

The Heat Treatment of Vanadium-Modified Alloy Steels

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SUMMARY

The hardenabilities of four alloy steel grades modified with vanadium were determined at various austenitizing temperatures depending on carbon content. The modification was made by substituting V for Mo; results show that a 1:2 substitution of V for Mo (in weight percent) was effective. The "micro-alloying" addition of 0.10-0.15%V, alone or in combination with a lesser amount of Mo, is sufficient to attain the hardenabilities of the standard grade containing 0.15-0.40%C with higher amounts of Mo. From the results, it was deduced that vanadium carbide can be dissolved in austenite at standard or slightly higher austenitizing temperatures for all the vanadium levels studied. It was also shown that grain coarsening of the austenite is induced more by vanadium than by molybdenum.

INTRODUCTION

At a recent symposium, Robinson¹ summarized the development of and the challenges faced by alloy steels in the automotive industry. Through the years since Henry Ford revolutionized car manufacture, constant changes in alloy steel compositions, to meet the demands of the times, were prevalent. At present, it appears that the technology of heat-treated alloy steels has reached its maturity, with work concentrated on both accurately predicting hardenability from chemical composition and balancing composition to minimize cost for the application desired. However, this is far from the reality, for specific effects of the various alloying elements, individually and in combination, on hardenability, materials properties, and service performance are far from being understood.^{1,2} The current use of alloy steels depends to some extent on the mystique, developed with their development, that either individual or combinations of alloying elements were considered uniquely responsible for the steel properties.

Despite this mystique, there persist changes in the selection of materials based on alloy costs and performance, i.e., response to varied and complex engineering and processing demands on the materials. The complexity of demands resulted in the establishment of an increased number of alloy grades to meet specific demands. In 1940, the SAE (Society of Automotive Engineers) listed 65 standard grades of low-alloy steels; today⁷ there are 86, not including the "H band" series, plus EX grades and numerous "modified" grades specified by individual manufacturers. In the course of the years, 96 former grades⁷ were deleted, i.e., no longer of major commercial use. Such continuing activity suggests that the technology of alloy steels is still in a state of flux.

Although wrought alloy steels face some competition in low-stress automotive components, they will continue to be the dominant materials for highly stressed components, such as power transmission gears and shafting, ball and roller bearings, and spring members. These components have high hardness ($\geq 50\text{R}_c$) and depend on the ability of the steel to be through hardened, case hardened by induction heating, or case carburized.

In predicting hardenability from composition, one finds no readily available factor for vanadium,³ in spite of the fact that vanadium was used in the early alloy steel grades

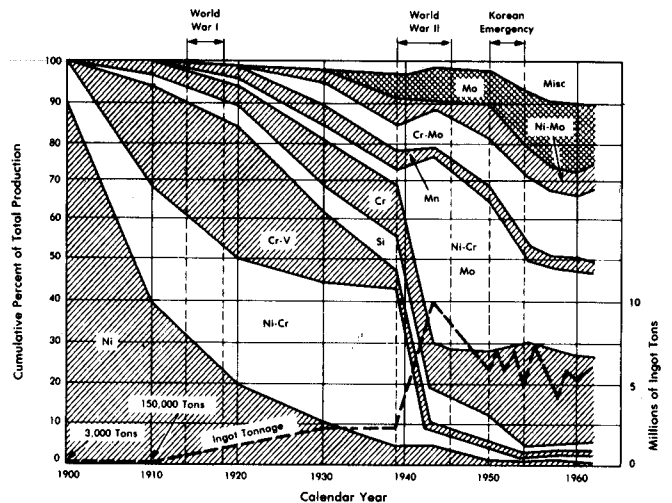


Figure 1. Alloy steel production in the U.S. showing cumulative percent of steel type produced in a given year from 1900.

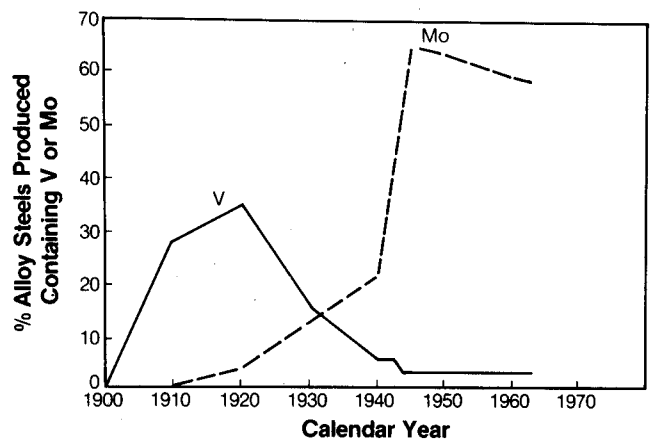


Figure 2. Relative percent of alloy steels produced containing V or Mo during same period as Figure 1.

(Figure 1). Relative to molybdenum, the percent of alloy steels containing vanadium through the years is shown in Figure 2. The unavailability of the factor for vanadium stems from vanadium's infrequent use in current alloy grades and conflicting data on its influence on hardenability. The current restricted application of vanadium in alloy steels is due mainly to the concept that during austenitization vanadium forms insoluble carbides which result in very fine austenitic grain size.⁴ Both the insolubility of the carbides and the fine austenitic grain size minimize hardenability.

