19	0.28	0.78	0.66	0.75	0.55	ND	ND	ND	ND
30	0.19	0.34	0.83	0.58	0.52	0.54	ND	ND	ND	ND
31	0.18	0.32	0.79	0.58	0.51	0.73	ND	ND	ND	ND

*ND = Not determined analytically; however, 0.015% P, 0.02% S, and 0.08% Al were added.
**Values in parentheses are taken from other ingots of the same heats.

Table II: Hardenability and Annealability Parameters for Test Steels

Steel	ASTM Grain Size No.	D_I Experimental from End-Quench Bar, mm (in.)	D_I Calculated from Multiplying Factors, mm (in.)	Minimum Pearlite-Finish Time (P_f) and Minimum Time to 200 HV10 (t_{200}), h	Optimum Transformation Temperature (T_t)	
					Experimental, °C (°F)	Calculated, °C (°F)
1	8-8.5	47.5 (1.87)	45.7 (1.80)	0.25	650 (1202)	658 (1216)
2	8-8.5	68.1 (2.68)	65.3 (2.57)	0.375	650 (1202)	654 (1209)
3	8-8.5	89.9 (3.54)	77.5 (3.05)	1.5	625 (1157)	641 (1186)
4	8-8.5	98.8 (3.89)	76.7 (3.02)	1.5	650 (1202)	644 (1191)
5	8-8.5	139 (5.46)	108 (4.26)	6	625 (1157)	640 (1184)
6	8-8.5	155 (6.10)	158 (6.22)	12	650 (1202)	648 (1198)
7	8-8.5	68.1 (2.68)	54.6 (2.15)	0.5	650 (1202)	645 (1193)
8	8-8.5	113 (4.44)	77.7 (3.06)	0.75	650 (1202)	653 (1207)
9	8-8.5	145 (5.70)	115 (4.51)	3	625 (1157)	649 (1200)
10	8-8.5	77.7 (3.06)	66.5 (2.62)	<0.25	675 (1247)	666 (1231)
11	8-8.5	114 (4.48)	96.0 (3.78)	0.75	650 (1202)	662 (1224)
12	8-8.5	139 (5.46)	135 (5.31)	2.5	650 (1202)	662 (1224)
13	8-8.5	68.8 (2.71)	66.0 (2.60)	0.75	650 (1202)	659 (1218)
14	8-8.5	104 (4.09)	95.5 (3.76)	1.5	650 (1202)	655 (1211)
15	8-8.5	105 (4.13)	96.5 (3.80)	0.75	675 (1247)	667 (1233)
16	8-8.5	134 (5.28)	111 (4.35)	1.5	650 (1202)	653 (1207)
17	8.2-8.5	34.5 (1.36)	33.8 (1.33)	<0.25	—*	675 (1247)
18	8.7-9.1	42.4 (1.67)	41.1 (1.62)	0.375	—	675 (1247)
19	8.6-9.0	49.0 (1.93)	44.2 (1.74)	<0.25	—	682 (1260)
20	8.6-9.0	65.5 (2.58)	55.9 (2.20)	0.375	—	682 (1260)
21	6.3-6.9	31.2 (1.23)	29.2 (1.15)	<0.25	—	675 (1247)
22	8.4-8.9	35.6 (1.40)	34.5 (1.36)	<0.25	—	671 (1240)
23	8.1-8.5	37.8 (1.49)	38.1 (1.50)	<0.25	—	682 (1260)
24	8.1-8.4	49.0 (1.93)	50.8 (2.00)	<0.25	—	679 (1254)
25	8	78.0 (3.07)	85.3 (3.36)	2	650 (1202)	648 (1198)
26	7	80.0 (3.15)	89.9 (3.54)	1	675 (1247)	659 (1218)
27	8	82.0 (3.23)	85.1 (3.35)	1	675 (1247)	668 (1234)
28	7	64.8 (2.55)	87.6 (3.45)	0.5	675 (1247)	660 (1220)
29	8	72.4 (2.85)	81.3 (3.20)	0.75	675 (1247)	665 (1229)
30	8	59.9 (2.36)	68.6 (2.70)	0.75	675 (1247)	664 (1227)
31	7	69.1 (2.72)	80.5 (3.17)	1	675 (1247)	664 (1227)

*Blanks in this column indicate that 200 HV10 was reached in the same time at more than one temperature.

