NIOBIUM IN ENGINEERING BAR STEELS

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Introduction

For purposes of this paper, "engineering bars" will be defined as special quality hot rolled bars and cold finished bars. Special quality hot rolled bars are bars intended for specific end application or fabricating method, e.g. cold forming or hot forging. Cold finished bars are hot rolled bars that have been specially processed (drawn, turned, swaged or rolled) to improve surface finish, straightness, tolerances and to enhance machinability and mechanical properties.

Table I includes some additional definitions that are necessary for this paper. Niobium microalloyed steel bars include low-C, medium-C and high C, plain-C and free machining steels but not alloy or stainless steels which may be modified by the addition of .02 to .05 percent Nb. The term microalloyed is used in part because HSLA steels are sometimes considered to be low carbon steels whereas a significant percentage of the bar steels of interest are medium carbon steels.

Typical applications for engineering bars are given in Table II based upon the type of industry: vehicular, aerospace and petroleum. This listing is intended to be descriptive but not exhaustive. Clearly, other applications, such as in structures, also exist. Those applications listed are reflective of the areas of most intense recent activity.

High-strength-low-alloy bar grades guaranteed to 345 MPa (50 ksi) and 414 MPa (60 ksi) minimum yield strength have been available for many years in the form of various proprietary grades. These, in most cases, are very similar to the comparable grades sold by the respective steel company in the flat rolled condition. These steels will not be discussed in any detail. Rather, recent achievement of yield strengths in hot rolled bars up to 689 MPa (100 ksi) and in cold finished bars up to 1035 MPa (150 ksi) will be treated at length including examples of applications. Also, the elimination of the need for the heat treatment of forgings can be achieved in some applications by the use of microalloyed steels. Significant cost reductions and energy savings have been realized by this approach in the automotive industry. A survey of the literature (1-14) is appended as a sample of the papers most appropriate to the topics at hand.

Table I. Types of Steel

Low Carbon Steels:	AISI 1005 - 1026
Medium Carbon Steels:	AISI 1029 - 1053
High Carbon Steels:	AISI 1055 - 1095
Free Machining Steels:	One or more additive (such as S or Pb) has been made to greatly enhance machinability
Alloy Steels:	Certain elements are added in amounts greater than specified levels, e.g. Mn greater than 1.65%
High Strength Low Alloys Steels:	Low carbon steels containing small amounts of niobium, vanadium, copper and other alloying elements

Table II. Typical Applications for Engineering Bars

Automotive, Railroad, Heavy Equipment, Farming Vehicles	Connecting rods, crankshafts, shafts, bolts, cams, gears, axles, universal joints, bearings, steering components, levers
Aerospace	Landing gear, missile bulkheads, pantry cranes, engine mounts, propellers
Petroleum	Drill heads, drill frames, sucker rods, valves, shafts, collars

Strengthening of Hot Rolled Bars by Niobium

Figure 1 (8) shows the increase in yield strength achieved by the addition of .05 percent Nb to plain-C steels as a function of C-content for air cooled, 1-1/8" diameter hot rolled bars. The increase in strength is seen to be most significant in the lower carbon range but persists to even very high levels of carbon.

Considering this low carbon domain at some length by reference to Tables III and IV. It is seen that the yield strength is increased by approximately 96 MPa (14 ksi), the tensile strength by 62 MPa (9 ksi), and the hardness by 9 pts. R_b by the addition of 0.05 percent niobium. In this carbon range, niobium is seen to be roughly twice as effective as vanadium in increasing the strength. However, as is well-known, the effect of niobium reaches its peak at about this level (12) except for very low carbon steels. Therefore, the combination of niobium and vanadium is a very cost effective means of achieving the best combination of properties. Note the superiority of the total elongation and reduction in area values of Nb+V vs V+N steels. Also, these data illustrate the beneficial effect of manganese (~ .75% in AISI

Table III. Tensile Properties and Hardness for 5/8" (15.9 mm) Hot Rolled Bars (10).