The present study was conducted to determine the hardenability response of vanadium-modified 4030, 4130, 4330, and 8630 alloy steels at the SAE specified standard temperature and slightly higher austenitizing temperatures. In addition, the interaction of carbon and vanadium was determined in the 8615 and 8640 steels. The modifica-

tion was made by partial and total substitution of Mo in the standard grades.

MATERIALS AND PROCEDURES

This study began with the 4330 steels which were examined in greater depth than the three other grades. The compositions of the steels studied are shown in Table I. For the 4330 steels, various combinations of molybdenum and vanadium were initially studied; subsequently, the compositions of the modified grades were kept at about 0.15%V-0%Mo and 0.15%V-0.05%Mo. The first alloys listed for the subsequent grades are the standard alloys with molybdenum. For determining the interaction of vanadium and carbon in 8615 and 8640, the modified grades do not contain molybdenum and two levels of vanadium were used for the 8640, i.e., 0.15%V and 0.10%V.

The steels were produced by induction melting in air and were all aluminum-killed. The experimental procedures to determine the hardenabilities and the austenite grain size are described elsewhere.⁵ The hardenability data are the averages of two readings, which did not differ by more than two R_c points, at each of the J-locations taken along two ground flat surfaces in the Jominy bar, 180° from each other. In every case the data of the modified grades were compared with those of the standard grade.

RESULTS AND DISCUSSION

4330 Steels

The initial results of this study on 4330 are shown in Figures 3-5 where austenitizing temperatures of 1600°F (871°C), 1700°F (927°C), and 1750°F (954°C) were used. For the carbon contents of the steel shown in Table I, the SAE specified austenitizing treatment is 1600°F (871°C). Examination of the hardenability data of the partially substituted alloys, i.e., combination of vanadium and molybdenum, indicates that at all three temperatures used the

combination of V and Mo yielded higher hardenabilities than the standard grade. This is significant in view of the fact that the sum of the contents of V and Mo in the modified grades is always less than the 0.30%Mo in the standard grade. At the present alloy costs of these elements, it provides an economic advantage with better hardenabilities. In fact, to obtain equivalent hardenabilities of the modified and standard grades, the results suggest that a 1:2 substitution of V for Mo is sufficient, e.g., 0.10%V for the 0.20%Mo taken out in Heat 289. This result was also demonstrated by Grange⁶ in his study of shallow-hardening steels where he used the 90% martensite criterion as a measure of hardenability.

The position of the hardenability curve for the standard grade remained essentially constant at the three austenitizing temperatures used. The vanadium-modified steels exhibit an increase in hardenability as the austenitizing temperature is raised (Figures 3a, 4a, and 5a). The quantitative D_i values were reported earlier⁵ but the greatest increase for the partially substituted alloys arose with the change from 1600°F (871°C) to 1700°F (927°C).

The characteristics of the totally vanadium substituted 4330 alloy steels were distinctly different from the partially substituted steels (Figures 3b, 4b, and 5b). At the standard austenitizing temperature of 1600°F (871°C) (Figure 3b) they exhibit lower hardenabilities, and the higher the vanadium content, the lower the exhibited hardenability. At 1700°F (927°C), Figure 4b shows the 0.15%V steel exceeding the hardenability of the standard grade; the hardenabilities of the 0.10%V and 0.24%V steels are about equivalent to the standard grade. At 1750°F (954°C), the hardenabilities of the 0.15%V and 0.24%V exceed those of the standard, while those for the 0.10%V are equivalent to the standard. These results suggest that heat-treating vanadium-modified alloys with no molybdenum requires about 100F° (55.6C°) higher austenitizing temperature to achieve the equivalent hardenability of the molybdenum grade. However, the results also suggest the 1:2 substitution of V for Mo as found in the

Table I: Composition of Alloy Steels (wt. %)

Alloy	Heat No.	C	Mn	P	S	Si	Ni	Cr	Mo	V	Al	N
STD 4330	254	0.30	0.49	0.003	0.017	0.21	1.78	0.53	0.30	<.01	0.056	0.0135
Partial V-Substitution 4330	288	0.28	0.51	0.005	0.009	0.23	1.93	0.53	0.05	0.15	0.065	0.0069
	289	0.28	0.49	0.004	0.016	0.20	1.94	0.53	0.10	0.10	0.057	0.0081
	255	0.30	0.48	0.001	0.014	0.22	1.76	0.53	0.10	0.16	0.063	0.0117
Total V-Substitution 4330	256	0.31	0.50	0.001	0.016	0.23	1.72	0.50	<.01	0.24	0.056	0.0134
	271	0.29	0.52	0.003	0.017	0.21	1.75	0.53	<.01	0.15	0.053	0.0082
	291	0.28	0.50	0.004	0.011	0.21	1.94	0.52	<.01	0.10	0.058	0.0048
4030	329	0.28	0.78	0.007	0.014	0.22	0.03	0.03	0.30	----	0.058	0.0116
	299	0.34	0.81	0.009	0.018	0.23	0.03	0.02	0.32	----	0.057	NA
	300	0.31	0.82	0.007	0.017	0.24	0.03	0.02	----	0.15	0.056	NA
	301	0.31	0.82	0.007	0.016	0.25	0.03	0.02	0.05	0.15	0.059	NA
4130	305	0.31	0.66	0.009	0.018	0.24	0.03	0.95	0.21	----	0.055	0.008
	306	0.31	0.80	0.008	0.019	0.25	0.03	0.96	0.01	0.16	0.057	0.009
	307	0.31	0.80	0.008	0.018	0.24	0.03	0.95	0.06	0.16	0.053	0.010
8630	302	0.31	0.81	0.008	0.018	0.24	0.55	0.53	0.21	----	0.057	0.010
	303	0.30	0.81	0.006	0.016	0.24	0.54	0.52	----	0.15	0.056	0.009
	304	0.31	0.83	0.007	0.018	0.26	0.56	0.53	0.06	0.15	0.057	0.010
8615	327	0.14	0.69	0.006	0.013	0.17	0.57	0.52	0.20	----	0.060	0.010
	328	0.14	0.73	0.004	0.013	0.19	0.55	0.52	----	0.14	0.058	0.010
8640	324	0.40	0.74	0.005	0.012	0.19	0.53	0.52	0.20	----	0.053	0.007
	325	0.42	0.78	0.004	0.013	0.23	0.53	0.52	----	0.15	0.059	0.010
	326	0.41	0.80	0.005	0.015	0.24	0.55	0.53	----	0.10	0.068	0.010