Metallography and Hardness

Sections of the isothermally transformed wafers were mounted and metallographically polished. Vickers hardness using a 10 kg load (HV10) was obtained as the average of four readings on each wafer. Selected mounts were etched with 4% nitric acid and 1% picric acid in ethanol. The etched mounts were examined and photographed in an optical microscope.

Prior austenite grain size was estimated by the linear intercept method in accordance with ASTM Standard E112 for the first 24 steels shown in Table I and by the McQuaid-Ehn test for Steels 25-31.

RESULTS AND DISCUSSION

End-Quench Hardenability

The hardenability results for the test steels are shown in Table II. The experimental D_I values obtained from the Jominy bars are compared with those calculated by the multiplying factor method (with the measured grain size) in Figure 1. The calculated and empirical values are in quite good agreement, indicating the validity of the alloy multiplying factors employed.

Isothermal Transformation

The results of the isothermal transformation (annealing) experiments are typified by the diagrams shown in Figure 2. The locus of transformation time to 200 HV10 was determined for each steel. An estimate of the pearlite-finish locus was also obtained by examining the metallographic mounts. The shortest transformation time at temperature required for the disappearance of austenite (martensite and bainite when actually observed under the microscope) was used as the criterion for determining the pearlite-finish time for each test condition, as illustrated by the microstructures in Figure 3. The minimum time to 200 HV10 (t_{200}) and pearlite-finish time (P_f) were virtually identical for each steel and are shown in Table II for all the steels. Note that seven steels exhibited t_{200} values below 0.25 h due to their limited hardenabilities. Since holding times of less than 15 min could not be employed

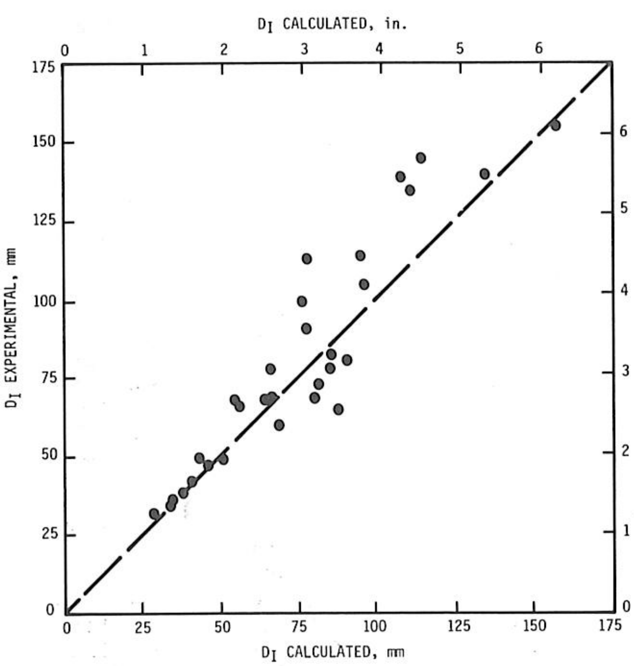

Figure 1. Experimental D_I determined from Jominy bar versus D_I values calculated from known alloy contributions.[4]