Material	Tensile Properties: Yield Strength ksi	Yield Strength MPa	Ultimate Tensile Strength ksi	Ultimate Tensile Strength MPa	Total Elongation, %	Reduction of Area, %	Hardness No. (R_b)
1022	43.6	301	66.6	459	43.0	64.2	72
1022 + 0.05% Cb	59.1	408	76.7	529	36.7	59.7	84
1022 + 0.05% V	51.3	354	71.9	496	37.2	61.5	79
1022 + 0.10% V	56.3	388	76.1	525	38.5	64.3	81
1022 + 0.15% V	62.7	432	82.9	572	34.5	62.5	87
1022 + 0.15% V + 0.015% N	73.5	507	93.0	641	31.7	59.9	91
1022 + 0.10% V + 0.05% Cb	67.5	465	86.6	597	33.2	59.7	87
1522	53.4	368	80.2	553	38.0	64.3	82
1522 + 0.05% Cb	67.8	468	90.7	625	34.2	62.9	90
1522 + 0.05% V	59.9	413	81.9	565	37.5	67.8	85
1522 + 0.10% V	68.4	472	88.5	610	36.0	66.6	91
1522 + 0.15% V	02.8	571	106.1	732	29.7	60.5	98
1522 + 0.15% V + 0.015% N	85.6	590	108.8	750	28.0	53.4	99
1522 + 0.10% V + 0.05% Cb	81.0	559	106.6	735	30.2	63.1	98

Table IV. Tensile Properties *and* Hardness for 1-1/8" (28.6 mm) Hote Rolled Bars (10).

Material	Tensile Properties: Yield Strength kri	Yield Strength MPa	Ultimate Tensile Strength ksi	Ultimate Tensile Strength MPa	Total Elongation, %	Reduction of Area, %	Hardness No. (R_b)
1022	42.6	294	62.5	431	35.2	62.2	70
1022 + 0.05% Cb	55.7	384	70.5	486	33.5	62.1	78
1022 + 0.05% V	46.2	319	66.3	457	33.7	62.0	74
1022 + 0.10% V	50.2	346	68.4	472	31.2	60.9	78
1022 + 0.15% V	54.1	373	73.9	510	30.2	60.3	82
1022 + 0.15% V + 0.015% N	63.0	434	82.8	571	27.2	58.3	87
1022 + 0.10% V + 0.05% Cb	61.3	423	76.5	528	31.2	62.2	84
1522	52.6	363	77.1	532	31.7	67.3	80
1522 + 0.05% Cb	64.2	443	82.3	568	30.7	66.1	86
1522 + 0.05% V	56.0	386	77.0	531	32.0	66.1	82
1522 + 0.10% V	61.9	427	81.2	560	29.2	64.4	85
1522 + 0.15% V	71.3	492	89.8	619	25.5	59.4	92
1522 + 0.15% V + 0.015% N	77.9	537	97.6	673	25.5	60.8	94
1522 + 0.10% V + 0.05% Cb	73.7	508	88.3	609	28.0	64.1	91

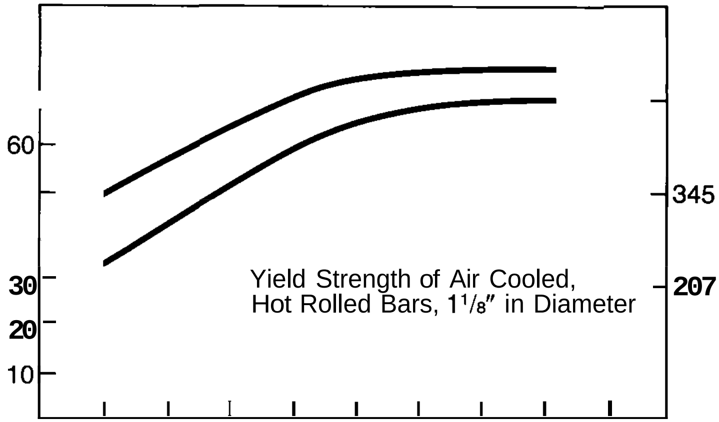


Figure 1. Effect of .05% Nb on the yield strength of plain carbon steels.

1022,– 1.4% in AISI 1522) on strength with no strong effect on ductility, e.g. 62 MPa (9 ksi) increase in yield strength. Furthermore, the faster cooling rate of the air cooled 5/8" bars vs. the air cooled 1-1/8" bars results in the former being slightly stronger for a given composition illustrating the necessity to adjust composition for processing or subsequent use, e.g. particularly for hot forging applications.

Table V was constructed utilizing data available in the literature (7, 8, 10, 12–14). The carbon and manganese contents of the base grades were increased with a view to obtaining the optimum in the strength–ductility balance. Moreover, minimization of C-content and increase in manganese (to a certain level) is known to be beneficial for optimization of toughness at a given strength level, e.g. a chemical composition richer in C (.36/44%) or Mn (1.35/1.65%) than AISI 1541 is generally avoided for many appications. Figure 2 (14) schematically shows the relationship between ductility and strength for hot rolled AISI 1541-grade bars in which the strength has been varied by microalloying the base composition with Nb and V. Particular microalloying additions with the exception of nitrogen (which has a detremental affect) do not significantly affect this trend.