partially substituted alloys; that is, the 0.15%V steel has hardenability equivalent to the 0.30%Mo steel at 1700°F (927°C).

It is appropriate to indicate here that vanadium-containing alloys such as the 6100 series usually require austenitizing temperatures about 30C° higher than those specified for alloys having an equivalent carbon content.⁷ As indicated, the standard austenitizing temperature based on carbon content is 1600°F (871°C) and the additional 100F° (55.6C°) higher temperature needed to achieve equivalent hardenabilities for the totally substituted alloy is just slightly higher than the commercially specified temperature. However, for the partially substituted alloy steels, i.e., when V and Mo are present together, it is not necessary to heat treat at a higher temperature than that specified at the carbon content of the steel. In fact, as seen earlier, the hardenabilities for these steels already exceed those for the standard grade at the standard temperature. It was found that the sum of the individual effects of V and Mo in 4330, when added singly, is less than the result when both are added simultaneously, indicating a synergistic effect. When analyzed statistically, this apparent synergism was ascribed to an increase in individual effects of V and Mo when added together as compared to effects when each was added singly.⁸

Examination of the prior austenitic grain sizes reveals that the vanadium-modified steels coarsen their grains more easily than the molybdenum steels.⁵ This was an unexpected result in view of the prevailing concept⁴ that vanadium carbides are insoluble at the austenitizing temperatures, thus inducing very fine austenite grain sizes. Figures 6 and 7 illustrate the grain sizes of the steels at different temperatures. Figure 6 compares the grain sizes of the standard steel and a totally substituted steel (0.15%V) at 1600 and 1750°F while Figure 7 shows the grain sizes of the

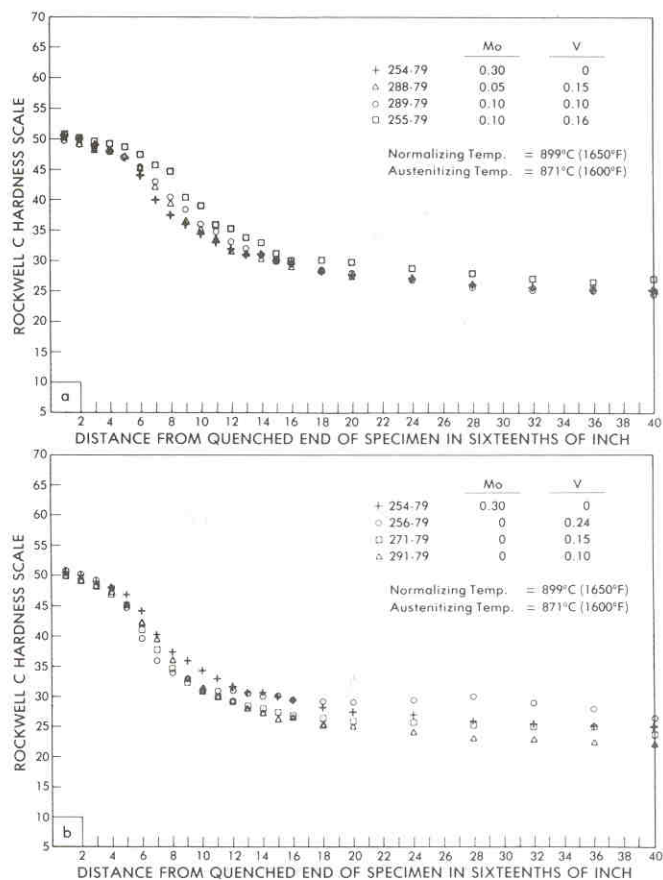


Figure 3. Hardenability data of 4330 steels after 1600°F (871°C) austenitization; (a) partially substituted alloys; (b) totally substituted alloys.