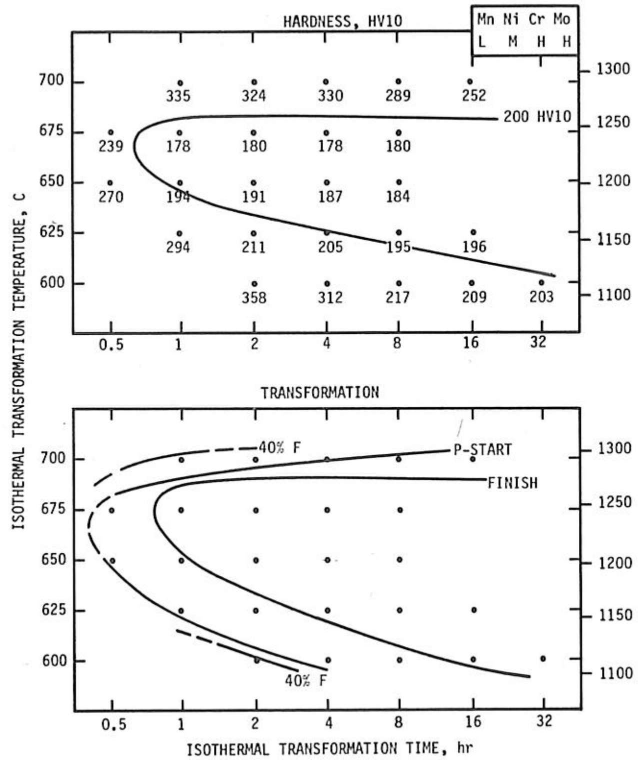

Figure 2. Isothermal transformation diagram of Steel 15.

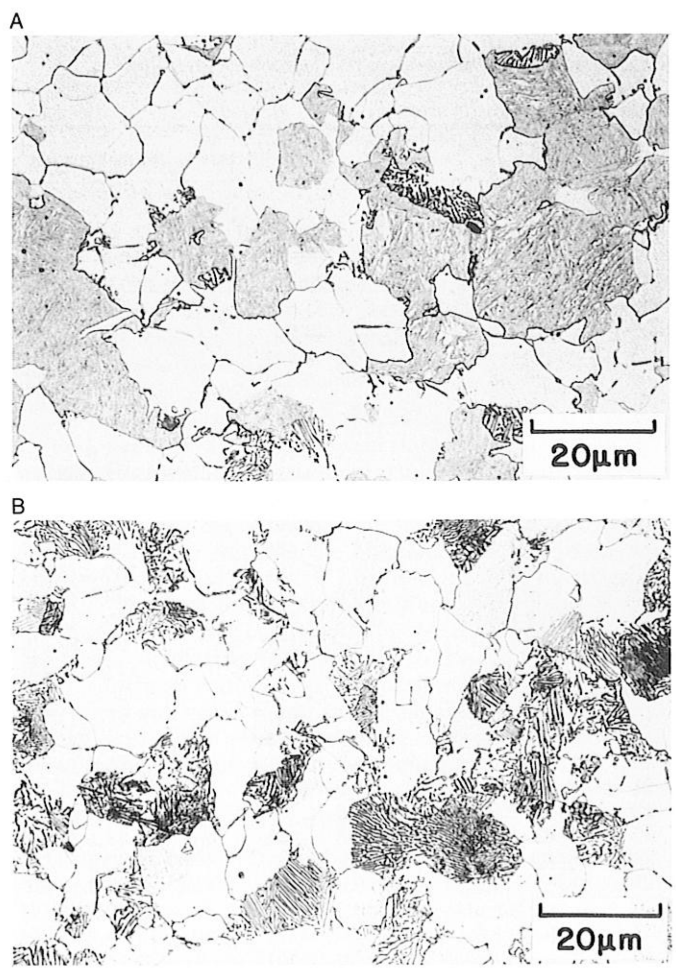

Figure 3. Microstructures of Steel 15; a) ferrite, pearlite, and martensite after isothermal transformation at 675°C (1245°F) for 30 min, 239 HV10; b) only ferrite and pearlite remain after isothermal transformation at 675°C (1245°F) for 1 h, 178 HV10.

with satisfactory accuracy using the lead-bath technique, t_{200} values in this range were not determined.

Regression Analysis

The quantity t_{200}/D_I was calculated for each steel and is shown in Table III. A regression analysis was performed using the model equation

$$t_{200}/D_I = a_1(\%Mn) + a_2(\%Ni) + a_3(\%Cr) + a_4(\%Mo) + a_5(\%Mn)(\%Cr) + a_6(\%Mn)(\%Mo) + a_7(\%Ni)(\%Cr) + a_8(\%Ni)(\%Mo) + a_9(\%Mn)(\%Ni) + a_{10}(\%Cr)(\%Mo) + b \quad (1)$$

where the alloying elements were entered in weight percent. The seven steels with t_{200} less than 0.25 h were eliminated from the regression data set (Table III) due to their undeterminable t_{200}/D_I values. In addition, the statistical parameters that were associated with the regression analysis showed higher significance when Steel 6 and the Ni-Cr (a_7) and Cr-Mo (a_{10}) terms were eliminated from the regression analysis. Steel 6 had the highest levels of Mn, Ni, and Cr and, therefore, the highest hardenability and an annealing time (12 h) much higher than any other steel in the data set.

