NIOBIUM IN STEEL CASTINGS AND FORGINGS

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Abstract

Microalloyed, niobium-containing steels have found increasing usage in cast steels over the past two decades. Progress is detailed especially in the offshore industry and for applications requiring elevated temperature properties. The paper also discusses the development of niobium-containing steels for forging applications, particularly for automotive components and fasteners.

Introduction

It is important to note that microalloyed steels consume around 80 percent of the world's niobium production, and, comprise over 10 percent of the world's steel production (over 80 million tonnes per year).

Apart from the large tonnage areas of automotive, linepipe, structural and constructional applications, microalloyed, niobium-containing steels are being increasingly employed in smaller tonnage fields such as castings, forgings, automotive forgings, and fasteners.

All of the steels developed for the above applications offer improved toughness, weldability and higher strength. Microalloyed steels also offer improved elevated temperature properties, which enlarges their potential field of application. Further, for certain applications, such as offshore nodes, niobium-containing cast steels provide an important improvement in fatigue properties due primarily to reduced stress concentrations.

While good progress has been made, the castings and forgings industries are still not mature and require concentrated efforts to successfully implement this "relatively new" technology.

The present paper reviews and presents some recent developments in the castings and forgings areas.

Design of Microalloyed Steels

Microalloyed steels are typically low-to-medium carbon steels containing small additions of niobium, vanadium, titanium and aluminum either as individual additions or in combination. The physical metallurgy, and development of improved mechanical properties in the majority of commercial microalloyed steels, are discussed in much more detail elsewhere (1-9) but briefly are based on:

(1) grain refinement for improved strength and toughness,
(2) relatively low carbon content (0.003% to 0.15%) for improved toughness and weldability,
(3) precipitation strengthening either from a normalizing treatment or during cooling after finish-rolling, or during an aging treatment after quenching or normalizing,
(4) substructural strengthening due to the presence of low temperature transformation products ranging from acicular ferrite to bainite to martensite, and
(5) solid solution strengthening, although this technique is limited since the most effective solid solution strengtheners, carbon, nitrogen, phosphorus and silicon have the most detrimental effect on toughness.

The basis of low carbon, strong-tough HSLA steels lies in transformation to a fine ferrite grain size. Grain refinement is the only strengthening mechanism that provides a concomitant and marked improvement in toughness.

In medium carbon steels, however, the pearlite colony size and lamellae thickness dictate the toughness. The former is influenced by austenite grain size and the latter by carbon content; the lower the carbon content the thinner the cementite lamellae and the better the toughness.

On the other hand, the strength in pearlitic steels is governed by the interlamellar spacing which, in turn, is controlled by the pearlite transformation temperature. The lower the transformation temperature the finer is the interlamellar spacing and the greater the strength.

The principle advantages of a Nb addition derive from the fact that Nb forms carbonitride precipitates in low to medium carbon steels. The precipitates are either completely or partially dissolved during reheating processes. The degree of solubility depends on the temperature, time at temperature, heating and cooling rate, and the solubility product [Nb] [C,N]. The kinetics of precipitation of Nb (C,N) therefore control the benefits that are achieved, with the level of niobium in solid solution dictating the transformation temperature.

Niobium in Steel Castings

The overwhelming tonnage of microalloyed steels, probably in excess of 98 percent, is wrought product, and introduction of these steels into the foundry industry, although begun over 40 years ago, has been extremely slow.

Unlike wrought products that are able to utilize the strong effect of niobium carbonitride precipitation on retarding the recovery and recrystallization processes which take place during rolling, cast steels have to rely on austenite grain refinement, control of the austenite-to ferrite transformation temperature, and precipitation strengthening of the ferrite in order to achieve optimum mechanical properties.

The effect of niobium on the microstructure, and hence mechanical properties, of cast HSLA steels is schematically presented in Figure 1. The interaction between casting and reheating practice on the precipitation of Nb (C,N) particles in relation to grain refinement, transformation control, and precipitation strengthening is shown.

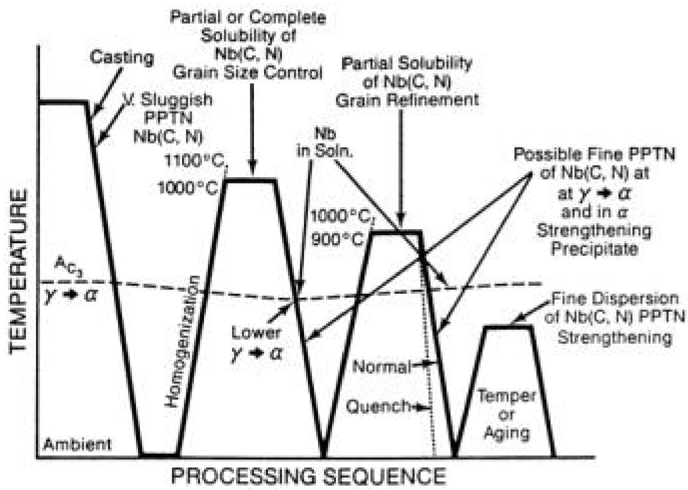

Figure 1: Effect of niobium on the microstructure of cast microalloyed HSLA steels during various processing procedures.

During cooling from the casting temperature, precipitation of Nb (C,N) most likely does not occur because of the absence of any external plastic deformation. However, some fine Nb (C,N) precipitation can take place during the austenite-to-ferrite transformation (precipitate-row formation) and in the ferrite phase. The degree of precipitation is dependent on the cooling rate of the casting.

If a casting is subsequently subjected to an homogenization treatment (usually only large castings) prior to normalizing, the temperature can be raised to 1100°C or above, resulting in complete or partial solution of the Nb (C,N). The Nb (C,N) particles that remain out of solution effectively pin the austenite grain boundaries thereby restricting grain growth resulting in significant grain refinement. This effect is more pronounced during a normalizing treatment since in this case the reheat temperature is lower (900°C-1000°C), the Nb (C,N) particles are more stable, and the driving force for austenite grain growth is reduced.

Niobium is much more effective than either vanadium or aluminum in preventing grain coarsening at high temperatures, Figure 2 (10). In normalized steels this effect translates to a niobium addition being most effective as a grain-refining agent especially at low concentrations (0.02-0.04%), see Figure 3 (11). To produce a similar refining effect using vanadium would require an addition of about 0.10% V coupled with a high nitrogen level of around 0.020%. In cast steels, titanium forms coarse nitride particles, which are relatively ineffective for grain refinement.

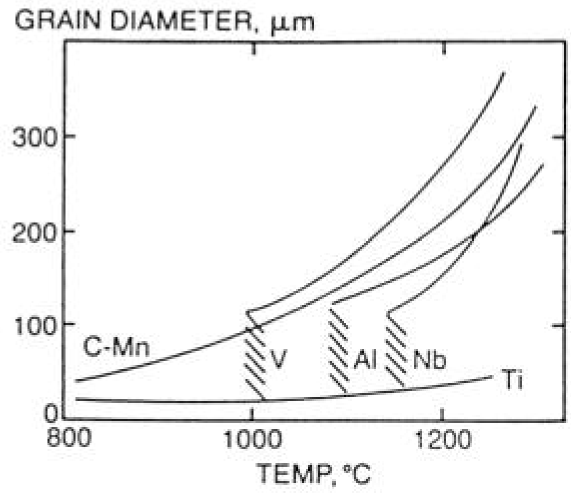

Figure 2: Austenite grain-coarsening characteristics of various microalloyed steels(10).

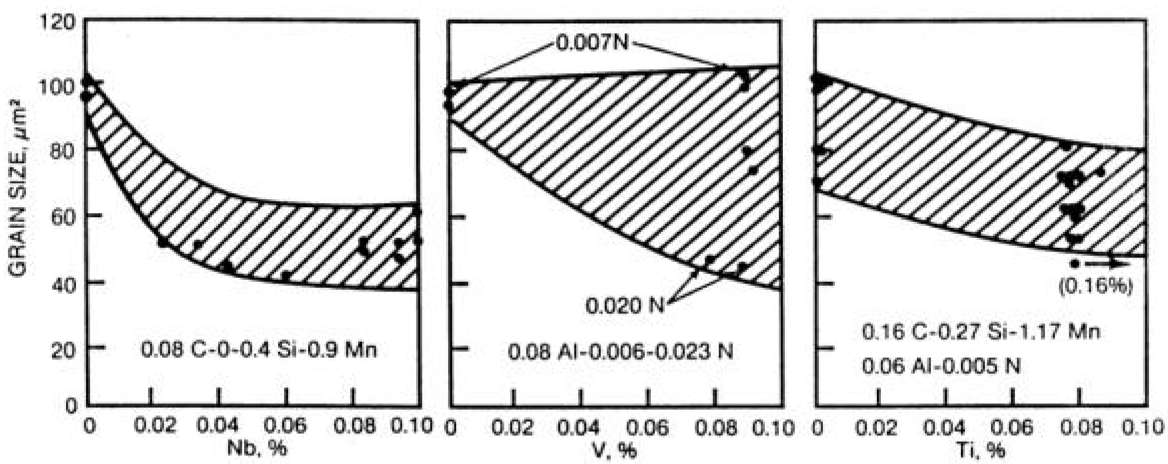

Figure 3: Effect of niobium, vanadium and titanium on the grain size of normalized HSLA steels (11).