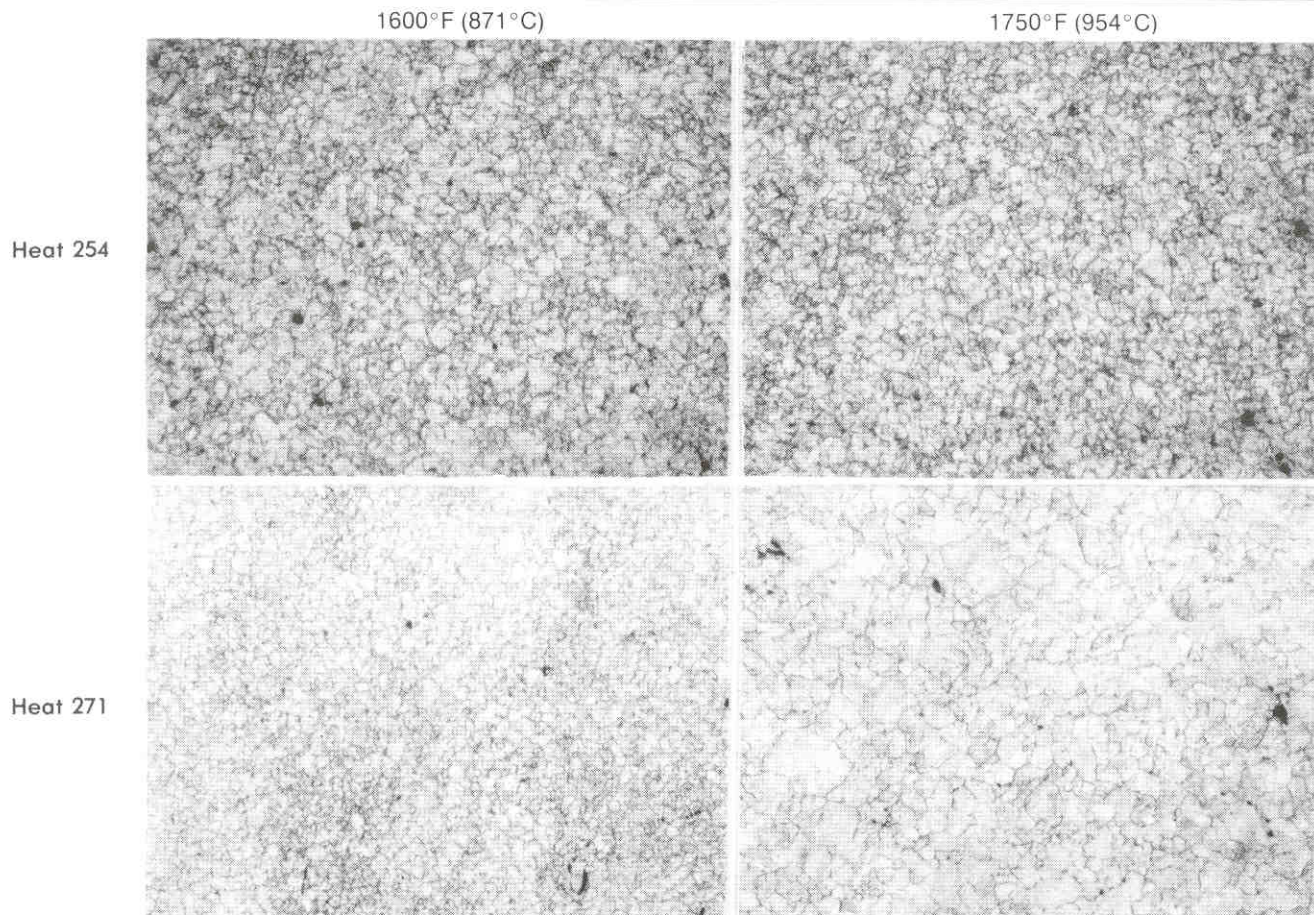


Figure 6. Prior austenite grain sizes of the 4330 standard grade (Heat 254) compared with the 0.15%V totally substituted 4330 alloy (Heat 271) at 1600°F and 1750°F.

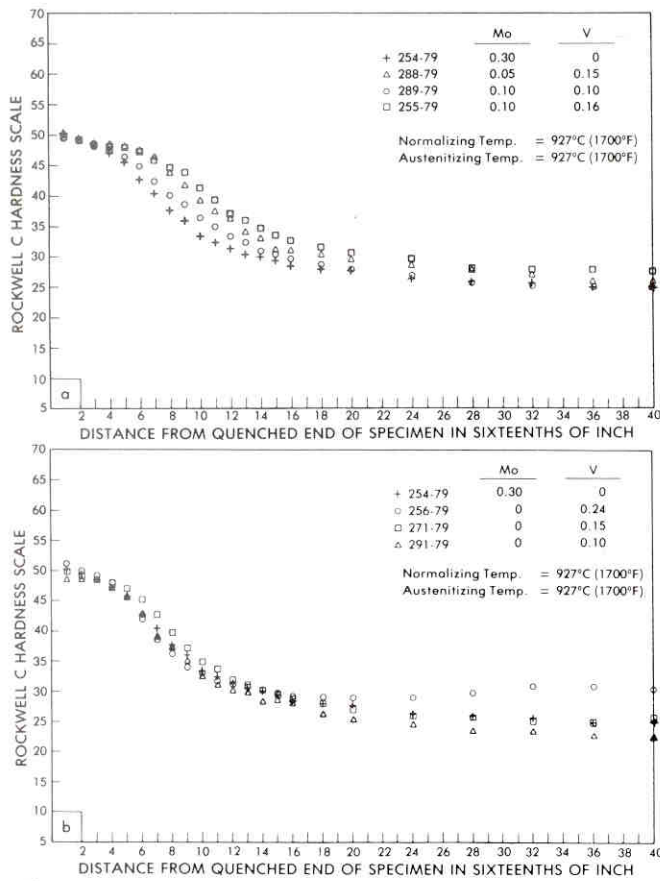


Figure 4. Hardenability data of 4330 steels after 1700°F (927°C) austenitization; (a) partially substituted alloys (b) totally substituted alloys.