The following optimized regression equations were obtained:

$$t_{200}(h) = \frac{D_I(mm)}{100} \times [-11.5(\%Mn) - 5.0(\%Ni) - 1.89(\%Cr) - 12.4(\%Mo) + 2.24(\%Mn)(\%Cr) + 14.8(\%Mn)(\%Mo) + 4.37(\%Ni)(\%Mo) + 6.14(\%Mn)(\%Ni) + 9.29] \quad (2)$$

or

$$t_{200}(h) = D_I(in.) \times [-2.92(\%Mn) - 1.27(\%Ni) - 0.48(\%Cr) - 3.14(\%Mo) + 0.57(\%Mn)(\%Cr) + 3.77(\%Mn)(\%Mo) + 1.11(\%Ni)(\%Mo) + 1.56(\%Mn)(\%Ni) + 2.36] \quad (3)$$

An analysis of variance was performed for the regression. An F-ratio with a tail probability of zero and a coefficient of determination (r^2) of 0.928 were obtained. The experimentally determined t_{200}/D_I values are compared with their respective values calculated using the above equations in Figure 4 for the 23 steels* used in the regression analysis. A statistically significant correlation was obtained.

Examples of annealing times (at constant D_I) calculated with the regression equation for various alloy substitutions are shown in Table IV. These results indicate that an alloy design practice which makes greater use of the ferrite-stabilizing elements Cr and Mo compared with the austenite-stabilizing elements Mn and Ni will generally result in reduced annealing times for the same level of hardenability. An example of a high-hardenability steel having relatively low annealing time is given by Steel 16, a low-Mn, high-Cr and Mo steel. Even though its D_I exceeded 130-mm (5.1-in.), the annealing time (t_{200}) was only 1.5 h as shown in Tables II and III. Other steels having D_I values exceeding 130-mm (5.1-in.) had annealing times ranging from 2.5 to 12 h. Use of molybdenum and chromium substitutions to reduce annealing time is most effective for steels with a high hardenability, since steels with low to medium hardenability will typically be annealed fully in the minimum practical time (determined by the thermal inertia of the furnace load) of a commercial annealing cycle. This point is illustrated in Tables II and III, where annealing times of 45 min or less were obtained for steels with D_I less than about 75-mm (3-in.).

*The regression equation as well as the statistical parameters associated with it were unaffected by the elimination of Steels 26 and 27 (high-silicon contents). Therefore, these two steels were included in the final data set.

Table III: Test Steels Tabulated in the Order of Increasing t_{200}/D_I

Steel	t_{200}/D_I h/mm (h/in.)	Minimum Time to 200 HV10 (t_{200}), h	D_I Experimental from End-Quench Bar, mm (in.)
17	—*	<0.25	34.5 (1.36)
19	—	<0.25	49.0 (1.93)
21	—	<0.25	31.2 (1.23)
22	—	<0.25	35.6 (1.40)
23	—	<0.25	37.8 (1.49)
24	—	<0.25	49.0 (1.93)
10	—	<0.25	77.7 (3.06)
1	0.00528 (0.134)	0.25	47.5 (1.87)
2	0.00567 (0.139)	0.375	68.1 (2.68)
20	0.00571 (0.145)	0.375	65.5 (2.58)
11	0.00657 (0.167)	0.75	114 (4.48)
8	0.00665 (0.169)	0.75	113 (4.44)
15	0.00717 (0.182)	0.75	105 (4.13)
7	0.00736 (0.187)	0.5	68.1 (2.68)
28	0.00772 (0.196)	0.5	64.8 (2.55)
18	0.00886 (0.225)	0.375	42.4 (1.67)
29	0.0104 (0.263)	0.75	72.4 (2.85)
13	0.0109 (0.277)	0.75	68.8 (2.71)
16	0.0112 (0.284)	1.5	134 (5.28)
27	0.0122 (0.310)	1	82.0 (3.23)
26	0.0125 (0.3175)	1	80.0 (3.15)
30	0.01251 (0.3178)	0.75	59.9 (2.36)
14	0.0144 (0.367)	1.5	104 (4.09)
31	0.0145 (0.368)	1	69.1 (2.72)
4	0.0152 (0.386)	1.5	98.8 (3.89)
3	0.0167 (0.424)	1.5	89.9 (3.54)
12	0.0180 (0.458)	2.5	139 (5.46)
9	0.0207 (0.526)	3	145 (5.70)
25	0.0257 (0.652)	2	78.0 (3.07)
5	0.0433 (1.099)	6	139 (5.46)
6	0.0774 (1.967)	12	155 (6.10)