Fatigue and Toughness of Microalloyed Bar Steels

Figure 3 (7) presents rotating beam fatigue data for (Nb+V) modified steels. The endurance limit to tensile strength ratio is approximately .60 which is typical of that observed by others for microalloyed bar steels (8, 10, 14) and for quenched and tempered steels. It has been further observed (7) that these steels cyclically soften at low strains and cyclically harden at high strains. Therefore, one can use the tensile properties as a guide to anticipate fatigue performance for these steels in the same fashion as is typically done.

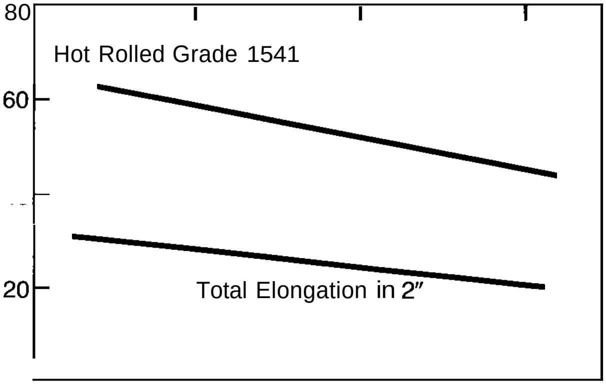


Figure 2. Effect of yield strength on ductility for microalloyed bar steels.

C	Mn	P	S	Si	Al	Nb + V
0.26 max.	1.65 rnax.	0.04 max.	0.05 max.	0.35 max.	0.06 max.	0.10 min

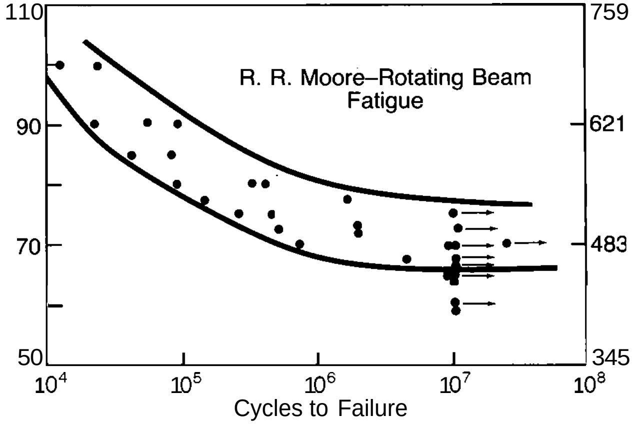


Figure 3. Fatigue data for 80 ksi (552 MPa) minimum yield strength Nb + V steels.

Figure 4 (10) shows that the impact properties as measured in the Charpy V-notch test are essentially unchanged even though the strength has been increased significantly by the addition of microalloying elements. This is because the main effect of microalloying is structural refinement. Figure 5 *(14)* shows that for AISI **1022** the yield strength obeys a typical Hall-Petch relationship for the microalloyed steels exclusive of the vanadium nitrogen steel for which the deviation from the straight line is indicative of - **34.5** MPa (5 ksi) additional precipitation strengthening. The slight elevation of the line over the data point for the control steel presumably is indicative of very slight precipitation strengthening.

Applications

Miscellaneous Hot Rolled Bars

Republic Steel Corporation *(7, 13)* has reported on the use of **552** MPa *(80* ksi) flat bars for the flange material for truck-trailer I-beams and floor cross-members. Similarly, this product is being used for forks in fork lift equipment and as side bars in conveyors. In the automotive industry, bars of various strengths are being used for steering center links, lug wrenches, idler arm brackets, stabilizer bars, tie-rods, shock obsorber rods, U-bolts and various fasteners. Significant usage in construction equipment such as excavators, back hoes, and cement mixers is reported.