During cooling from a normalizing temperature two major effects due to niobium are possible depending on the amount of niobium remaining in solid solution prior to cooling, and the subsequent cooling rate. First, niobium in solution has a marked hardenability effect although this is likely to be limited because of the relatively low normalizing temperatures used, and offset to some extent by the grain refining effect. Even so, niobium can lower the austenite-to-ferrite transformation temperature as shown in Figure 4(12).

In fact, of all the microalloying elements, niobium, when in solution, has the largest effect in reducing the austenite-to-ferrite transformation temperature from a given grain size.

The solute effect of niobium can be combined with molybdenum (or boron) to produce acicular ferrite or bainite in air-cooled castings. The presence of molybdenum ensures the attainment of the required mechanical properties throughout a heavy casting.

Depending on the cooling rate from the reheat temperature, precipitation of Nb (C,N) can occur during the austenite-to-ferrite transformation and in the subsequent ferrite phase. This finely dispersed precipitate provides for an increase in yield strength. The time-temperature range for the precipitation of Nb (C,N) particles is indicated on the CCT curves in Figure 4 (12).

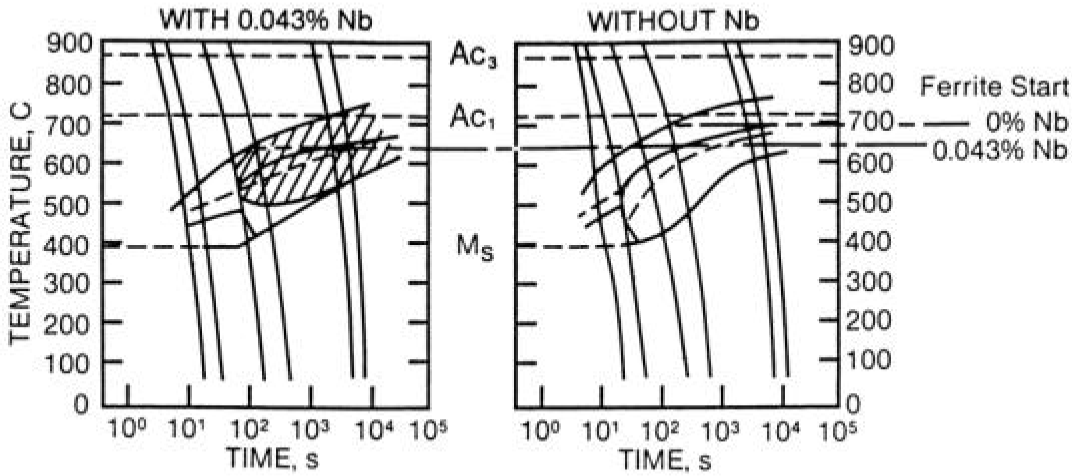

Figure 4: Continuous cooling transformation curves for low carbon steels with and without Nb (quenched from 1300°C) (12). The crosshatched area indicates the region carbonitride precipitation. At a cooling time of 10^2s a 0.043% Nb addition lowered the ferrite start temperature by about 50°C.

Any niobium still remaining in solution in the ferrite can be precipitated as a fine dispersion of Nb (C,N) particles during a subsequent tempering (aging) treatment resulting in an increase in yield strength. The precipitation strengthening effect on aging due to Nb (C,N) is much more pronounced after quenching since an increased amount of niobium would be retained in solid solution after the faster cooling rate, and would be available for subsequent precipitation.

In addition, molybdenum has been shown to retard precipitation of Nb (C,N) in austenite (13,14) enabling more niobium to be retained in solid solution in the austenite and to be available for increased precipitation of Nb (C,N) in the ferrite where its strengthening effect is more pronounced. Molybdenum has also been identified in the precipitates themselves, which would increase their strengthening effectiveness by increasing coherency strains and/or by increasing the volume fraction of precipitate (15). More recent work (16) has shown that molybdenum strongly segregates to the Nb (C,N)/ferrite matrix interface in Nb-Mo steel which probably suppresses the diffusion of Nb atoms into the Nb (C,N) particles from the ferrite matrix. This maintains a fine precipitate size even at elevated temperatures with a concomitant increase in strength. The net result is that a molybdenum addition to Nb (V) steels effectively raises the yield strength without detriment to toughness.

Developments in Microalloyed Cast Steels

Many of the applications of microalloyed steels over the past two-three decades have been well documented, (17-19) and include Mn-Mo-Nb (±V) steels for housings, drag buckets, connectors, nodes and other offshore components, railway couplings, slag pots and rolling mill rolls.

Two applications which found immediate use in the 1970's were connecting parts for the supporting frame of a nuclear reactor weighing 665 kg (Figure 5), and welded-in parts for building machinery (Nb+V steel) weighing 120 kg each (Figure 6). The mechanical properties taken from the center of the 350-mm diameter nuclear support connecting parts are given in Table I (20).

Figure 5: Connecting part weighing 665 kg (1465 lb) cast from 0.40% Mo-0.04% Nb-0.06% V steel for the supporting frame of a nuclear reactor (20). Courtesy of Thyssen Giesserei AG.

Figure 6: Machinery parts from 0.04% Nb-0.06% V steel (20). Courtesy of Thyssen Giesserei AG.

Table I Mechanical properties of cast 0.4%Mo-0.04%Nb-0.06%V microalloyed steel connecting parts for the supporting frame of a nuclear reactor (20)

	Y.S. MPa	T.S. MPa	El %	Hard. HB	Impact Energy Absorbed (DVM**) +20°C J	-20°C J	-40°C J
Average	420	540	15	160	92	70	29
Minimum	390	510	11	150	76	49	8

*Specimen taken from center of 350mm (14in.) diameter casting. Heat treatment, 950°C (1750°F)-oil quench +600°C (1110°F) precipitation hardening treatment.

**10mm (0.394 in) square specimen containing a 3mm (0.118) deep, 1mm (0.039 in.) radius notch.

The excellent weldability of this type of steel (0.08% carbon) is illustrated in Figure 7 (20) which shows that under normal welding conditions the hardness is lower than 280 H_V10. Only after welding at an abnormally low heat input (7.5J/cm) was higher maximum hardness observed.

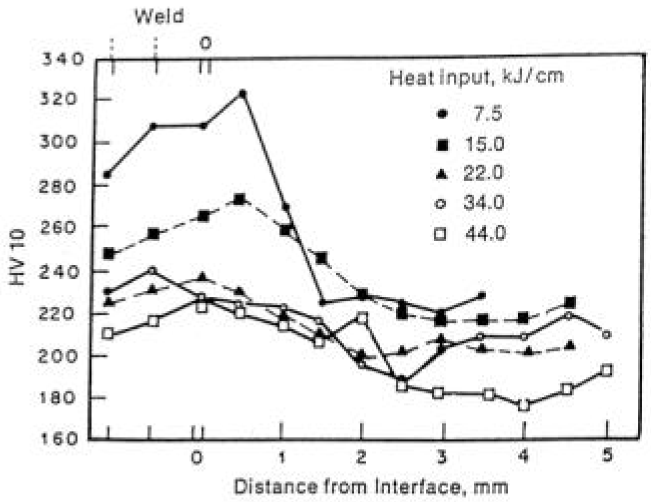

Figure 7: Effect of heat input on the hardness traverse across the weldment of Nb-V steel (20).