*Blanks in this column indicate undetermined t_{200}/D_I values of heats with t_{200} less than 0.25 h.

Optimum Transformation Temperature

The temperature at which the fastest transformation occurs often depends on chemical composition. Substitutions of elements which affect the A_{c_1}, the temperature at which austenite begins to form on heating, would presumably affect the upper portion of the isothermal transformation C curves in a similar manner.

The effects of alloying elements on the A_{c_1} temperature have been determined by Andrews[5] as given below. Without the terms for tungsten and arsenic in the original equation, the A_{c_1} is expressed as

$$A_{c_1}(°C) = 723 - 10.7(\%Mn) - 16.9(\%Ni) + 29.1(\%Si) + 16.9(\%Cr) \quad (4)$$

Equation 4 can be modified to estimate the optimum transformation temperature, T_t, on the assumption that the effect of an alloying element on T_t is the same as that on A_{c_1}. The first term (constant) of the right-hand side of Equation 4 should then be different for T_t. To compute a new constant, the difference between the sum of the four chemical terms on the right-hand side of Equation 4 and the experimentally determined T_t shown in Table II was computed for each of the 23 steels with discrete values of T_t. The mean of the sum of these differences (664) was chosen as the new constant to replace the value of 723 in Equation 4. The optimum annealing temperature (fastest transformation to 200 HV10) can then be stated as follows:

$$T_t(°C) = 664 - 10.7(\%Mn) - 16.9(\%Ni) + 29.1(\%Si) + 16.9(\%Cr) \quad (5)$$

The calculated values of T_t using Equation 5 are shown in Table II. The agreement between the calculated and exper-

Table IV: Effect of Alloy Substitutions on Annealing Time at Constant Hardenability

	Substitution	Alloy Content, % Mn	Ni	Cr	Mo	D_I,* mm (in.)	t_{200},** h	Increase(+) or Reduction(–) in Base Annealing Time, min
	Base	0.85	1.5	0.75	0.3	100 (3.94)	1.92	0
α for γ Stabilizer	Mo for Mn	0.67	1.5	0.75	0.4	100 (3.94)	1.65	–16
	Mo for Ni	0.85	0.75	0.75	0.4	100 (3.94)	1.21	–43
	Cr for Mn	0.72	1.5	0.9	0.3	100 (3.94)	1.38	–32
	Cr for Ni	0.85	0.98	0.9	0.3	100 (3.94)	1.12	–48
	Mo+Cr for Mn+Ni	0.78	1.0	0.85	0.35	100 (3.94)	1.27	–39
γ for α Stabilizer	Mn for Mo	0.95	1.5	0.75	0.24	100 (3.94)	1.81	– 7
	Mn for Cr	0.95	1.5	0.63	0.3	100 (3.94)	2.28	+22
	Ni for Mo	0.85	1.7	0.75	0.27	100 (3.94)	2.00	+ 5
	Ni for Cr	0.85	1.7	0.7	0.3	100 (3.94)	2.23	+19
	Mn+Ni for Mo+Cr	0.95	1.7	0.7	0.24	100 (3.94)	2.18	+16

*Calculated from known alloy contributions[4] with 0.2% C and a grain size of ASTM No. 7
**Calculated using Equations 3 and 4

imental T_t values was fairly good, considering that the experimental temperature is a value rounded to the nearest 25C° (45F°) interval. It is noteworthy that similar overall agreement (sum of residuals between experimental and calculated T_t) was obtained after another equation[6] relating A_{c_1} and chemical composition was altered in an identical manner.