Table V. Niobium Modified (.05%), Hot Rolled, High-Strength-Low Alloy, Bar Steels

Minimum Yield Strength	Base Grade	Plus	Typical Tensile Properties			
	AISI		YS	UTS	%RA	%TE
345 MPa (50000 psi)	1022	-	55 ksi 380 MPa	70 ksi 483 MPa	62	34
414 MPa (60000 psi)	1522	-	65 ksi 449 MPa	82 ksi 566 MPa	60	31
483 MPa (70000 psi)	1536	-	75 ksi 518 MPa	98 ksi 677 MPa	58	29
552 MPa (80000 psi)	1541	-	85 ksi 587 MPa	115 ksi 794 MPa	54	26
621 MPa (90000 psi)	1541	.10% V	95 ksi 656 MPa	130 ksi 897 MPa	50	23
689 MPa (100000 psi)	1541	.15% V	105 ksi 725 MPa	135 ksi 932 MPa	45	20

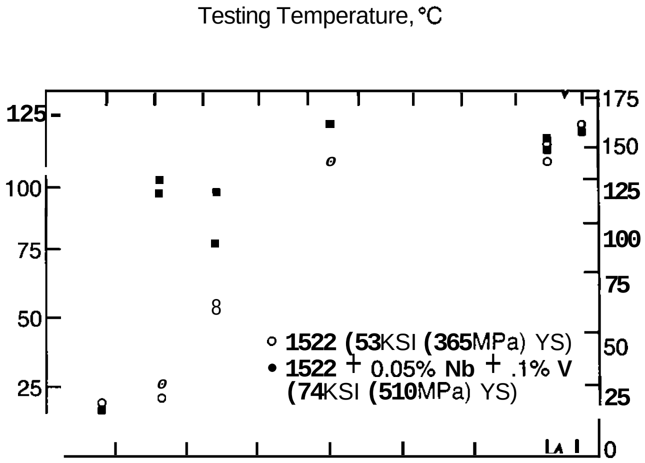


Figure *4.* Charpy V–notch data for plain–C and microalloyed steels.

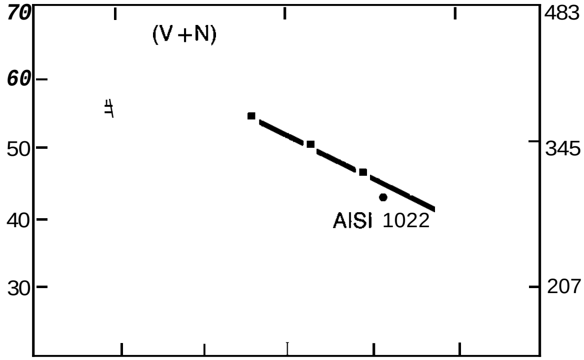


Figure **5.** Structural refinement is the primary means of strengthening microalloyed steels.

Cold Finished Bars

Jones and Laughlin Steel Corporation have reported on high-strength cold finished bars (8, 10, 14) utilizing microalloying, most commonly by the addition of vanadium. More recently, the Republic Steel Corporation has described (13) the achievement of yield strengths up to 1035 MPa (150 ksi) in microalloyed (Nb+V) cold finished bars. Table VI illustrates the potential of this approach using AISI 1144 grade as the base chemical coposition. This composition is frequently used for high-strength cold finished bars because of its relatively high-strength and good machinability. Assuming a strengthening increment of 69 MPa (10 ksi) by the addition of .05 percent Nb to the hot rolled bar, we see that this advantage is maintained as the bar is subsequently processed permitting greater flexibility in meeting a specified yield strength minimum, i.e. lower draft or elimination of stress relief treatment. Cold finished bars with strengths previously unobtainable except with alloy steels are achieved by the use of microalloyed hot rolled bars as the starting material. High-strength cold finished bars are used for a myriad of applications, many of which can be described under the generic terms of shafting and rods. In general, they are used for those high-strength applications where the inherent advantages of cold finished bars vs. hot rolled bars dictate their use.