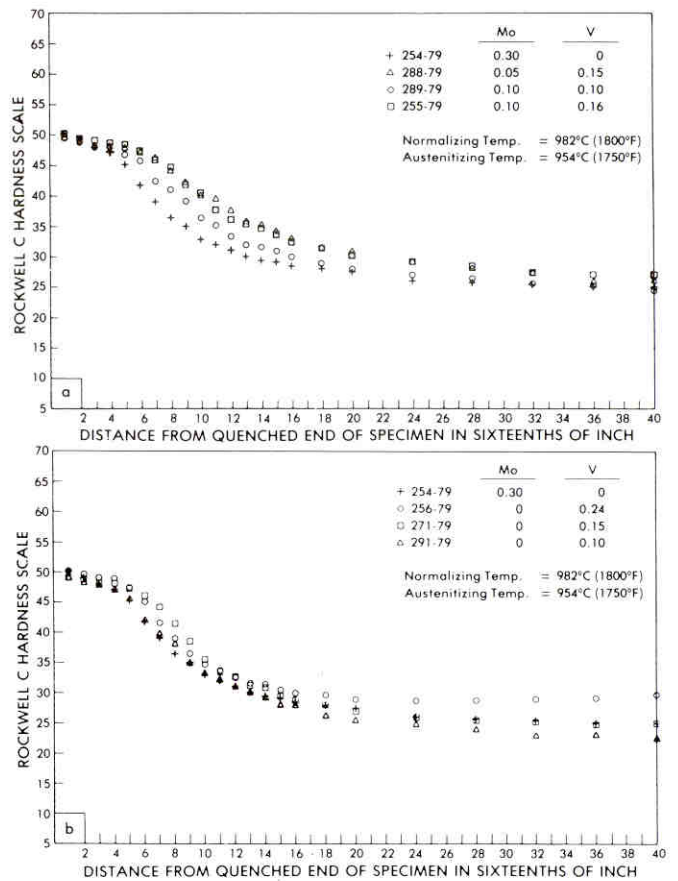


Figure 5. Hardenability data of 4330 steels after 1750°F (954°C) austenitization; (a) partially substituted alloys (b) totally substituted alloys.