A similar cast steel (0.10%C, 0.4%Mo, 0.04%Nb, 0.06%V) has been proposed for railway couplings, Figure 8 (18), to meet minimum yield and tensile strength levels of 415 MPa (60 ksi) and 620 MPa (90 ksi) respectively. The minimum toughness requirement for this fine-grained polygonal ferrite steel is a 34J Charpy V-notch impact energy (CVN) at -40°C. Couplers encounter high shocks and other dynamic stresses under service conditions and have to be weld-repaired on site. Low-carbon, microalloyed steel has proven highly successful in this application.

Since the 1970's, the offshore industry has provided the impetus for the development of high quality steels for a number of components, primarily nodes. Originally, nodes for offshore platform construction were exclusively fabricated by welding but because of their sensitivity to fatigue damage, work was initiated to design and develop cast nodes (21-25). Typical commercial cast nodes produced by River Don Castings Ltd., a member of the Sheffield Forgemasters Group, Sheffield, England, are shown in Figure 9. The extent to which cast HSLA steel technology progressed in a short period of time can be appreciated when considering the large, complex 63-tonne prototype node cast in Sheffield for Britoil, Figure 10.

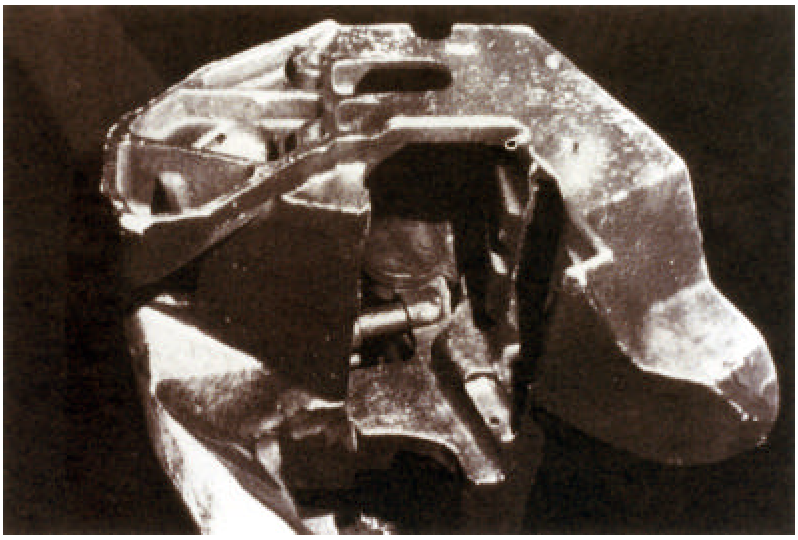

Figure 8: Automatic coupler for railway carriages made from welding together two separate, low carbon, microalloyed steel castings(18). Courtesy of Fonderies et Acieries d'Outreau, France.

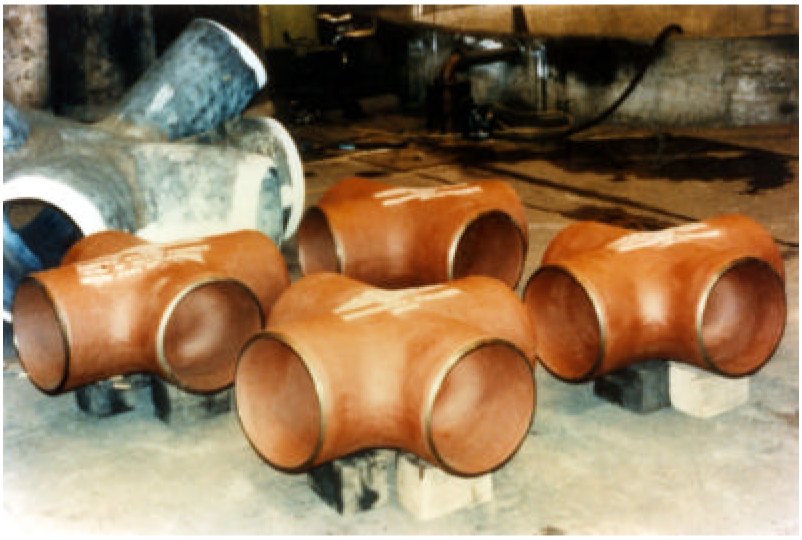

Figure 9: Niobium-containing cast steel nodes of offshore platform construction. Courtesy of River Don Castings, a member of Sheffield Forgemasters, Sheffield, England.

Many benefits of cast nodes over welded nodes have been noted and include:

a) greatly improved fatigue life (X4 to X18 depending on the type of node) (22);
b) reduced stress concentrations;
c) no weld (or associated microcracks) in critical areas;
d) uniformly high toughness in all directions (especially at low temperatures);
e) increased joint stiffness (improves shock resistance); and

f) reduced buckling tendencies.

In addition, it has been reported that compared with fabricated nodes, cast nodes can provide for a cost saving of the order of 20% (21).

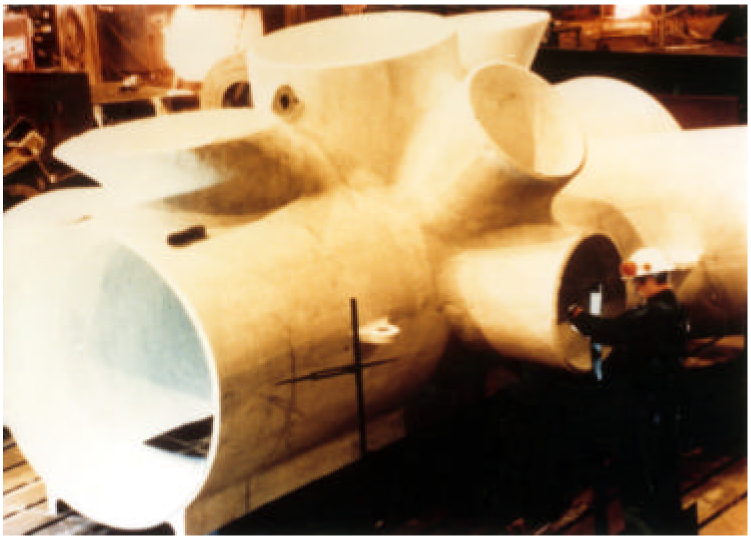

Figure 10: A 63-tonne, nine-brace prototype launch leg node cast from Mo-Nb-V steel for Britoil. Courtesy of Don Castings, a member of Sheffield Forgemasters, Sheffield, England.

The chemical composition and typical mechanical properties of the Mo-Nb-V steel are given in Table II.

Table II The steel composition and mechanical properties of microalloyed steel for offshore castings (24).

Composition, wt %											
C	Mn	Si	S	P	Ni	Cr	Mo	Al	Cu	Nb	V
0.16	1.2-1.7	0.6	0.01	0.02	0.6	0.2	0.2	0.05	0.3	0.04	0.08
carbon equivalent 0.46 max.; all elements max. except Mn											

Yield Strength, MPa (ksi)	340 – 360 (49.3 – 52.2)
Tensile Strength, MPa (ksi)	480 - 510 (69.6 – 74.0)
Elongation, %	30
Reduction of Area, %	70
Charpy V-notch Impact Strength At -40°C, J (ft-lb)	70 – 100 (52 – 74)
Crack Opening Displacement (COD) at -10°C, mm (in.)	0.8 – 1.2 (0.03 – 0.05)

Other applications of this cast steel grade include:

i) insert castings (Figure 11) in fatigue-prone regions of off-shore structures. Their use on Conoco's Hutton tension-leg platform enabled the stress concentration factor to be reduced from eight for a fabrication down to three for the casting. A significant cost reduction was also achieved.

ii) sub-sea riser tie-in modules, Figure 12, which are piled into the seabed and pass oil from a tensioned riser into a pipeline through a 90° bend. Microalloyed cast steel is used for the main body of this complex, highly stressed component while forged microalloyed steel is used for the connections to the pile and the pipeline, and

iii) padears to aid module lifting (26) and spreader bar ends.

The use of microalloyed cast steels at elevated temperatures is based upon their tensile characteristics, creep behavior and resistance to thermal shock and oxidation. Results of two cast Mo-Nb-V steels are presented in Table III (18).

Table III Elevated temperature yield strengths (MPa) of microalloyed cast steels (18).

Composition, wt%					Temperature, °C							
C	Mn	Mo	V	Nb	20	100	200	300	350	400	500	600
0.05	1.03	0.30	0.09	0.09	450	440	400	-	330	320	320	-
0.02	1.82	0.36	-	0.057	460	-	-	440	-	400	370	290

Figure 11: Insert castings for Conoco's Hutton tension-leg platform cast from Mo-Nb-V steel. Courtesy of River Don Castings, a member of Sheffield Forgemasters, Sheffield, England.