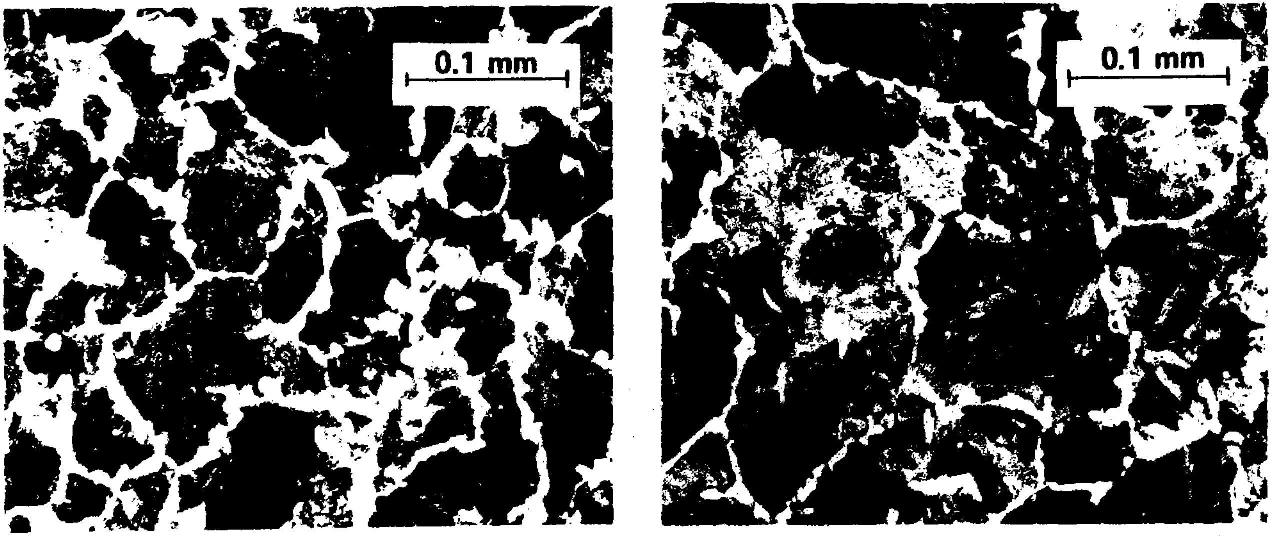
Table VI. Yield Strength as a Function of Processing History

Condition	Yield Strenpth 1144		1144 + .05% Nb	
	(ksi)	(MPa)	(ksi)	(MPa)
As-Hot-Rolled	60	414	70	483
Cold Drawn 14%	95	656	105	725
Cold Drawn 21%	110	759	120	828
Stress Relieved (14%)	105	725	115	794
Stress Relieved (21%)	120	828	130	897

Hot Forgings

Elimination of Heat Treatment. Structural refinement during hot forging is enhanced by the addition of niobium as it is for all high-temperature thermal-mechanical treatments due to the retarding of austenite recrystallization. Moreover, precipitation strengthening of the forging can be realized. Forgings made from microalloyed steel vs. the standard grade of steel will usually be stronger and tougher as a result of the finer microstructure. Figure 6 (10) compares the structures of AISI 1141-Nb modified and standard AISI 1141 steel taken from forged connecting rods such as illustrated in Figure 7. This structural refinement increased the hardness of the niobium-modified forging to 97 Rb vs. 92 R_b for the standard grade.

In the past, automotive connecting rods typically had been heat treated by quenching and tempering. However, by controlled heating and cooling after forging, several producers in the USA have successfully obtained the necessary mechanical properties in the air cooled rods eliminating the subsequent heat treatment with significant cost savings and reduction in energy consumption. Although the air cooled structures are, in general, not as tough as the quenched and tempered ones, their toughness has been found to be more than adequate for connecting rods. Fatigue resistance is the primary design criterion for many automotive applications.



Cb–FG Strand cast.

AK–FG Ingot cast.

Figure 6. Microstructures of microalloyed (left) and regular (right) AISI 1141 connecting rods.

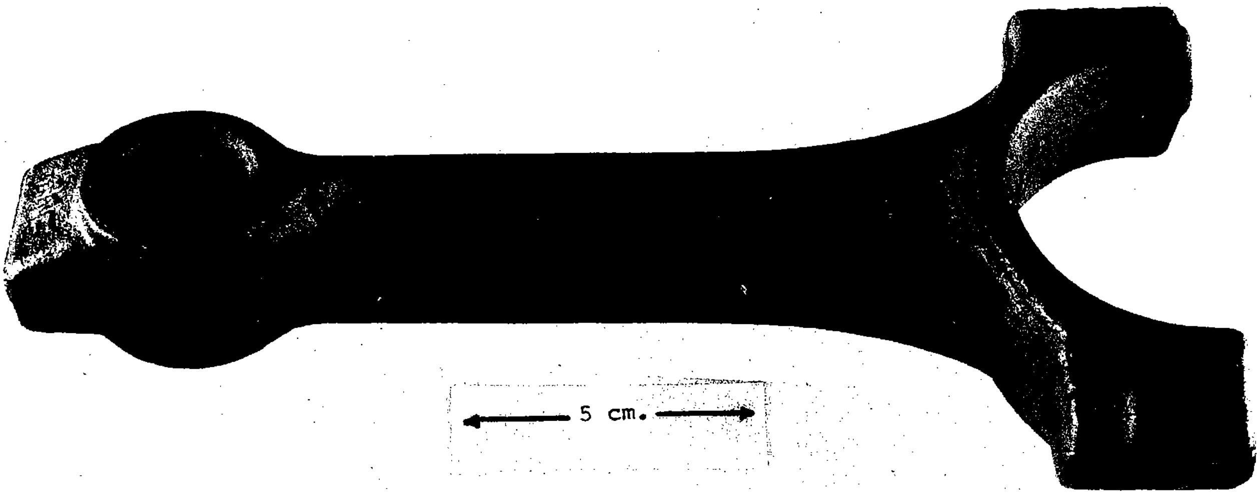


Figure 7. Typical fo g automotive connecting rod.