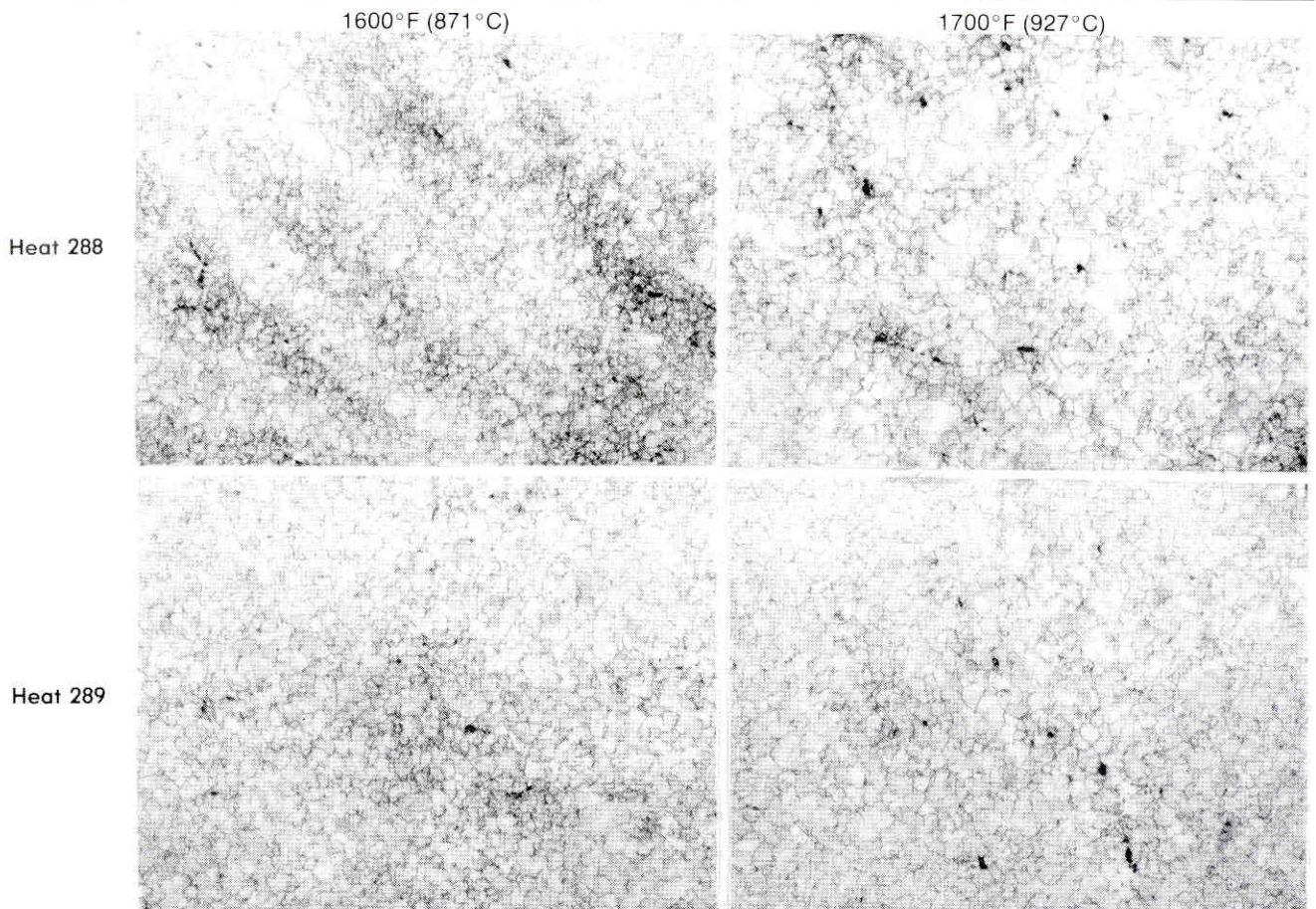


Figure 7. Prior austenite grain sizes of partially modified 4330 steels showing the retarding influence of Mo and grain coarsening of Heat 288, 0.05Mo-0.15V and Heat 289, 0.10Mo-0.10V at 1600°F and 1700°F.

partially substituted alloys, with differing Mo and V contents, at 1600 and 1700°F. In both these figures (more quantitative information is given in reference 5) the vanadium-modified alloys tend to have a slightly finer grain size than the standard grade at 1600°F; at higher temperatures the vanadium-modified alloys have coarser grain sizes. The more the vanadium content, the coarser the grain sizes appear to be, while the presence of molybdenum tends to inhibit grain coarsening.

When the effect of the austenitic grain size was subtracted from the measured D_f values,⁵ the results indicated that all the vanadium carbides were in solution at 1600°F, even for the 0.24%V. The increase in hardenability at the

higher austenitizing temperatures was apparently due to the increase in austenite grain size. The apparent complete solubility of the 0.24%V was also an unexpected result, although not entirely without explanation. According to the recent work of Wriedt and Hu,⁹ the amount of vanadium in solution in austenite for 0.30%C is 0.13%. However, this does not take into account the influence of the other elements in the steel. Woodhead¹⁰ has shown the strong influence of manganese in increasing the solubility of vanadium in austenite. A parallel study on niobium carbides by Koyama et al.¹¹ shows that manganese and chromium remarkably increased the solubility of NbC. Nickel increases the NbC solubility at comparatively low temperatures but has only a minor effect at higher temperatures. The influence of these elements is to decrease the activity of carbon; thus, one would expect a similar effect on vanadium carbide when these are present in the steel, which is the case in the 4330 steels. Within the framework of the analysis, the influence of these elements apparently enables the dissolution of 0.24%V in austenite at 1600°F (871°C).⁵

Other Alloy Steels — 4030, 4130, and 8630

The hardenabilities of these steels (compositions listed in Table I) are shown in Figures 8, 9, and 10 respectively for the 4030, 4130, and 8630 steels at 1600°F (871°C). Each figure shows that the austenitic grain sizes (shown with legends) of the steels are about the same and that the behavior of the vanadium-modified steels is similar to that of the 4330 modified steels relative to the standard grade.

In Figure 8, the hardenabilities of two standard molybdenum steels with 0.28%C and 0.34%C bracket the hardenabilities of the 0.31%C vanadium-modified steels. Again in this case, the combination of 0.05%Mo-0.15%V exhibits a very slight advantage over the 0.15%V steel. At the higher austenitizing temperature of 1700°F (927°C) the hardenabilities (not shown here) of the 0.31%C vanadium steels exceeded those of the 0.34%C standard steel. This effect is primarily due to the coarser austenitic grain size of the vanadium steels at 1700°F. As in the 4330 steels, the standard steel maintained its austenitic grain size when austenitized from 1600°F to 1700°F and thus its hardenability remained essentially constant.

Figure 9 shows the 0.16%V 4130 steel with slightly lower hardenability and the 0.05%Mo-0.16%V steel with higher hardenability than the standard Mo grade. In Figure 10, both the 8630 modified alloys exhibited significantly higher hardenabilities than the standard 8630 steel. In comparing the results of Figures 9 and 10, the hardenability curves of the 8630 and 4130 modified alloys almost coincided. These results suggest the relatively minor influence in the changes of nickel and chromium contents in these two grades (see Table I). All the modified 4130 and 8630 steels also exhibited increased hardenabilities and coarser austenite grain sizes when austenitized at 1700°F.

