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DEVELOPMENT OF MICROALLOYED MEDIUM CARBON HOT ROLLED BAR PRODUCTS

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The application of microalloying technology in the production of bar products was initially employed by Jones & Laughlin Steel for cold finished bars. These products are available in a variety of grades with guaranteed strength levels. More recently, hot rolled microalloyed bar steels have found acceptance in a number of applications spanning products with high strength properties produced directly from the bar stock, to air cooled forgings which do not require heat treatment. As is the case for cold finished bars, microalloyed hot rolled bars can be produced with guaranteed strength properties. These properties are a function of the base composition, the type and amount of microalloying addition, the bar diameter and thermal practice. This paper will address each of these factors and describe several commercial applications involving the production of forged parts from microalloyed bar steels.

THE APPLICATION OF MICROALLOYING technology for enhancement of strength properties in bar steels has been practiced for a considerable period of time. Examples of various applications are hot rolled bars having guaranteed strength properties,[1,2] bar stock for production of air cooled forgings which have guaranteed properties without the need for costly heat treatment,[3-7] and also rough stock for the production of high strength cold finished bars.[7-9]

The specific properties that can be obtained in microalloyed bar steels are known to be a function of the base chemistry plus the added effects of the type and amount of microalloying addition.[10-12] It is recognized that the properties of the microalloyed bars are further influenced by thermal conditions such as the rolling or finishing temperature,[13] and also to some extent by the cooling rate of the bar.[9,12]

In order to more fully define the relative effects of composition, a number of laboratory bar heats were produced and tested. These heats contained carbon contents of 0.24%, 0.30% and 0.36%. For each carbon level, the manganese content was varied from 1.35% to 0.65%. Within each base composition vanadium contents from 0 to 0.20% were examined, in some cases with a columbium addition of 0.03%, and in some cases with a nitrogen addition of 0.015%. The steels were hot rolled on a labooratory bar mill to 1.7 inch x 1.7 inch squares with a finishing temperature of 1830/1840°F. The materials were evaluated on the basis of tensile properties, hardness and impact strength over a range of temperatures.

TENSILE PROPERTIES - Tensile properties for the hot rolled steels are shown as a function of vanadium content in Figures 1-4. The additional effect of base carbon content on tensile properties is also shown in Figures 1-3, each of which represents a discreet manganese level, while the effect of varying manganese content is shown in Figure 4 at a fixed carbon level. In all cases, both yield and tensile strength increase linearly with increasing vanadium, while both total elongation and reduction in area decrease linearly. Both yield strength and tensile strength increase at a rate of ∿1300-2150 psi per 0.01% vanadium for the composition ranges examined. With a given vanadium level the effect of raising the carbon content from 0.24% to 0.36% is to increase yield strength by ∿900 psi per 0.01% carbon, and to increase tensile strength by ∿1665 psi per 0.01% carbon. The relative effect of manganese variations between 0.35% and 0.65% changes with the vanadium content as illustrated in Figure 4. For example, at the 0.10% vanadium level, the relative effect of manganese is to increase yield strength by ∿135 psi and tensile strength by ∿365 psi per 0.01% manganese. However, at the 0.20% vanadium level yield strength is increased by ∿300 psi and tensile strength by ∿665 psi per 0.01% manganese.

The relative effects of vanadium, carbon and manganese additions on yield and tensile strength are summarized in Table I. In this table the smallest observed effect, that of an addition of 0.01% manganese on yield strength, is given a ranking of 1.0. For a similar addition, carbon will produce a four-fold increase in yield strength, but vanadium will produce an eight-fold increase in yield strength. It also indicated that an addition of 0.01% manganese will increase tensile strength more so than yield strength but that a similar addition of either carbon or vanadium will produce a three-fold increase in tensile strength. Both manganese and carbon additions have a greater effect on tensile strength than upon yield strength, but microalloying with vanadium has approximately the same effect on yield and tensile strength.

Additional heats containing 0.36% C and 1.50% Mn were produced to establish the combined effects of vanadium plus columbium, and vanadium plus nitrogen. Although either combination influenced yield and tensile strength above the levels achieved by vanadium alone, the effects appeared to be different at various levels of vanadium as shown in Table II. For example, optimum strengthening was achieved by either combination at the 0.10% vanadium level, with the nitrogen effect being somewhat larger than that of columbium on yield strength. At the 0.20% vanadium level, negligible additional strengthening was obtained by either combined microalloying combination.

HARDNESS - Brinell hardness readings were taken at mid-radius positions on all hot rolled materials, and are shown in Figures 5-8. As expected, the effects of vanadium, carbon and manganese additions are similar to those shown previously for tensile strength. The relationship between hardness and vanadium content is essentially linear, and both vanadium and carbon contents influence hardness to a greater extent than does a similar variation in manganese.

The relative effects of the three elements on Brinell hardness can be evaluated on the basis of the hardness increment due to a 0.01% addition, similar to that shown in Table I for tensile properties. On this basis, an addition of 0.01% vanadium will increase hardness by 3.2/4.7 BHN points, and an addition of 0.01% carbon will likewise increase hardness by 3.1/4.6 BHN points. In contrast, the addition of 0.01% manganese will only increase hardness by 0.6 BHN points.

The combined effects of vanadium plus columbium and vanadium plus nitrogen on hardness are shown in Table III. As was the case with tensile properties, a greater hardness increase resulting from combined additions occurs at the 0.10% vanadium level than occurs at the 0.20% vanadium level. In fact, at the 0.20% vanadium level there was no increase in hardness after an addition of 0.015% nitrogen, just as there was little effect on tensile properties.