Another forged part where heat treatment has been successfully eliminated is the weld yoke or universal joint coupling (Figure 8) (11, 14). One automotive producer has used AISI 1141-Nb modified for some time and another is in the final stages of approval. The cross section of this forging is particularly amenable to this approach because of its relative uniformity. Figure 9 shows that for this sample the hardness is actually more uniform for the air cooled forging than for the quenched and tempered example (11, 14). The microstructures of the air cooled and heat treated yokes are shown in Figure 10 (11, 14).

Other examples of successful elimination of heat treatment include suspension components (12) and stabilizer bars (11). As well as the size and geometry of the part, control of the forging process is necessary. Figure 11 (12) shows the effect of heating temperature on the hardness of microalloyed forgings. Heating at 1200 C (2192°F) or slightly higher is to be recommended to insure solution of carbonitrides. Figure 12 (12) shows the effect of cooling rate on hardness. The chemical composition and cooling rate should be selected to give the desired hardness and other mechanical properties. Japanese investigators (12) have defined a parameter H_{eq} which is the hardness of a steel after forging under certain conditions. Figure 13 (12) shows that for a given set of forging conditions as defined by an H_{eq} value, a certain hardness results for the forgings examined and that linear relationships are indicated between hardness and H_{eq} for the various examples, i.e. connecting rods and caps, and suspension components. Figure 14 (12) is generated as a guideline for selecion of the necessary H_{eq} value to achieve the required hardness as a function of the weight of the forging.

Summary

The use of niobium as a microalloying addition to hot rolled and cold finished bars offers many opportunities to achieve enhanced mechanical properties in a very cost effective manner. By the addition of niobium (sometimes in combination with vanadium) to selected carbon steel grades, it is possible to produce hot rolled bars with minimum yield strengths up to 689 MPa (100 ksi) and cold finished bars with yield strengths up to 1035 MPa (150 ksi). These high-strength-low-alloy bars have a myriad of applications particularly for automotive parts such as shafts, stabilizer bars, tie rods, piston rods, fasteners such as U-bolts, brackets, and various transmission parts. Of particular value has been the specification of Nb-microalloyed steels for such hot forgings as connecting rods and caps, and weld yokes a situation which has permitted elmination of post-forging heat treatment (quenching and tempering). Significant reductions in cost and energy consumption have been realized.

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Figure 8. Universal Joint Coupling **or Weld Yoke.**