The retention of strength at elevated temperatures is excellent relative to many conventional grades, due in large part to the stable precipitate resulting from heat treatment. In the case of higher Mn-Nb steel the room temperature yield strength value is maintained to almost 400°C, and even at 500°C the yield strength remains close to 400 MPa.

Applications taking advantage of these elevated temperature properties include ingot tong arms, Figure 13 (17), ingot molds, charging-discharging arms for bloom furnaces, boiler vessels in power plants, and, more recently, slag pots.

Slag pot producers in the USA have commercially developed low C-Mo-Nb steels to replace their normal higher carbon (0.25% C)-Mn steel for cast slag pot application. Slag pots that undergo repeated thermal cycling experience creep problems and exhibit either simple cracking or a "coke-bottle" effect, that is, sagging in the central region of the pot which eventually leads to fracture, Figure 14 (27). The failures are due to either high service temperatures caused by operators running steel into the slag pot to avoid putting slag into the tundish, or the combined effect of buckling under its own weight and slag pushing outward in the hottest zone of the pot.

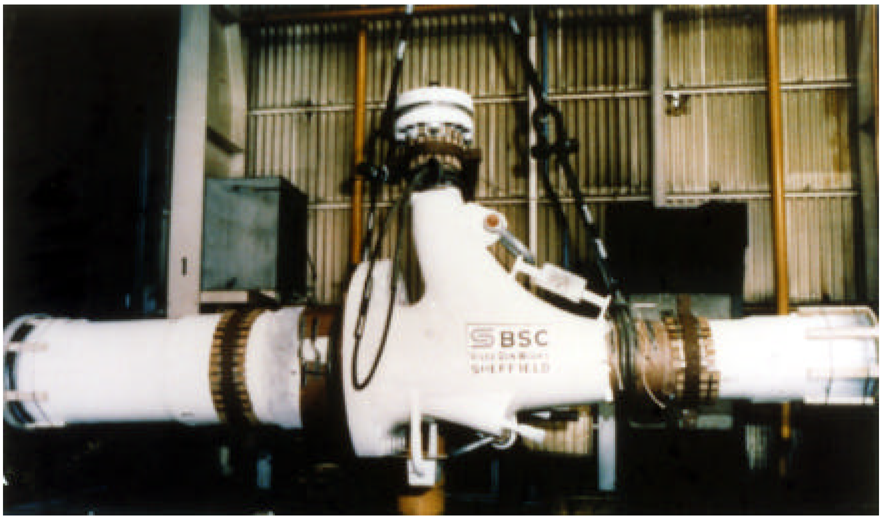

Figure 12: Sub-sea riser tie-in module. Courtesy of River Don Castings, a member of Sheffield Forgemasters, Sheffield, England.

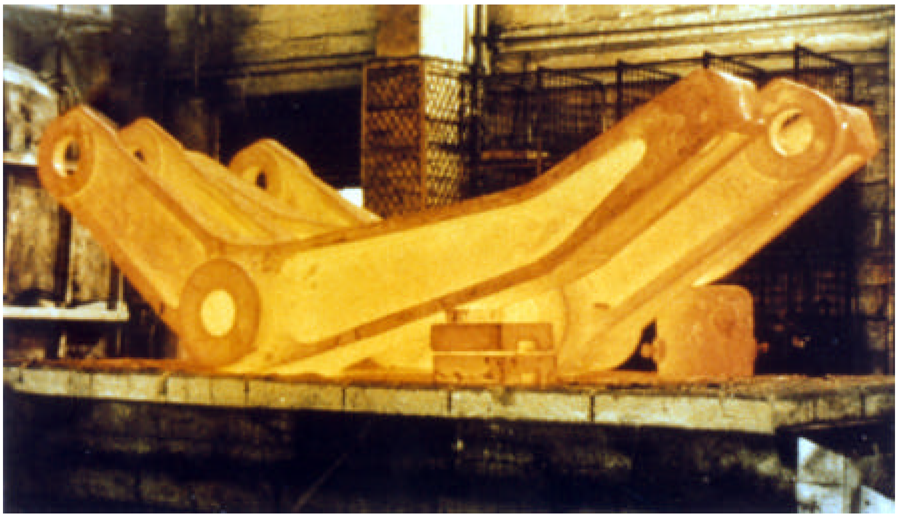

Figure 13: Arm of ingot tongs made from cast niobium-containing, microalloyed steel (17). Courtesy of Fonderies et Acieries d'Outreau, France.

A Mo-Nb steel chemistry which has been developed, together with typical mechanical properties, is given in Table IV (28). The Mo-Nb steel exhibits a yield strength of 335 MPa at room temperature, which is about 40% higher than that of conventional 0.25% C-Mn steel, Figure 15 (27). This differential also exists after testing at 760°C.

The usual heat treatment for slag pots includes a solutionizing anneal and forced air cool to room temperature. In a production casting, this heat treatment refines the as-cast ferrite grain size to ASTM 4-7, depending on the section thickness.The principle benefit of the niobium-containing steel is its ability to enhance resistance to creep stress, which reduces distortion and tearing. High temperature (875°C) yield strength is about three times greater than that of the traditional higher C-Mn steel.

Figure 14: Conventional C-Mn steel slag pot showing "coke bottling" and fracture. Cast microalloyed slag pots exhibit a significant improvement in life (27). Courtesy of Johnstown Corporation, Johnstown, Pennsylvania, USA.

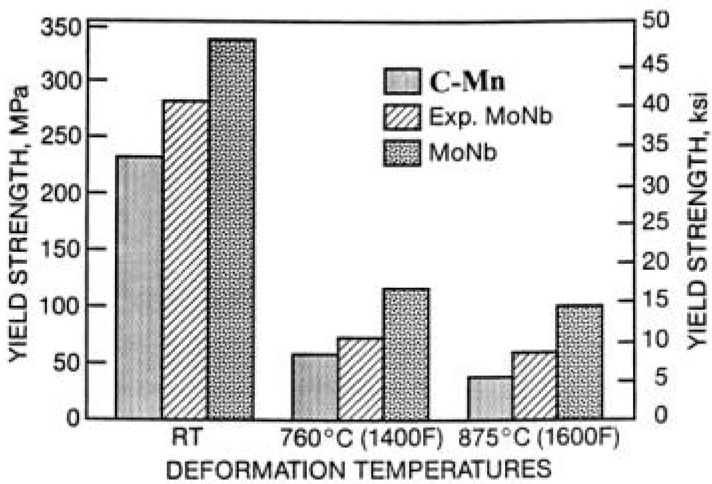

Figure 15: Comparison of the yield strength of C-Mn and Mo-Nb cast steels at different test temperatures (27).

Table IV Steel chemistry (wt%) and typical mechanical properties of Mo-Nb steel cast slag pots produced at WHEMCO (28)

C	Mn	Si	S	P	Ni	Cr	Al	Mo	Nb
0.05/ 0.10	0.50/ 0.60	0.05/ 0.06	0.02 max	0.02 max	0.08 max	0.40/ 0.50	0.01/ 0.02	0.40/ 0.50	0.03/ 0.05

Yield strength:	335 Mpa
Tensile strength:	515 MPa
RA%:	65%
EI%	40%
CVN @ RT:	70 Joules

Furthermore, as can be seen in Figure 16 (27), the yield strength of the Mo-Nb steel fell only to 42 MPa after a hold of 1h at 875°C as compared with the C-Mn steel, which dropped to 12 MPa. The lower carbon level of the microalloyed steel markedly reduces the pearlite content with a concomitant improvement in both toughness and weldability. The impact toughness of the Mo-Nb steel at RT is about double the value previously attained with the C-Mn chemistry. Indeed, impact toughness exceeding 260J at RT has been recorded by the microalloyed steel. The major improvement in impact toughness is a valuable back-up property in case of pot abuse.