CONCLUSIONS

The minimum isothermal annealing time (t_{200}) for 0.2% C carburizing steels to reach a hardness of 200 HV10 can be stated as a function of ideal critical diameter (D_I) and chemical composition as follows:

$$t_{200}(h) = \frac{D_I(mm)}{100} \times [-11.5(\%Mn) - 5.0(\%Ni) - 1.89(\%Cr) - 12.4(\%Mo) + 2.24(\%Mn)(\%Cr) + 14.8(\%Mn)(\%Mo) + 4.37(\%Ni)(\%Mo) + 6.14(\%Mn)(\%Ni) + 9.29] \quad (6)$$

or

$$t_{200}(h) = D_I(in.) \times [-2.92(\%Mn) - 1.27(\%Ni) - 0.48(\%Cr) - 3.14(\%Mo) + 0.57(\%Mn)(\%Cr) + 3.77(\%Mn)(\%Mo) + 1.11(\%Ni)(\%Mo) + 1.56(\%Mn)(\%Ni) + 2.36] \quad (7)$$

This equation is valid for 0.2% C steels in the composition range of 0.6-1.0% Mn, 0-1.8% Ni, 0.5-1.0% Cr, and 0.2-0.7% Mo with D_I values in the range of approximately 50-145 mm (2-5.7 in.) and annealing times in the range of 15 min-6 h. Although the equation is valid for low-hardenability steels having compositions within the above stated ranges, its practical significance is reduced when comparing steels with t_{200} values of less than 1.5 h. The thermal inertia involved in commercial heat treatments of a large number of parts and the normal range of compositions expected within a given grade of steel necessitates longer annealing times to ensure that all parts are adequately softened.

The full utility of the t_{200} equation is best realized when designing steels with high hardenability when the annealing times can vary from 1.5 to 12 h, depending on the selection of alloy additions. For steels with high hardenability, the substitution of the ferrite-stabilizing elements Cr and Mo for the austenite-stabilizing elements Mn and Ni will generally result in a reduced annealing time at an identical hardenability. The optimum annealing temperature (T_t), the fastest transformation to 200 HV10, can be stated as a function of composition as follows:

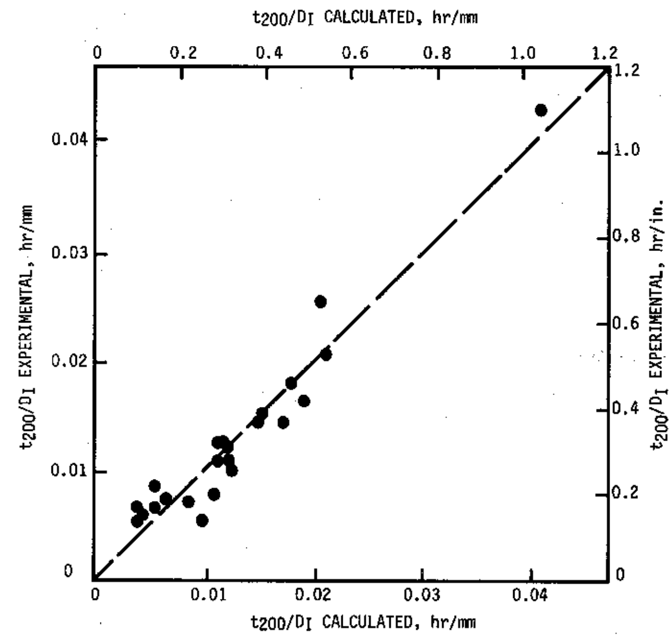

Figure 4. Experimental t_{200}/D_I determined from isothermal transformation experiments and Jominy tests versus calculated t_{200}/D_I from Equations 2 and 3.

$$T_t(°C) = 664 - 10.7(\%Mn) - 16.9(\%Ni) + 29.1(\%Si) + 16.9(\%Cr) \quad (8)$$

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