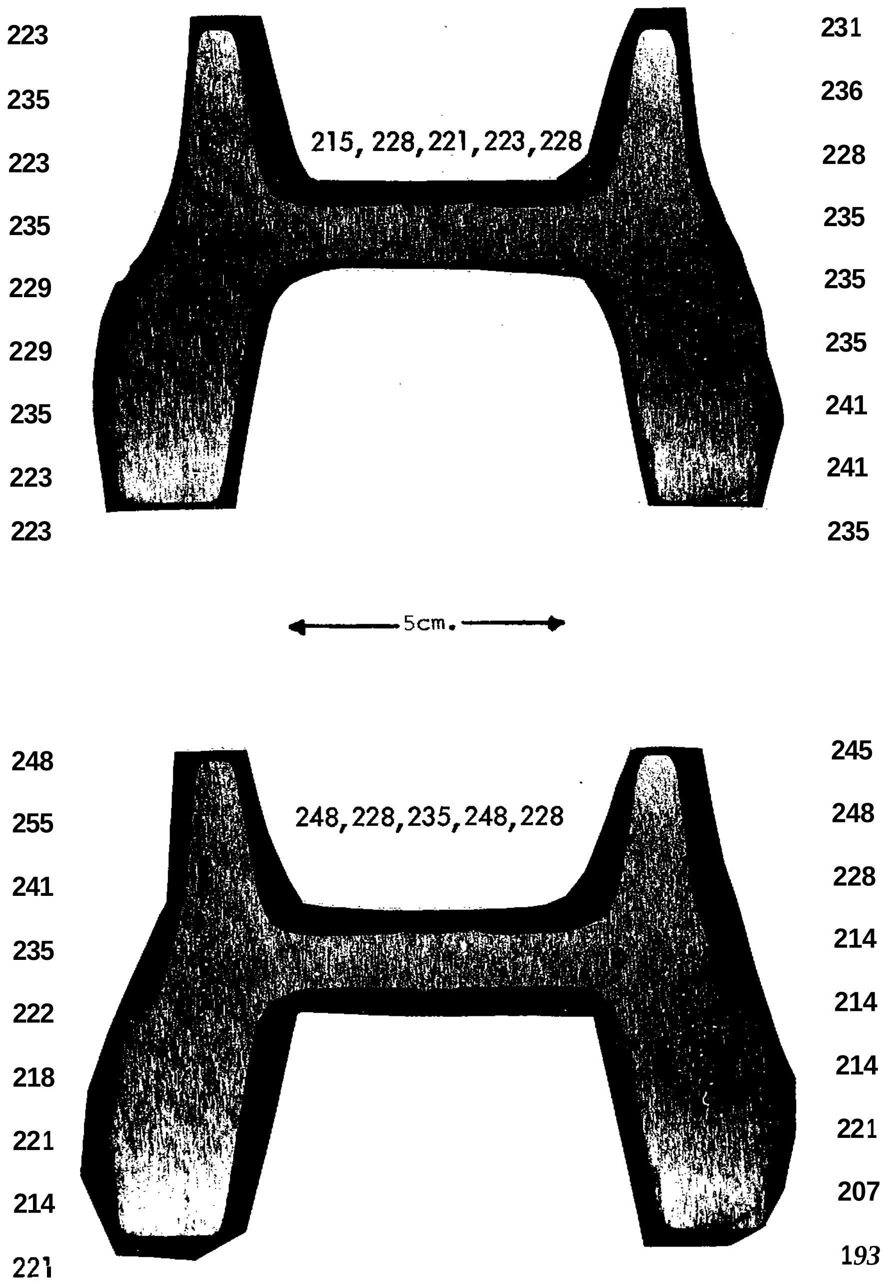
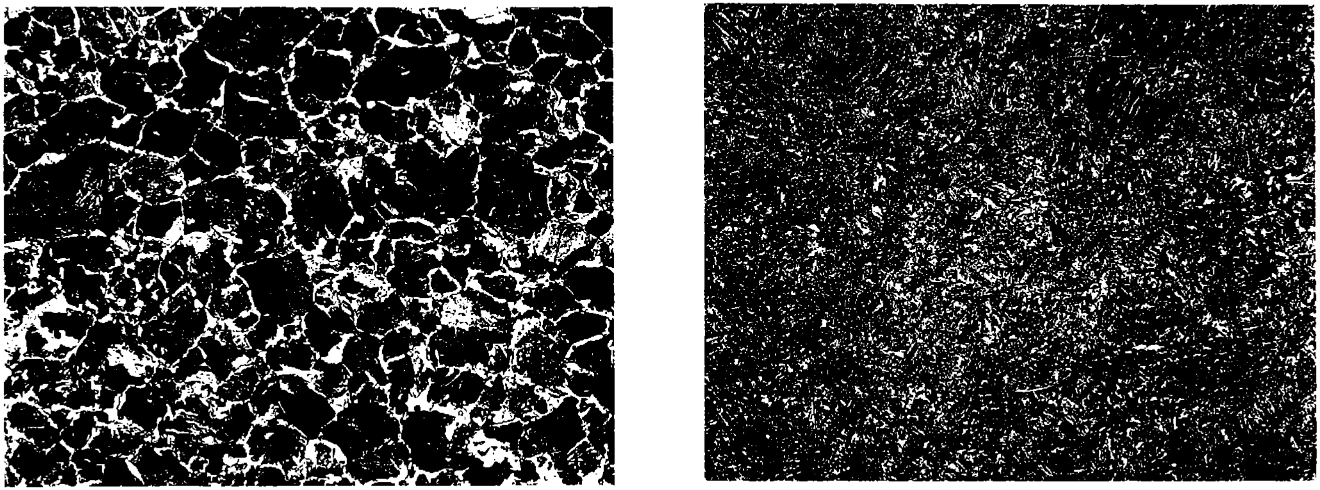


Figure 9. Hardness profiles in Brinnell hardness numbers.



← .1 mm →

MICROALLOYED STEEL AS-FORGED, 400 X

STANDARD GRADE QUENCHED AND TEMPERED, 400 X

Figure 10. Comparison of the microstructures of air cooled and heat treated weld yokes.