IMPACT PROPERTIES - Although significantly improved strength and hardness can be achieved through microalloying, one property that is known to be adversely affected is toughness.[5,12] In order to characterize the magnitude of this effect, full size Charpy V-Notch tests were performed at various temperatures. Data illustrating the effect of vanadium content on impact strength of 0.30% carbon, 1.50% manganese hot rolled steel are shown in Figure 9. This figure shows quite clearly that shelf energy decreases significantly with increasing vanadium additions, together with an increase in the ductile-brittle transition temperature. An exception to this behavior, not quite fully understood, is that room temperature toughness appears to increase slightly with 0.05% vanadium but not for larger vanadium additions.

At a fixed vanadium level, impact strength is primarily influenced by the carbon content of the steel as illustrated in Figure 10. For all temperatures above -20°F, improved toughness can be achieved in vanadium microalloyed steels having low rather than higher carbon contents, although the improvement will be at the expense of lower strength and hardness.

The effect of vanadium additions up to 0.20% on the fracture appearance transition temperature (F.A.T.T.) is shown in Figures 11-13 for steels of various carbon contents. Whereas strength and hardness properties varied linearly with vanadium content, the F.A.T.T. appears to be relatively unaffected by vanadium additions up to 0.05%. In fact, in some instances it appears that the transition temperature may be somewhat lowered with a vanadium addition of 0.05%. Above 0.10% vanadium, the F.A.T.T. appears to increase more or less linearly with increasing vanadium contents.

Figure 14 depicts the effect of manganese variations on the F.A.T.T. of 0.30% carbon steels as a function of vanadium content. The figure shows that higher manganese contents raise the F.A.T.T., but that the observed effects are smaller than those for similar variations in carbon content, or for vanadium additions larger than 0.10%.

As was done previously for strength and hardness, the relative effects of a 0.01% addition of vanadium, carbon or manganese on F.A.T.T. can be compared as follows. For vanadium contents between 0.10% and 0.20%, the transition temperature is increased by 11-15°F per 0.01% vanadium. For all vanadium contents, the F.A.T.T. is increased by 6-11°F per 0.01% carbon. Finally, the effect of manganese variations is to increase F.A.T.T. but only by 1-2°F per 0.01% manganese.

A rather dramatic illustration of the effects of not only vanadium but also carbon content on room temperature toughness is shown in Figure 15. This figure is for 1.50% manganese steels and shows a distinct drop in toughness for vanadium additions exceeding 0.05%. The magnitude of the drop is greater in the lower carbon steels, primarily because these steels have higher room temperature impact toughness in the non-microalloyed condition. The drop in impact energy in higher carbon steel is less noticeable because its room temperature toughness in the non-microalloyed condition is not as high to begin with.

The effects of columbium and nitrogen additions in combination with vanadium on impact properties are shown in Table IV. As seen previously for strength and hardness, the F.A.T.T. is affected to a greater extent at the 0.10% vanadium level than at the 0.20% vanadium level. In fact, at 0.20% vanadium, the F.A.T.T. is slightly reduced with additions of either columbium or nitrogen, while either addition raises F.A.T.T. at the 0.10% vanadium level. Room temperature toughness is relatively unaffected by combined microalloying except at lower vanadium levels where 0.03% columbium produced a higher toughness value in spite of its higher transition temperature.

EFFECT OF THERMAL PRACTICE - Laboratory rolling experiments were conducted to examine the effects of finishing temperature and bar cooling rate variations on properties of vanadium microalloyed steels. The steels used for this purpose contained 0.36% carbon and 0.75% manganese, and were microalloyed with vanadium additions from 0.15% to 0.25%. Each heat was rolled to an 1-1/8 inch diameter round bar in 10 passes from a 4-inch square cast ingot. After the sixth rolling pass a section was cut off and placed back into the reheat furnace. The finishing temperature of the direct rolled section was ∿1600°F, while the reheated section finished at ∿1800°F. After rolling, one end of each bar was cooled in still air while the other end was cooled in a forced air blast to approximately 1000°F. The bars were evaluated on the basis of tensile properties and hardness, as well as room temperature Charpy V-Notch impact tests. As shown in Figure 16, both yield and tensile strengths were increased approximately 10 ksi in the steels finished at the higher temperature. Although not shown in this figure, forced air cooling of the 1600°F steels had approximately the same effect as did finishing at 1800°F, i.e., both yield strength and tensile strength increased by ∿10 ksi. A similar 10 ksi increase in strength occurred from forced air cooling the steels which finished at 1800°F.

Previous investigations have shown that finishing temperature can influence not only strength but also impact transition temperatures of hot rolled microalloyed steels.[13] This was particularly true for low carbon grades microalloyed with columbium versus vanadium. Our investigation supports this behavior in medium carbon levels as indicated in the lower portion of Figure 16. In this instance the use of 1600°F finishing temperature increased room temperature toughness by a factor of 4 over that of steel finished at 1800°F. The significance of this observation is to point out the necessity of insuring that laboratory rolling simulations indeed reproduce actual mill rolling conditions if meaningful data are to be obtained.

The effect of cooling rate is also evidenced by the variation of yield and tensile strength for hot rolled bars of various diameters as illustrated in Figure 17. Although all bars were cooled by natural convection, the strength of the smaller size bars which cool at a faster rate is increased in comparison with that of larger size bars.

FORGED PARTS - Because of the improved strength and hardness in microalloyed bar steels, it is possible to utilize them for production of many forged parts and eliminate the need for subsequent heat treatment. This is particularly true when air cooling is applied to the as-forged parts. Numerous forgings weighing as little as 3 to well over 25 pounds have been produced by this approach with acceptable results in all cases.[7] The type of parts produced from microalloyed steel includes connecting rods and caps, stub yokes, weld yokes, wheel hubs, stabilizer bars, blower shafts, sucker rods, anchor bolts and U-bolts.