Influence of Carbon Content—8615 and 8640 Steels

Results are shown in Figures 11 and 12 for the 8615 and 8640 steels respectively. In both these grades, only the totally substituted vanadium-modified steels were studied relative to the standard. Two levels of vanadium, 0.10%V and 0.15%V, were studied for the 8640 and only the 0.14%V steel was studied for the 8615. In each of these grades the lower austenitizing temperature corresponds to the standard for the carbon content of the steel. For the 8615 grade, the results (Figure 11) indicate essentially no difference in the hardenabilities of the modified and standard grades at the two austenitizing temperatures. The hardenabilities at the higher austenitizing temperature of 1800°F (982°C) are slightly higher than those at 1700°F (927°C). At 1800°F, the Mo steel also exhibited austenite grain size coarsening, as did the vanadium steel.

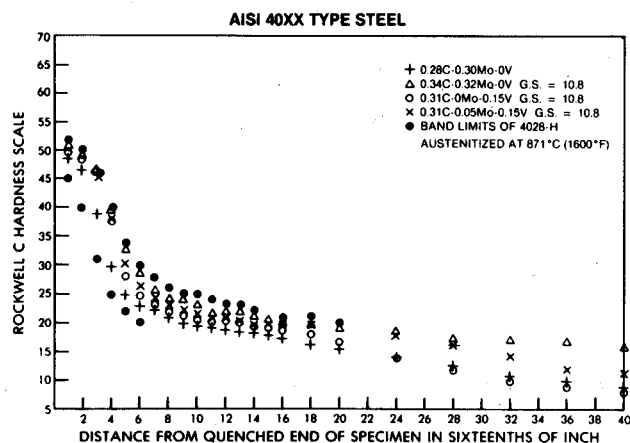


Figure 8. Hardenability data of AISI 4030 steels austenitized at 1600°F (871°C).

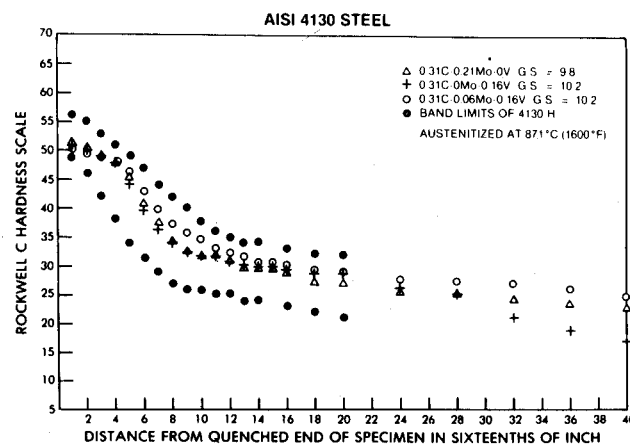


Figure 9. Hardenability data of AISI 4130 steels austenitized at 1600°F (871°C).

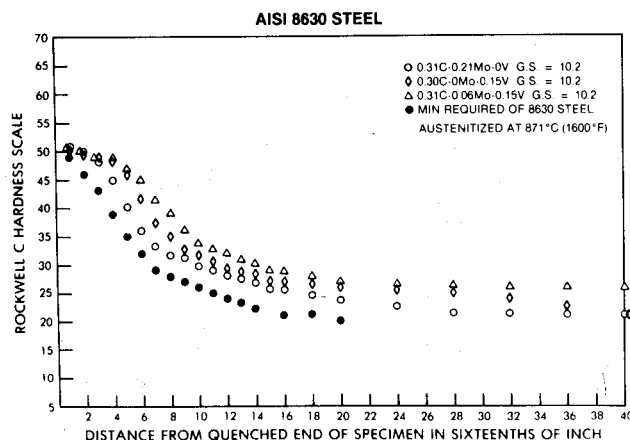


Figure 10. Hardenability data of AISI 8630 steels austenitized at 1600°F (871°C).

For the 8640, Figure 12a indicates the hardenability of the 0.15%V to be substantially lower, and the hardenability of the 0.10%V to be only slightly lower than the standard grade. At the higher austenitizing temperature, Figure 12b shows the hardenabilities of both vanadium alloys to be essentially the same and to exceed those of the standard grade. As in the 0.30%C steels, the hardenability and austenite grain size of the standard grade remained constant from the lower to the higher austenitizing temperature. The vanadium-modified steels exhibited the usual grain size coarsening. In the case of the 0.15%V 8640 steel, the increase in hardenability when austenitized at 1650°F is probably due to both the increase in vanadium in solution and the increase in grain size.

Commercial Application

Independent of the results of the laboratory work presented here, Bertolo et al.¹² succeeded in developing a cost effective Ni-Cr-V steel which is currently being used commercially in an automotive part. The properties of this steel in the carburized and forged conditions approached those of higher nickel grades. It is significant that these properties were obtained with no special heat treatment, i.e., higher temperature austenitization, given the vanadium steel. While not mentioned in this paper, their results substantiate the 1:2 substitution of vanadium for molybdenum which was found in this study.

CONCLUSIONS

Modifications of alloy steels with 0.10-0.15%V additions, singly or in combination with Mo, yield equivalent or better hardenabilities than the standard Mo-containing alloy steel grades. Using the parlance of HSLA steels, this vanadium microalloying replaces twice as much of the Mo. When added singly, a higher austenitizing temperature may be needed to attain the equivalent hardenability, depending on the carbon content. In this study, it was shown for all the grades studied that a temperature 100°F (56°C) higher than the standard austenitizing temperature is more than sufficient to attain the desired result for the 0.30%C and 0.40%C steels. It is entirely possible that the SAE recommended 50°F (30°C) higher austenitizing temperature might be sufficient. At any rate, extraordinarily high temperatures are not necessary for the vanadium to be effective in these medium carbon steels, as might have previously been thought.⁴ In fact, when combined with Mo, the higher temperature treatment need not be used.