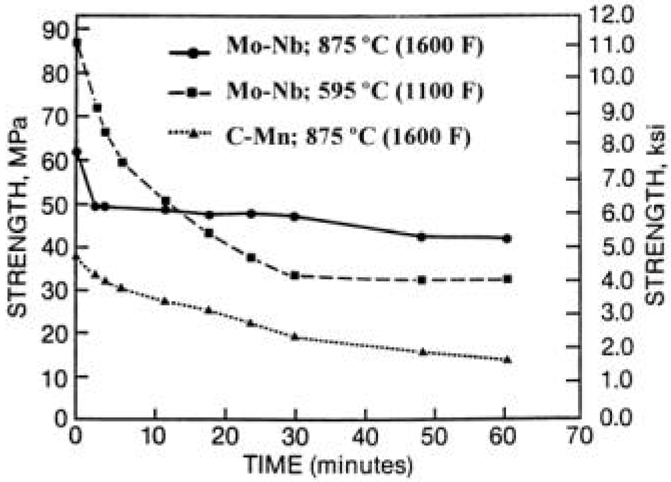

Figure 16: Comparison of the stress relaxation behavior between C-Mn and commercially produced Mo-Nb cast steel (27).

By enhancing the hot strength, solidification problems have been eliminated at WHEMCO (28) together with other foundry cost-savings. This has enabled WHEMCO to capture a major percentage of the slag pot market in North and South America and molybdenum-niobium slag pots of up to 60 tonnes in weight, with a capacity of 1050 cu. ft., are now produced.

It is not possible to discuss all the niobium-containing cast steels developed over the years but worthy of note include a higher chromium steel (3.5%) containing 0.06%Nb, which has a very low carbon level (0.03-0.05%) so as to reduce quench cracking (29), and a medium carbon steel (0.40%), containing 0.10%Nb for back-up rolls (30).

The former steel, designated Imacro (trademark of Ovako OyAb, Finland), has a martensitic microstructure with a yield strength ranging between 680 and 850 MPa. The nominal composition and mechanical properties are given in Table V (29). The steel exhibits excellent weldability by virtue of its low carbon content.

Applications of Imacro include supporting rolls, spindles for rolling mills, crane wheels, jaws of a crane designed for moving ingots and welded roller-table rolls for a blooming mill. The latter application enabled the cross-section of the rolls to be reduced by 20% resulting in a significant reduction in the weight and inertia of the whole roller-table system. Crane wheels made from the 3.5%Cr-0.06%Nb steel have at least a X3 greater life than conventional C-Mn steel.

The microalloy addition of niobium in medium carbon cast steel back-up rolls has been developed in the USA(30). Figure 17 shows a large back-up roll to be used on a hot-strip mill. An addition of 0.10%Nb has been substituted for 0.15%V for grain size control. The weight of such castings ranges between 40 and 60 tonnes and the nominal composition is: 0.40%C-0.45%Si-1.0%Mn-2.0%Cr-0.80%Mo-0.10%Nb.

Figure 17: Cast steel back-up roll for hot-strip mill, grain refined using a 0.10% Nb addition (30). Courtesy of Blaw Knox Rolls, Wheeling, WV, USA.

The rolls are typically annealed at 925°C for 30 hours. The tensile strength of the rolls is normally between 1300 to 1400 MPa with a hardness of 46-48 R_c to a depth of 12.5cm, and a CVN of 65J at RT. Without a niobium addition the impact energy could be as low as 10J at RT.

Table V The nominal chemical composition and mechanical properties of Imacro, a cast Cr-Nb Steel (29)

Composition, wt %					
C	Si	Mn	Cr	Nb	
0.05	0.50	0.60	3.8	0.06	
Mechanical Properties*					
0.2% Y. S.:	UTS:	El:	RA:	CVN:	Impact Energy:
680-850 MPa	900-1100 MPa	> 10%	> 45%	> 25J @ 0°C	> 20J @ -20°C

* up to 100 mm section thickness

Niobium in Forgings and Cold-Heading Steels

Ferrite-Pearlite Steels

The development and application of microalloyed steels (31-40) for such products as automotive forgings, forgings for agricultural and industrial machinery, fasteners and other cold-headed components provides for improved mechanical properties coupled with significant cost savings. This is because not only are microalloyed steels less costly compared to conventional alloyed steels but in many cases they allow for the elimination of major processing steps such as quenching and tempering, straightening and stress relieving during manufacture, Figure 18, which, in fact, provides for greater savings than incurred by alloy cost savings.

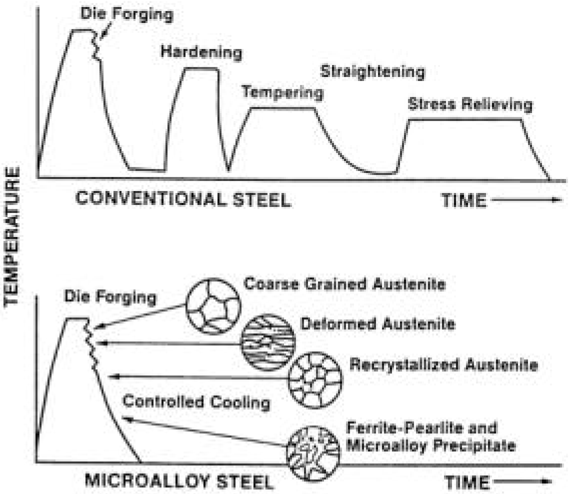

Figure 18: Comparison of the processing routes for microalloyed forging steels and conventional low alloy, quenched and tempered steels.

The first microalloyed steels developed for automotive forgings were of the V-N type (49MnVS3) but while strength could be increased linearly with increasing vanadium content toughness was adversely affected (31).

Because of the safety requirements imposed by the automotive manufacturers, improved toughness soon became a major requirement for microalloyed forgings. This led to the development of Nb-V steels in France (41-43), Germany (44) and Italy (45), and at the later stage V-Ti steels in Germany (46). The latter steel design can produce a useful strength-toughness combination provided a minimum vanadium level of 0.10% is coupled with a high nitrogen level, and a stoichiometric Ti:N ratio is maintained.

The development of Nb-V forging steels took advantage of the triple role of niobium to grain refine, reduce pearlite interlamellar spacing and precipitation strength. The "METASAFE" steels became the main family of Nb-V microalloyed forging steels (41-43), and the chemical compositions of the principal grades are given in Table VI. Depending on the grade, the carbon content varies between 0.15% - 0.45%, the lower end of which is much lower than that of V-Ti-N steels and provides a major contribution to improved toughness. The lower carbon content also ensures good weldability.

Table VI Average composition (wt%) of the principal METASAFE steels (42)

	C	Si	Mn	Cu	Ni	Nb+V
METASAFE 800	0.22	0.15	1.5	---	---	0.19
METASAFE 1000	0.43	0.15	1.5	---	---	0.16
METASAFE 1200	0.21	0.55	1.5	1.4	1.5	0.13

Charlier and Bacher (42) have shown that in the METASAFE 1000 steel (minimum tensile strength of 1000 MPa) about 0.03 to 0.04% niobium is taken into solution after soaking for 1.5h at 1250°C, Table VII. The metallurgical design of Nb-V forging steels, therefore, should be such that about 0.02% Nb remains undissolved so as to effectively grain refine, while the niobium in solution contributes to interlamellar spacing control and subsequent precipitation strengthening. As shown in Figure 19 , the precipitation strengthening effect due to niobium is of the order of 150 MPa (Y.S.) at a 0.03% Nb level. This compares to only 50MPa (Y.S.) for the equivalent amount of vanadium. To realize a similar precipitation strengthening effect to that of 0.03%Nb, a vanadium level of about 0.08% would be necessary.

The optimum level of niobium, therefore, is slightly in excess of that which will be taken into solution, and consequently, in the case of METASAFE 1000 would be between 0.05% - 0.06%. The effectiveness of only about 0.02% Nb out of solution on the austenite grain size is shown in Table VIII (42).

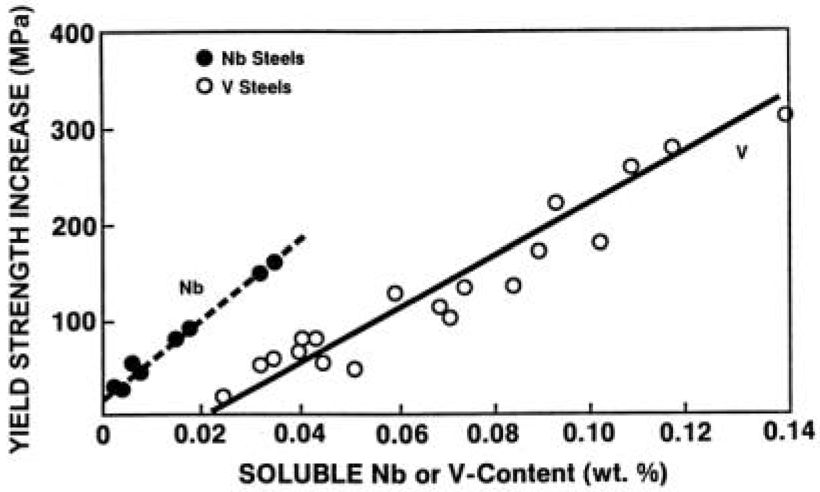

Figure 19: Yield strength increase by precipitation hardening of 0.45% C steels (47).