An interesting example of improved properties that can be obtained is indicated in Figure 18, where the cross-sectional hardness of an air cooled microalloyed Grade 1541 forged part is compared with a similar quench and tempered Grade 1043 part. The hardness is much more uniform in the microalloyed part, and as a result the fatigue life at this location in the part was five to six times greater than in the Q&T part.

Another example which illustrates the ability of air cooled microalloyed steel to eliminate heat treatment of forged parts is shown in Figure 19. In this instance, the required hardness of Rc 21 near the I.D. surface of the hole running from top to bottom could not be met using Grade 1541 unless a heat treatment was used. With the correct microalloyed composition, the required hardness was readily achieved in the air cooled condition, and the time and expense of heat treatment was eliminated.

IN SUMMARY, higher strength and hardness can be achieved in hot rolled bar steels by the technique of microalloying. The precise strength is a function of the base chemistry, microalloy additions, and thermal practice. This approach can be utilized to produce hot rolled bars with guaranteed strength and hardness properties. While impact strength is generally reduced in microalloyed steel, adequate toughness can be achieved by selecting the best combination of carbon content and microalloying addition. Microalloyed hot rolled bars can be used to produce numerous air-cooled forgings which have acceptable properties without the need for heat treatment. Because of uniform cross-sectional hardness, the air-cooled microalloyed forgings can have superior fatigue properties.

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TABLE I

RANKING OF MICROALLOYING ADDITIONS (0.01%) RELATIVE TO THE EFFECT OF MANGANESE ON YIELD STRENGTH

	RELATIVE EFFECT OF 0.01% ELEMENT		
PROPERTY	MANGANESE	CARBON	VANADIUM
YIELD STRENGTH	1.0	4.1	8.3
TENSILE STRENGTH	2.3	7.5	7.4

TABLE II

COMBINED EFFECTS OF VANADIUM PLUS COLUMBIUM, AND VANADIUM PLUS NITROGEN ON TENSILE PROPERTIES OF 0.36% C, 1.50% MANGANESE STEEL

	0.10% VANADIUM			0.20% VANADIUM		
PROPERTY	BASE	0.03% Cb	0.015% N_2	BASE	0.03% Cb	0.015% N_2
Y.S. (KSI)	78	83.5	86	96	98	97.7
U.T.S. (KSI)	117	120	120	134	135.5	130.8
R.A. (%)	53.5	45.3	48.0	36.0	37.2	30.0
TOTAL ELONGATION (%)	21.8	19.5	21.0	16.8	17.3	16.5

TABLE III

COMBINED EFFECTS OF VANADIUM PLUS COLUMBIUM, AND VANADIUM PLUS NITROGEN ON BRINELL HARDNESS OF 0.36% C, 1.50% Mn STEEL

	0.10% VANADIUM			0.20% VANADIUM		
PROPERTY	BASE	0.03% Cb	0.015% N_2	BASE	0.03% Cb	0.015% N_2
HARNDESS (BHN)	235	248	248	277	285	277

TABLE IV

COMBINED EFFECTS OF VANADIUM PLUS COLUMBIUM, AND VANADIUM PLUS NITROGEN ON IMPACT PROPERTIES OF 0.36% CARBON, 1.50% MANAGANESE STEEL

	0.10% VANADIUM			0.20% VANADIUM		
PROPERTY	BASE	0.03% Cb	0.015% N_2	BASE	0.03% Cb	0.015% N_2
F.A.T.T., °F	162	210	235	300	292	265
80°F, C.V.N., FT. LBS	7	10	6	4	4	4

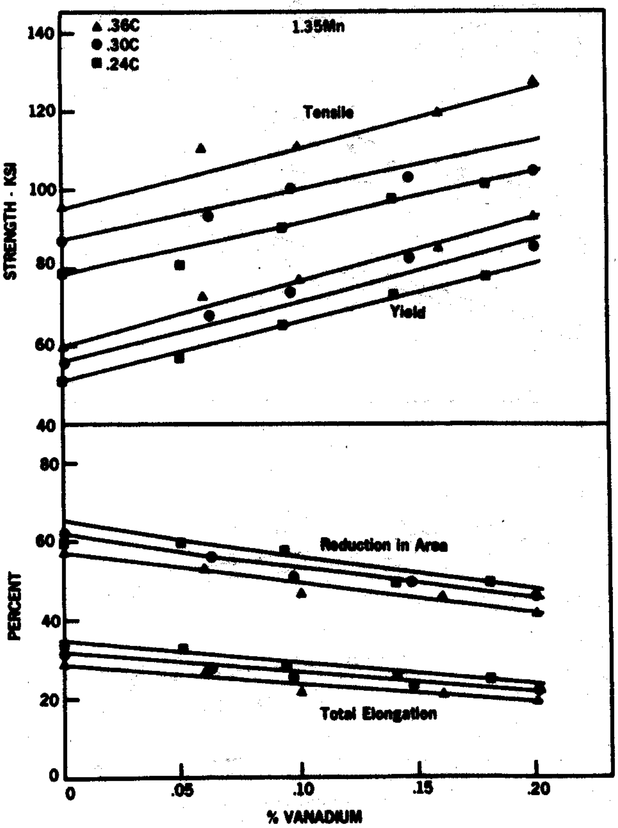


Fig. 1 - Tensile properties of hot rolled microalloyed laboratory bar steels containing 1.35% Mn as a function of carbon and vanadium content.