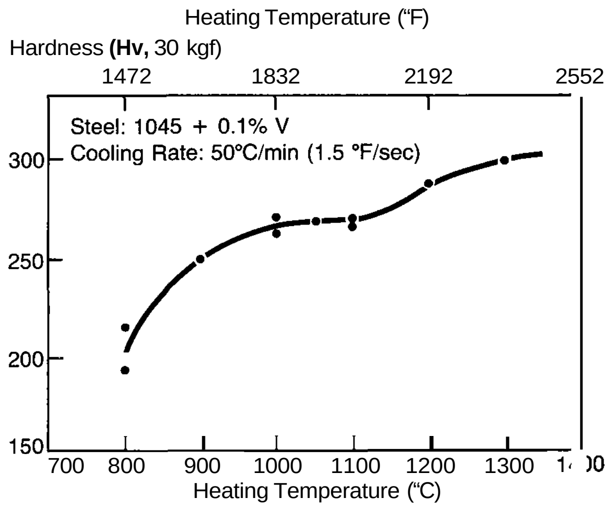


Figure 11. The effect of heating temperature on the hardness of forgings.

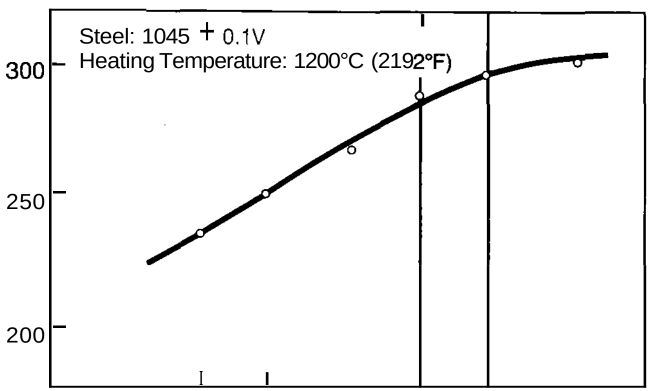


Figure 12. Effect of cooling rate on the hardness of typical forgings.

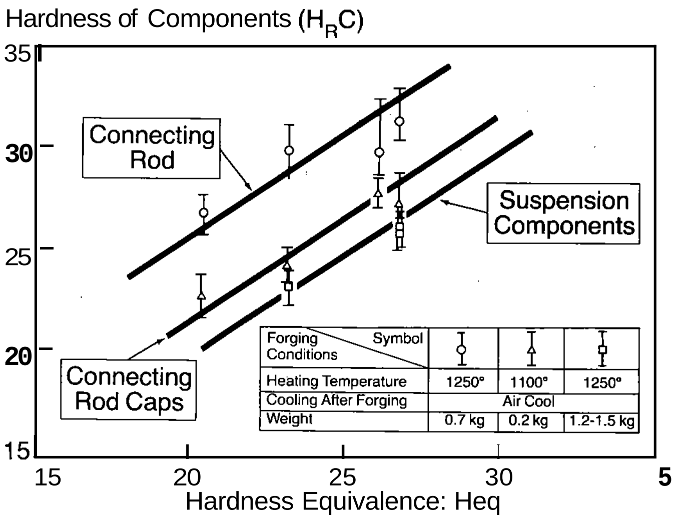


Figure 13. Hardness as a function of forging conditions.

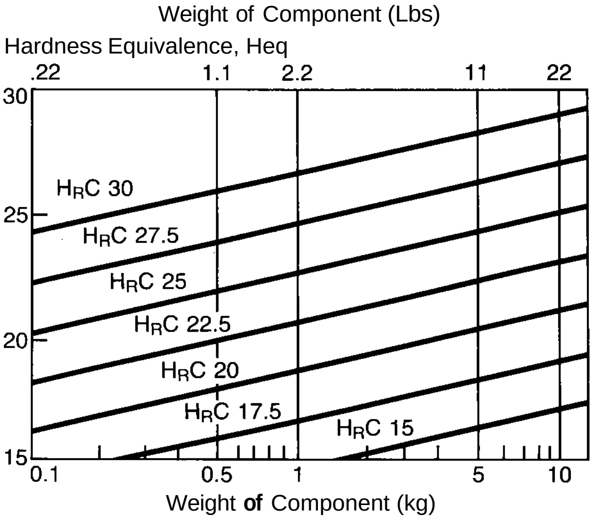


Figure 14. Necessary forging conditions are determined by the required hardness and size of the forging.

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