Of significance also is that the fatigue life behavior has been shown to be related to prior austenite grain size (44), in a linear relationship. Thus, a fine austenite grain size is beneficial for fatigue life in addition to improving toughness.

Table VII Chemical compositions and solubility data of steels used to optimize METASAFE 1000 (42)

a) Chemical Compositions (wt%)

Steel	C	Si	Mn	S	Al	V	Nb	N
A	0.45	0.26	1.57	0.033	0.027	-----	-----	0.013
B	0.53	0.28	1.49	0.030	0.033	0.106	-----	0.012
C	0.47	0.36	1.55	0.022	0.022	0.120	0.065	0.030
D	0.45	0.30	1.52	0.035	0.035	0.120	0.073	0.033
E	0.46	0.30	1.50	0.038	0.038	0.116	0.042	0.018
F	0.45	0.34	1.48	0.035	0.035	0.110	0.070	0.018

b) Solution of Nb, V and Al After Holding for 1h 30 min. at 1250°C

Steel	%V Total %V Dissolved	% Nb Total	% Nb Dissolved	% Al Total	% Al Dissolved
A	0.106	-------	-------	0.033	n.d.
C	0.120	0.065	0.030	0.061	0.038
D	0.120	0.073	0.042	0.034	0.021
E	0.116	0.042	0.032	0.041	0.033
F	0.110	0.070	0.030	0.050	0.034

Table VIII Austenite grain size in the six steels (A to F) after holding for 15 minutes at 1200°C (42)

Cast	A	B	C	D	E	F
Austenite Grain Size (ASTM No.)	3.7	3.5	(5.7	5.6 Nb Steels	6.2	5.4)

In addition to the METASAFE steels, other Nb-V microalloyed forging steels have been produced commercially and a selection is listed in Table IX.

Applications are varied, and in addition to the more common such as connecting rods (Figure 20), crankshafts, camshafts, and steering knuckles, other parts such as anti-sway bars, rear-swivel axel spindles (Figure 21), reaction rods and swivel axle spindle carrier plates (Figure 22) are being produced.

Table IX Some Nb (±V) microalloyed steels for forgings

Steel	Chemical Composition								Mechanical Properties		
									YS	TS	A
	C	Mn	P	S	Si	Nb+V	Nb	V	MPa	MPa	%
C38 mod-BY[1]	0.35 0.40	1.30 1.45			0.50 0.70		0.05 Max	0.05 0.12	600 Min	900 Min	12 Min
Perlitico de Forja[2]	0.48 0.55	0.60 1.00		0.035 0.005	0.40 Max		0.05 0.10		450 Min	800 900	
HVO 80 SL[3]	0.41 0.40	0.60 1.00	<0.035	0.020 0.040	0.15 0.35		0.04 0.06	0.08 0.13	500 Min	800 Min	15 Min
HVO 90 SL[3]	0.48 0.54	0.80 1.10	<0.035	0.020 0.040	0.20 0.35		0.04 0.08	0.08 0.13	550 Min	900 Min	12 Min

*Notes:
1. Steel developed by Gerlach-Werke in Germany.
2. Steel developed by Krupp and Volkswagen in Brazil.
3. Steel developed by Fiat Auto and Deltasider in Italy.

Low Carbon, Multiphase Steels

The "multiphase" family of steels is based on alloying a low carbon (0.10%) steel with manganese, molybdenum and niobium. Two steel grades, which have been developed in North America: BHS-1 (33-36) and FreeForm^{TM} (37), and their basic steel chemistry specifications are listed in Table X.

Niobium is added for both austenite conditioning during controlled hot processing and to control transformation characteristics during cooling. Manganese (1.4% to 2.0%) and molybdenum (0.10% to 0.50%) are also added for transformation control.

Table X Steel compositions of low-carbon, microalloyed, multiphase steels (wt%)

Type	C	Mn	Mo	Nb	Ti	B
BHS-1	0.10	1.6/2.0	0.40/0.50	0.05		
FreeForm™	0.10/0.15	1.4/1.65	0.12 max	0.05/0.12	0.035 max	0.001/0.004

Commercial trials undertaken using the BHS-1 steel have involved the manufacture of connecting rods, idler arm brackets (steering brackets) and lower control arms. The latter component was directly quenched after hot forging and did not undergo any subsequent heat treatment. The mechanical properties exhibited by the latter two components made from conventional and BHS-1, Mn-Mo-Nb steel are given in Table XI [36].

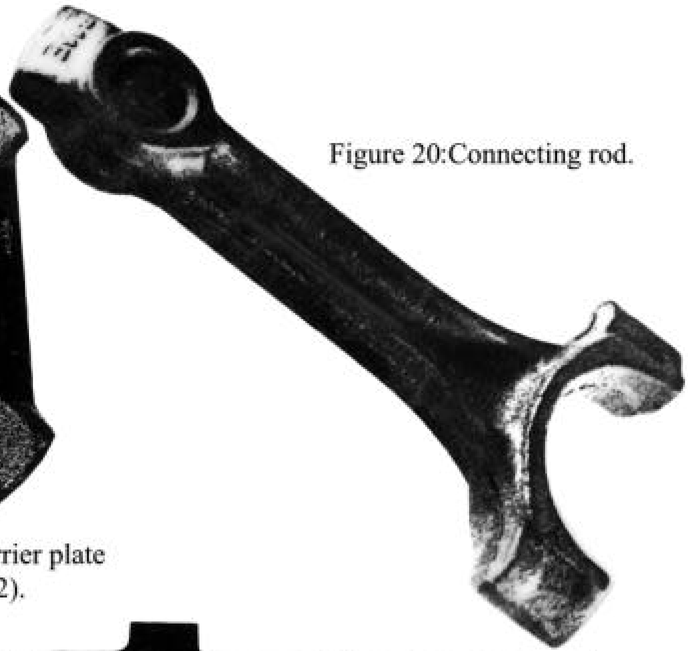

Figure 20:Connecting rod.

Figure 22:Swivel axle spindle carrier plate (METASAFE 700), hot forged(42).

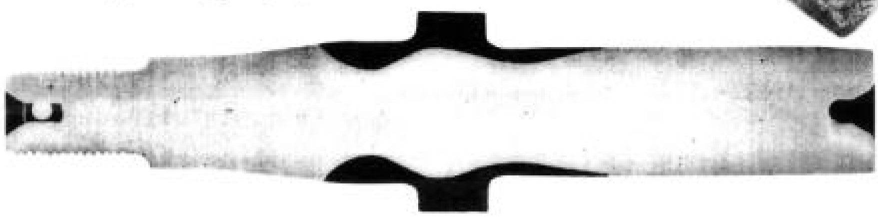

Figure 21:Rear axle spindle (METASAFE 800), induction treated(42).

While the multiphase steel showed higher strength levels with comparable toughness, the obvious advantage of these steels is their vastly superior fatigue properties, a highly important product quality and safety benefit. From a production point-of-view, multiphase steel products can also be manufactured without the need for a costly reheat, quench and temper treatment.

The stress-strain characteristics of the ferrite-bainite-martensite multiphase type of microstructure exhibited by the Mn-Mo-Nb steels are ideal for cold-drawing and cold-heading operations. The continuous work hardening behavior, together with a rapid rate of work hardening, ensures a significant increase in strength after only a small amount of deformation.

Further, the high ductility of the feedstock eliminates fracture during the cold forming operations and also allows complete filling of the die cavity.

Table XI The mechanical properties of commercially produced components from Mn-Mo-Nb (BHS-1) steel (36)

a) Idler Arm Bracket					
Steel	YS MPa	UTS MPa	RA (%)	CVN@RT (Joules)	Average Kilocycles-to-Failure
BC 1038 (QT)	607	697	59	86	134.79±36.5
BHS-1	828	1049	43	96	261.85±46.9

b) Lower Control Arm						
Steel/Processing	YS MPa	UTS MPa	RA (%)	CVN (Joules)	Average Kilocycles-to-Failure	
				25°C - 40°C	Smooth	Notched
1541 (QT)	820	930	60	60 22	105.7	58.6
BHS-1 (DWQ)	935	1197	63	50 32	>1000	>500

A high level of ductility is retained after 40 percent cold reduction, Table XII , and sufficient toughness exists in the final component to resist fracture under service conditions, Table XIII.