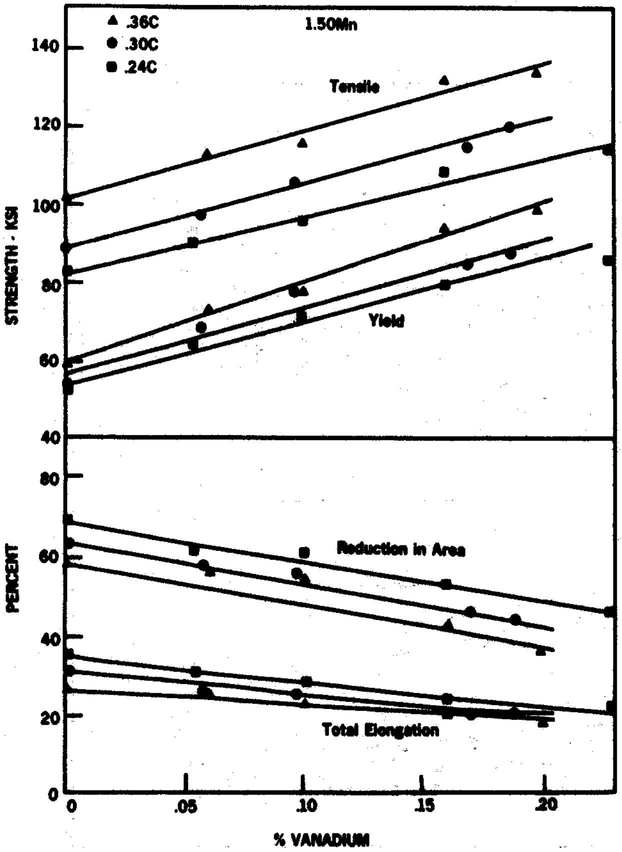


Fig. 2 - Tensile properties of hot rolled microalloyed laboratory bar steels containing 1.50% Mn as a function of carbon and vanadium content.

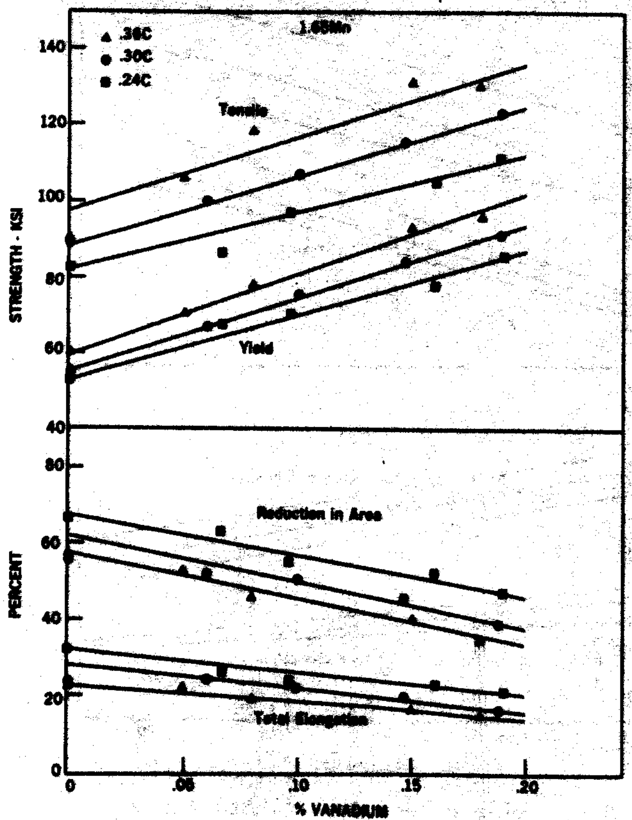


Fig. 3 - Tensile properties of hot rolled microalloyed laboratory bar steels containing 1.65% Mn as a function of carbon and vanadium content.

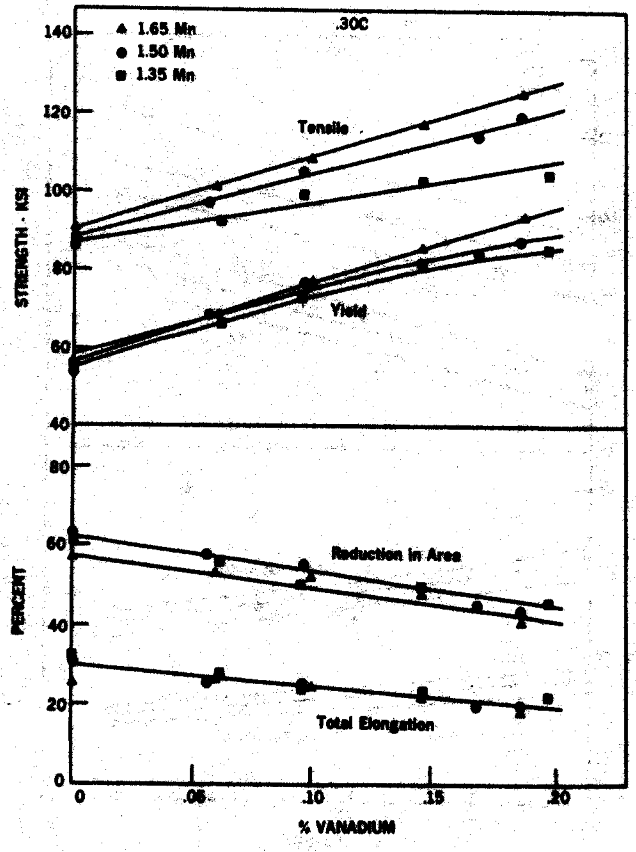


Fig. 4 - Tensile properties of hot rolled microalloyed laboratory bar steels containing 0.30% C as a function of manganese and vanadium content.