With the exception of the 0.15%V addition in the 0.40%C steel, it appears that all the vanadium is in solution at the standard austenitizing temperatures. The higher austenitizing temperatures induce austenite grain coarsening in the vanadium steels to increase hardenability. In contrast, the molybdenum steels, except for the 8615 grade, retained their grain sizes at the higher temperature. Depending on the application, vanadium alone or a combination of vanadium and molybdenum might be used. Because of the favorable interaction between vanadium and molybdenum, it may be desirable to take advantage of the influence of both elements. It appears that the steel containing 0.10%V and 0.10%Mo will attain or exceed the hardenability of a 0.30% Mo steel.

ACKNOWLEDGMENT

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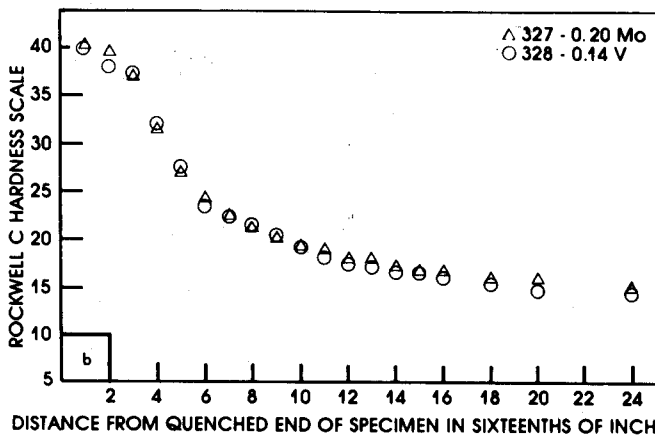
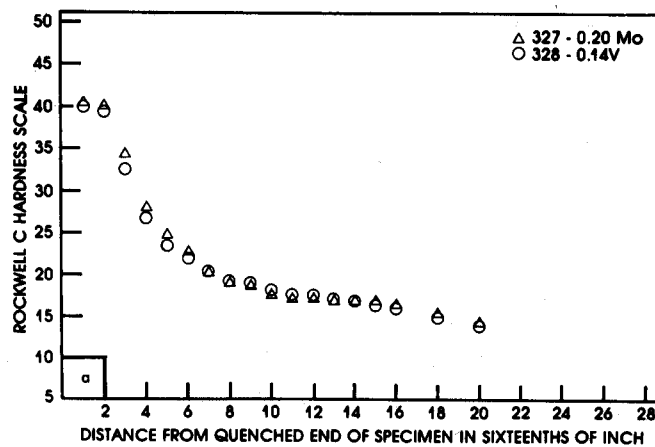


Figure 11. Hardenability data of 8615 steels austenitized at (a) 1700°F (927°C) and (b) 1800°F (982°C).

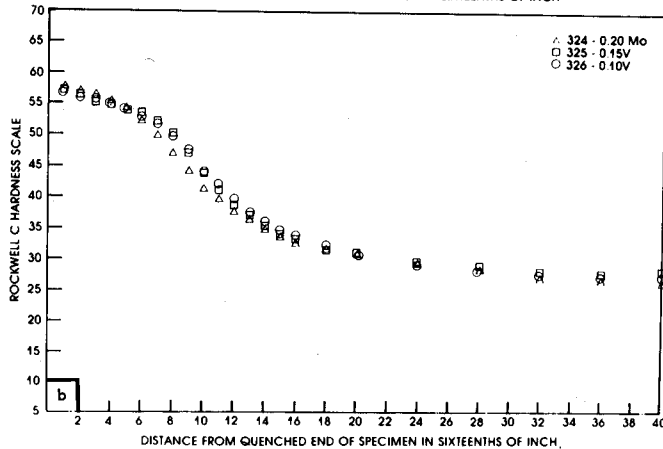
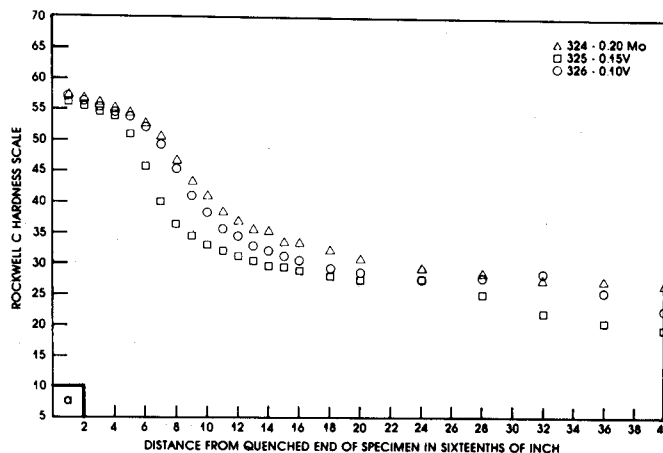


Figure 12. Hardenability data of 8640 steels austenitized at (a) 1550°F (843°C) and (b) 1650°F (899°C).

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