Table XII Tensile test data for cold drawn FreeForm^{TM} steel, starting hot rolled size 0.562-inch (37)

% Draft	Y.S. MPa	T.S. MPa	% Total Elongation	% Reduction of Area
0	484	690	24.5	66
26	815	877	14.0	59
40	864	932	12.5	57

* FreeForm^{TM} is a trademark of Ispat Inland Steel Company.

Higher levels of cold drawing reduction produce an increase in strength and fatigue resistance.

Table XIII Mechanical properties of Mn-Mo-Nb 1.27-1.90 cm diameter bars subjected to cold heading trials (34)

Condition	YS MPa	UTS MPa	% RA	CVN Impact Energy, Joules	
				RT	-50°C
Air Cooled (AC)	460	750	65	154	113
AC+20% Red.	972	1012	53	84	54

By comparing the strength properties listed in Tables XII and XIII, the greater work-hardening rate of the higher-manganese, higher-molybdenum steel (BHS-1) is readily apparent. However, both steels, even the leaner-alloyed FreeForm^{TM}, are able to meet Grade 5 and Grade 8 bolt specifications; BHS-1 data is shown in Table XIV (36).

Table XIV Final bolt properties from production trials (36).(Grade 8 Bolt)

Steel	YS MPa	UTS Mpa	RA (%)	CVN @ RT Joules
Grade 8	896	1033	35	----
1335 QT	999	1144	64	47
BHS-1	965	1157	67	58

Notes:
(1) All BHS-1 bolts passed 10° wedge test
(2) BHS-1 bolts had high resistance to H_2 cracking

In addition to the strength and toughness properties, the fatigue properties of fasteners made from Mn-Mo-Nb steel are superior to those produced from conventional quenched and tempered C-Mn (±Mo), AISI 1038 or AISI 4037 steels. While the fatigue limit of the leaner-alloyed Mn-Mo-Nb (TiB) FreeForm^{TM} steel is about 20 percent higher than that of Q&T AISI 1038, Figure 23 (37), it is at, or near, the yield strength of cold-worked FreeForm^{TM}, Figure 24 (37).

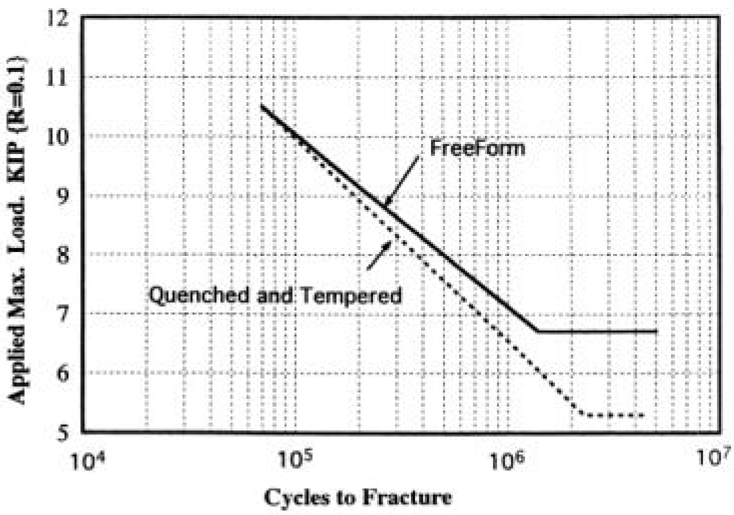

Figure 23: Comparison of fatigue properties of bolts made from Freeform^{TM} steel compared to quenched and tempered AISI 1038 steel (37)

Prior to the aforementioned steels, niobium-boron steels were developed for cold-headed parts (48). The chemical compositions of these low carbon, bainitic matrix steels, with homogenously distributed martensite islands, are presented in Table XV.

Table XV Typical Compositions (wt%) of Nb-B microalloyed steel rod for fasteners (48)

	C	Mn	B	Nb
Grade 1	0.20	1.25	0.005	------
Grade 2	0.15	1.25	------	0.05
Grade 3	0.10	1.50	0.005	0.08

* maximum values.

The Nb-B "grade 3" steel exhibits a tensile strength of about 1000 MPa after 75% wire drawing. Since the yield strength follows a similar trend, and the ductility is sufficient for excellent cold headability, bolts of class 8-8 and 10-9 can be produced to SAE standards from as-rolled wire rod without the need for subsequent heat treatment.

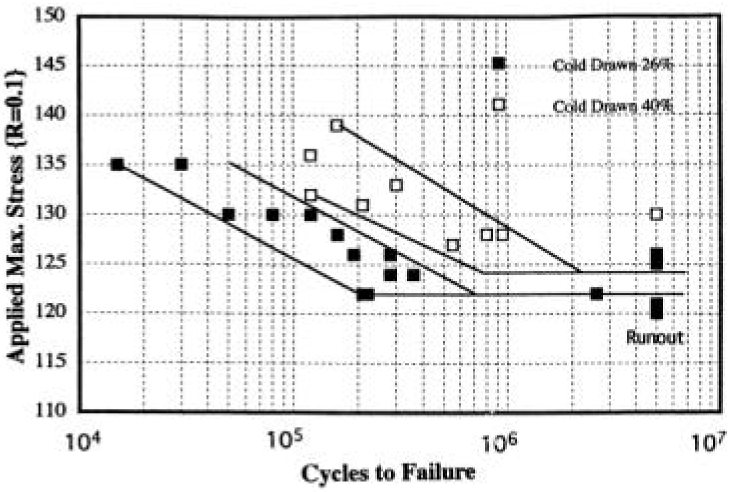

Figure 24: The influence of cold drawing on fatigue strength of Freeform^{TM} steel (37).

In addition, an acicular ferrite steel was developed in Japan for cold forging applications (49,50). The main difference between this Nb-containing microalloyed steel and those discussed above is that a final tempering treatment is needed in order to meet high strength fastener specifications. Even so, a spheroidize anneal and a subsequent reheat and quench are not necessary.

The chemical compositions of the acicular ferrite Mn-Mo-Nb and Mn-Cr-Nb steels are given in Table XVI. A relatively high billet temperature of 1250°C is needed so as to keep niobium in solution in the austenite. The finish rolling temperature is about 850°C and coupled with a heavy hot rolling reduction of 99% results in a very fine acicular ferrite microstructure.

Table XVI Typical steel compositions (wt%) of acicular ferrite Mn-Mo-Nb and Mn-Cr-Nb steels for cold forging applications (49,50)

C	Si	Mn	P	S	Cr	Mo	Nb
0.05	0.25	1.72	0.015	0.011	0.07	0.33	0.051
0.09	0.23	1.59	0.011	0.015	0.51	Tr	0.045

This type of steel easily outperformed conventional quenched and tempered steels in the production of Grade 8.8 bolts. Production of ball tie-rods and other automotive components have been successfully produced using the Mn-0.5%Cr-0.05%Nb steel.

Conventional steels currently used for high strength, cold drawing-heading applications (bolts, nuts, tie rods, studs, and other fasteners) are typically medium carbon steels (AISI 1038 & 1045) sometimes containing alloying elements such as chromium and molybdenum (AISI 4037, 4135, 4140, 5140). To successfully cold form these steels, the wire rod has to undergo spheroidize annealing to facilitate wire drawing and cold heading, and must subsequently be reheated, quenched, and tempered in order to achieve the desired combination of mechanical properties. A comparison of the steps involved in the processing of both conventional and microalloyed steels is shown in Figure 25.