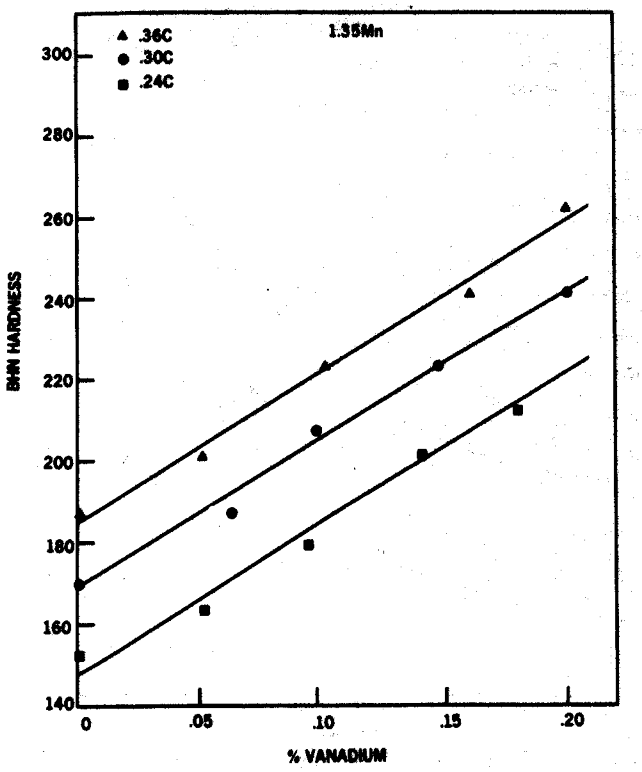


Fig. 5 - Brinell hardness of hot rolled microalloyed laboratory bar steels containing 1.35% Mn as a function of carbon and vanadium content.

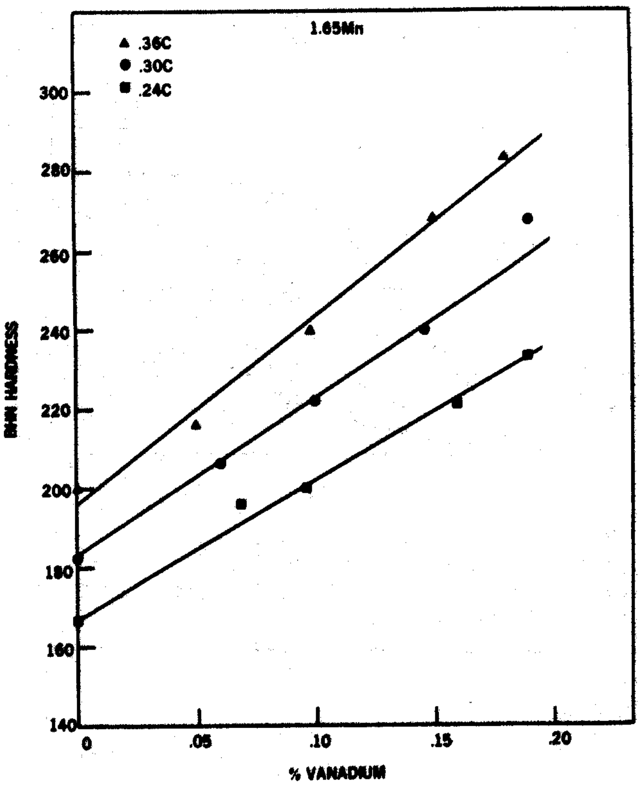


Fig. 7 - Brinell hardness of hot rolled microalloyed bar steels containing 1.65% Mn as a function of carbon and vanadium content.

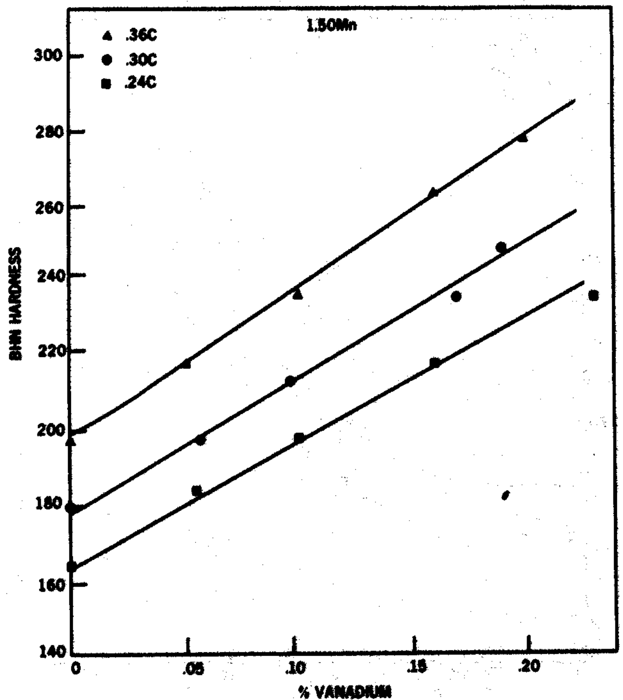


Fig. 6 - Brinell hardness of hot rolled microalloyed laboratory bar steels containing 1.50% Mn as a function of carbon and vanadium content.

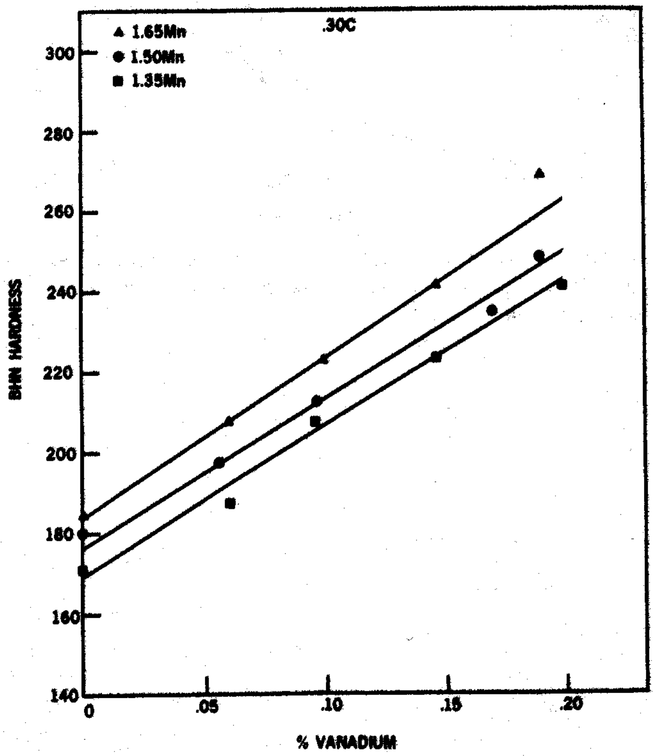


Fig. 8 - Brinell hardness of hot rolled microalloyed laboratory bar steels containing 0.30% carbon as a function of manganese and vanadium content.

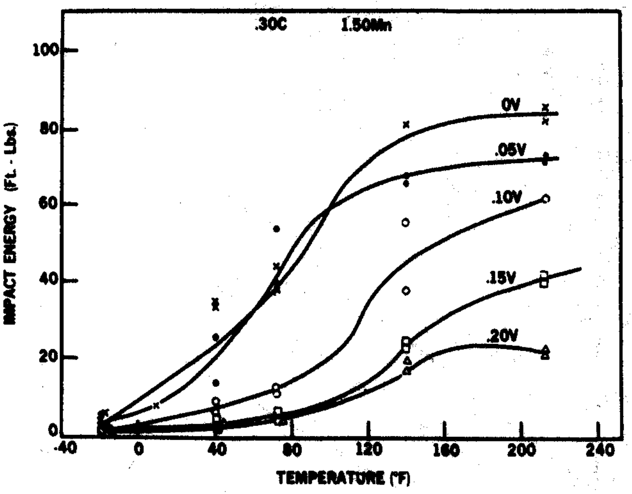


Fig. 9 - Effect of vanadium on toughness of hot rolled microalloyed laboratory bar steels at various temperatures. The steels contained 0.30% carbon and 1.50% manganese.

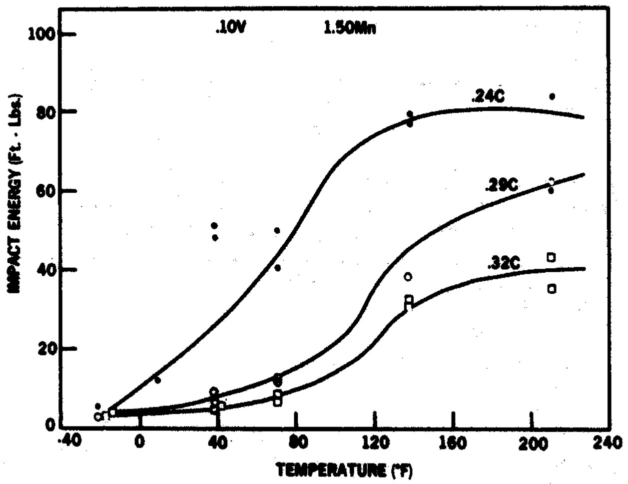


Fig. 10 - Effect of carbon content on toughness of 0.10% vanadium, 1.50% manganese hot rolled laboratory bar steels.

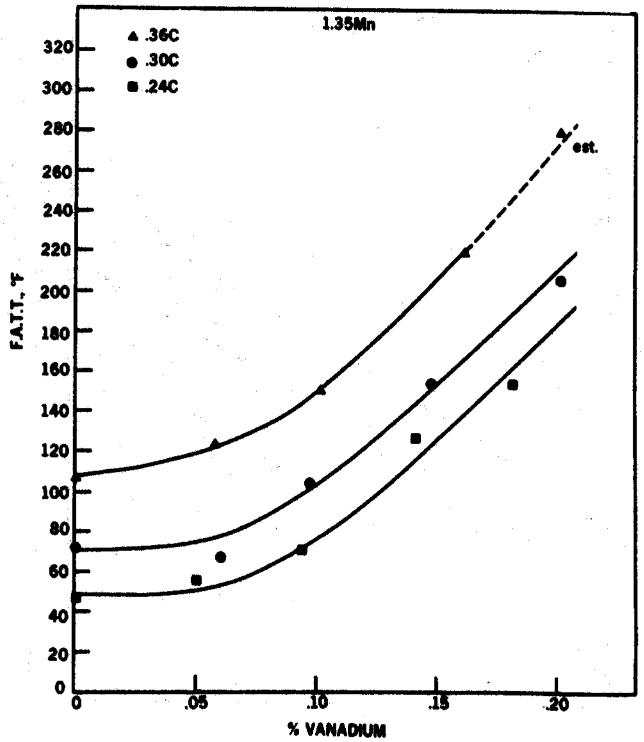


Fig. 11 - Fracture appearance transition temperature of hot rolled microalloyed laboratory bar steels containing 1.35% manganese as a function of carbon and vanadium content.