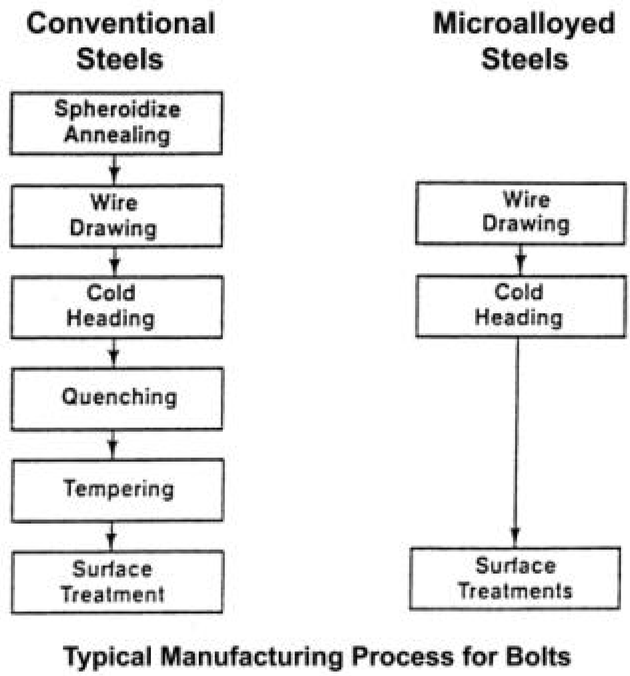

Figure 25: Comparison of processing routes for fasteners/bolt production.

It is the elimination of all the costly and time consuming heat treatments which is by far the major advantage of switching to microalloyed multiphase steels for cold heading and drawing applications. However, the other important costs associated with the elimination of component heat treating problems such as handling and processing damage, potential decarburization problems, reduced handling, and reduced materials inventories, add up to significant savings.

Direct Quenched Forgings

During the 1990's, direct quenching of microalloyed forgings (in addition to multiphase steel) was commercialized in the USA (51,52). The steel, designated Microtuff^{R}, is a 0.10% to 0.20% carbon steel containing about 0.10% niobium. A fine dispersion of undissolved Nb (C,N) particles retards recrystallization and prevents austenite grain growth during forging, trimming, and during any entry delay into the quenchant that might be experienced. The grain size remains fine with better than ASTM 5 at forging temperatures up to 1290°C (2350°F). Niobium taken into solution acts as a potent hardenability agent and is reportedly responsible for providing a 20 percent increase in strength. (Microtuff^{R} is a trademark of Chaparral Steel Company).

Direct quenching produces a martensitic microstructure which is allowed to autotemper. The fine-grained autotempered martensitic forging exhibits exceptionally high yield strength (945-1225 MPa) coupled with an impact transition temperature well below zero.

The Microtuff^R compositions and mechanical properties are given in Table XVII (52). The mechanical properties achieved in Microtuff 10^R are similar to those attained by the conventional reheated, quenched and tempered low alloy AISI 4140 steel. New applications using Microtuff^R are being introduced and a listing of some of the components produced to date is given in Table XVII.

Table XVII The chemical composition (wt%) and mechanical properties of Microtuff^R (52)

C		Mn	P	S	Si	Cu	Ni	Cr	Mo	Nb	N
0.10 or	0.15	1.65	0.03*	0.03*	0.50	0.35*	0.20*	0.25	0.15	0.09	0.012
0.15	0.20	2.00			0.70				0.20	0.12	0.020

*Denotes a maximum value

Y.S. MPa	T.S. MPa	RA%	EI%	Hr_c	CVN Energy at 0°C Joules
945	1190	25	8	38	40
1225	1540	min.	min.	45	min.

Applications of Microtuff^R

-HAND TOOLS
Striking tools, cutting tools, wrenches

-HARDWARE
Hooks, tie down connectors, barge connectors

-INDUSTRIAL
Digger teeth, conveyor chains, rail anchors

-AGRICULTURAL
Tillage tools, cutting blades, fertilizer knives

Heavy Forgings

Impressive elevated temperature properties have been developed in a 0.06% Nb-modified, 9 Cr-1 Mo-0.2 V forging steel. This steel was commercially melted in the United States some two decades ago and has been successfully fabricated into tubes, pipes, plates, bars, and forgings.

As an example, a heavy-walled (67mm) cylinder saddle-forged from a billet and normalized at 1050°C and tempered at 760°C exhibited isotropic properties with a yield strength of around 550 MPa at room temperature. A yield strength above 400 MPa (450 MPa T.S.) was retained at a temperature in excess of 500°C[53].

The 68 J Charpy V-notch impact transition temperature for the ¼ and ½-thickness sections were -36°C and -37°C, respectively, indicating uniform toughness throughout the wall thickness.

Modifications to 1%Cr-Mo-V steels, which include a 0.04% Nb addition for austenite grain refinement and enhanced tempering resistance, have resulted in a creep rupture strength that exceeds that of the standard 1%Cr-Mo-V grade[(54)]. Also, the niobium addition generally improved both toughness and creep rupture ductility through austenite grain refinement.

The modified steel is used for high-temperature turbine rotor applications and in high-temperature-low temperature rotors.

Other grades of steel for heavy forgings include the high Mn-0.10% Nb, FAMA steels (55), a typical application being anchor chains, and Imacro (4.4%Cr-0.08%Nb).

In summary, all of the aforementioned grades utilize a niobium addition for austenite grain size control, transformation hardening and precipitation strengthening to produce an optimum combination of mechanical properties.

Summary

In addition to the well-established products and main applications of Nb-microalloyed steels in wrought plate and strip, these steels are now finding increasing usage in smaller but still developing fields such as castings and forgings. Their combination of high strength, good toughness, good weldability, and good fatigue properties enables microalloyed steels to replace heavier non-alloyed or lower-alloyed steels.

In microalloyed steels, niobium is instrumental in ensuring high strength coupled with good toughness, while vanadium offers an additional precipitation strengthening contribution. The synergistic effect of molybdenum and niobium contributes to increased precipitation strengthening due to Nb(Mo)(C,N) particles. In addition, molybdenum provides an individual effect on austenite transformation control.

The flexibility in the design of castings also provides an opportunity to replace fabricated components. Castings can be produced with varying cross-sections so as to optimize thickness relative to the prevailing stress concentrations and rigidity requirements. This enables significant weight savings to be made as in the case of construction nodes. The use of microalloyed cast steels to replace similar or lower strength, higher alloyed wrought steels in a fabricated structure not only offers direct cost savings but also gives an excellent improvement in fatigue properties and the elimination of weldments from critical areas of the construction. Irrespective of the latter, the lower carbon content of microalloyed steels ensures good weldability, and a preheat and/or a post-heat treatment may not be necessary.

Because of the nature of the foundry industry the widespread adoption of microalloying technology is a more difficult proposition than that experienced by its wrought steel producing counterparts. The production of large tonnages of a single wrought product at only a few sites, for example, linepipe skelp, plates for offshore construction, and automotive strip, has enabled microalloying technology to be more readily adopted.

Substitution of currently used cast steels by microalloyed steels has to be considered on an individual product basis and is consequently dependent on the acceptance of such technology by an individual foundry. The replacement of fabricated components by microalloyed steel castings is undoubtedly even more difficult irrespective of the numerous advantages offered. This makes the progress made in the offshore industry during the last two to three decades of great significance.

The combination of excellent properties exhibited by microalloyed steels would seem to ensure that they will continue to find increasing application in the foundry industry. As a word of caution, the inherent processing procedures of individual foundries dictate that mechanical properties exhibited by a particular steel composition in one foundry may not necessarily be exactly reproduced in another foundry, and some "optimzation" may be required. However, in such a case, microalloying technology has progressed to the stage whereby "fine-tuning" of cast products can be readily undertaken and the required properties readily achieved.
Also, microalloyed steels exhibit improved elevated temperature properties when compared with conventional steels and the effect of niobium on increasing high temperature creep resistance has resulted in such steels being recently employed in cast slag pots and other applications.

Microalloyed steels, especially Mo-Nb steels, offer a new dimension to forging and cold-heading industries enabling spectacular processing cost savings (about $200 per ton) by eliminating the reheating, quenching and tempering, and straightening treatments of forgings, and additionally, the need for a spheroidizing anneal in the case of cold-headed products.

Microalloyed forging steels not only exhibit enhanced combinations of strength and toughness but certainly in the case of forged components for automotive applications enable vastly superior fatigue properties to be produced. The latter provides a much needed safety benefit.

Direct quenching of Mn-Mo-Nb forged steels also provides for an exceptionally high yield strength coupled with excellent toughness with niobium being instrumental in transformation control. Such direct quenched steels are finding increasing applications in the tool and machinery industries. Cost savings associated with reduced processing procedures makes these direct quenched steels prime candidates for many applications.

To conclude, niobium-containing, microalloyed steels are not only finding increasing usage within a proven application by enhancing steel properties and establishing a new frontier with respect to cost savings, but are also establishing themselves in new or less-proven applications.

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