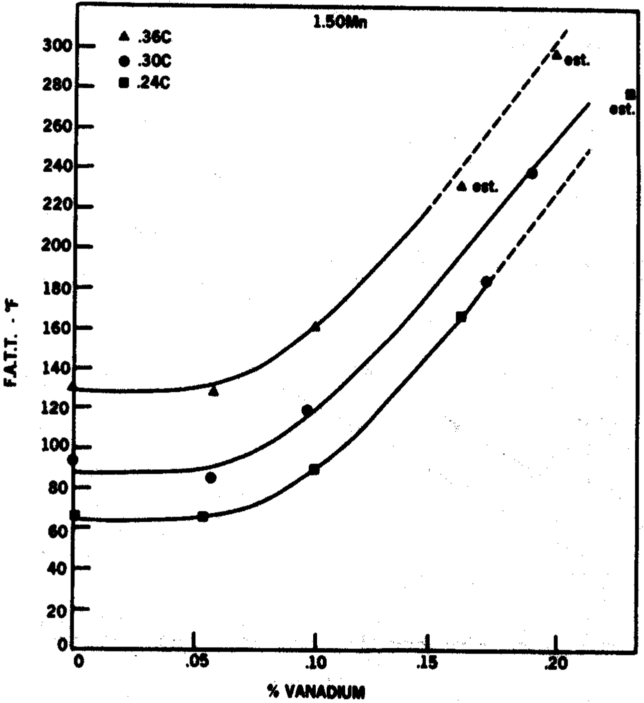


Fig. 12 - Fracture appearance transition temperature of hot rolled microalloyed laboratory bar steels containing 1.50% manganese as a function of carbon and vanadium content.

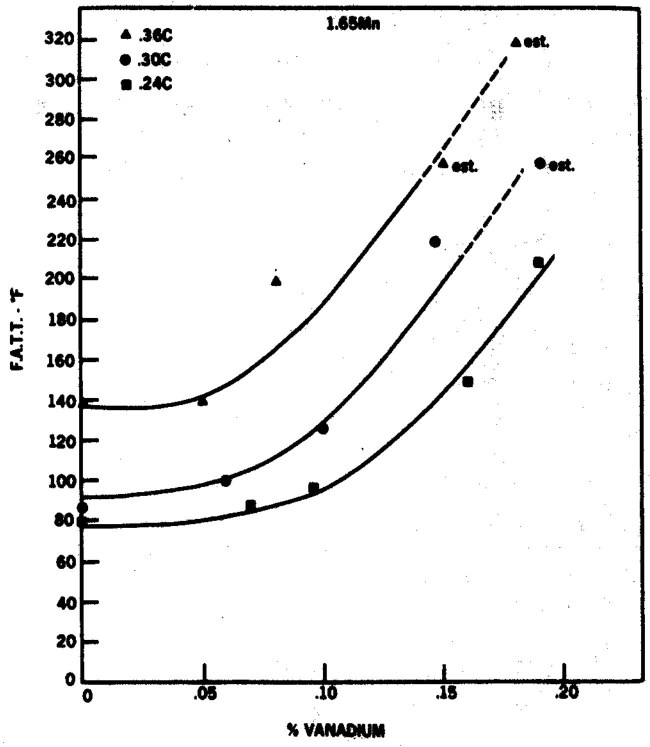


Fig. 13 - Fracture appearance transition temperature of hot rolled microalloyed laboratory bar steels containing 1.65% manganese as a function of carbon and vanadium content.

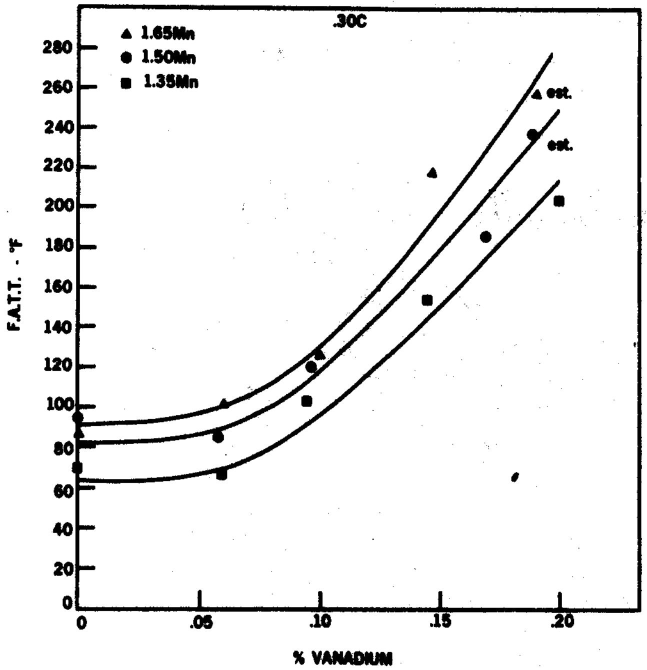


Fig. 14 - Fracture appearance transition temperature of hot rolled microalloyed laboratory bar steels containing 0.30% carbon as a function of manganese and vanadium content.

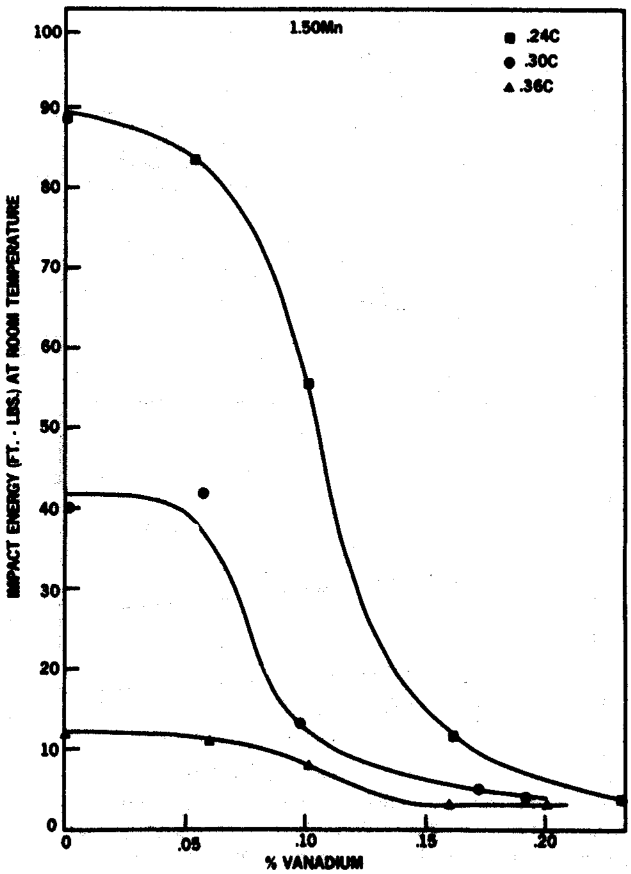


Fig. 15 - Effect of carbon and vanadium content on room temperature toughness of hot rolled laboratory bar steels containing 1.50% manganese.

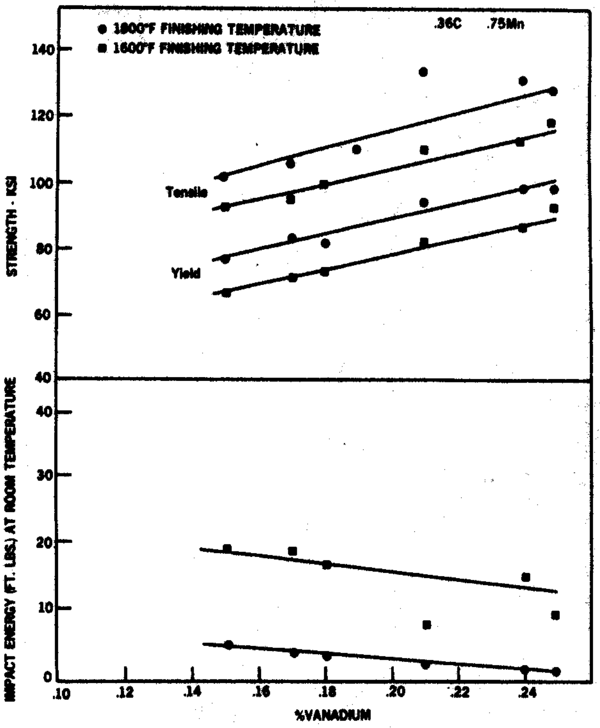


Fig. 16 - Effect of hot mill finishing temperature on strength and toughness of 0.36% carbon, 0.75% manganese laboratory bar steels as a function of vanadium content.

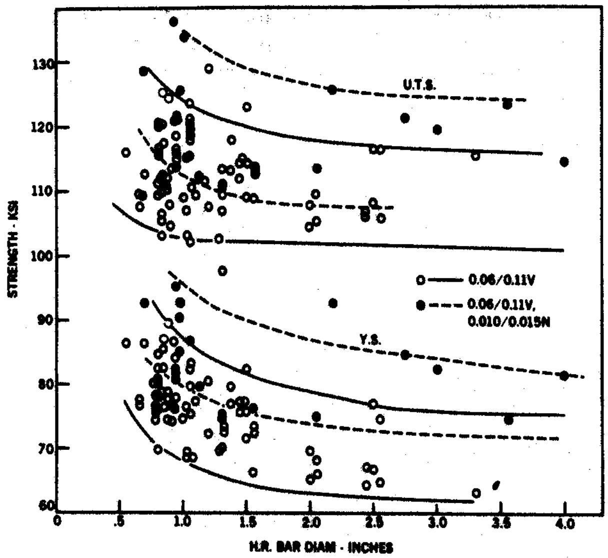
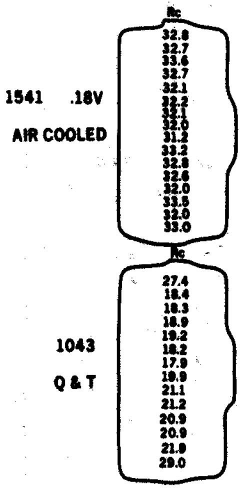


Fig. 17 - Yield and tensile strength of hot rolled microalloyed Grade 1144 bars of various diameters.



FATIGUE TEST RESULTS

STRESS, KSI	CYCLES TO FAILURE
75	219,700
80	113,200
75	29,100
80	18,400

Fig. 18 - Better uniformity of hardness and higher fatigue strength can be achieved in air cooled microalloyed forgings compared with quench and tempered standard grades.

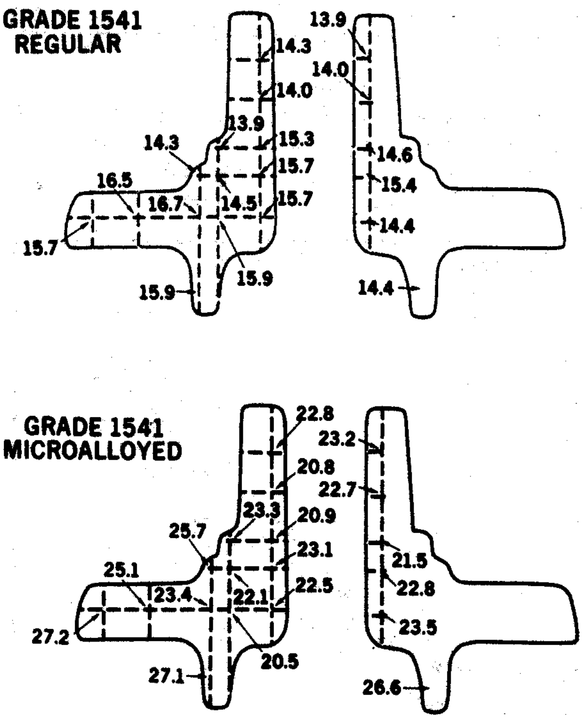


Fig. 19 - Increased hardness in air cooled forgings produced from microalloyed steel permits elimination of heat treatment of the standard grade.