NIOBIUM IN STRUCTURAL SECTIONS

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Introduction

Most of the early high strength, structural sections* were based on medium carbon steel. For example, the steel supplied in 1929 for the Sydney Harbor Bridge was made to the following specification:

%C	%Si	%Mn	Y.S. N/mm^2	UTS N/mm^2	%el(200 mm)
.32/.42	.15/.25	.60/1.00	323 (min)	551/659	17/20

Although in later specifications there was a small decrease in the maximum C content it was not until the widespread use of fusion welding that significant decreases in C content were made. For example, in 1941 in the UK, BS 968 was introduced which specified steels with C contents of 0.23 percent maximum and with optional alloying additions of Ni and Cr.

From about 1959, after its introduction to structural steels in the USA, the use of Nb as a micro-alloy addition to plates, sections and bars became widespread and BS 968 was revised in 1962 to take account of this. By allowing a reduction in the C, Mn and Cr contents the Nb addition conferred improved weldability. Another attribute of Nb, of special significance in countries like the USA and the UK, was its effectiveness in semi-killed steels.

Certain companies in the UK offered steels with a strength higher than that of BS 968 1962 (1,2), viz, a minimum yield strength of 470 N/mm^2 for section thicknesses up to about 12 mm with an addition of Nb up to 0.08 percent. In 1968 a single comprehensive specification was issued as BS 4360 which included all the widely-used structural steels in the UK including both

*Sections are often referred to as shapes and these terms can be used interchangeably.

plates and sections. Similar specifications have been issued in other countries to include structural steels which contain Nb as an alloying element. In general, for weldable structural steels, the C-Mn grades have a minimum yield strength of about 250 N/mm^2 while an addition of Nb allows the minimum yield strength to increase to about 350 N/mm^2 (BS 4360, DIN 17100, NFA 35/501, UNI 5335, ASTM A572, Euronorm 25/72). Certain grades have minimum Charpy V notch impact requirements. However, the greatest proportion of structural sections is sold with no impact requirements; for example only 3 1/2 percent of those sold by British Steel Corporation in 1978 were required to possess an impact test certificate (3).

The majority of structural sections sold are of the C-Mn type since it is difficult in many applications to be able to take advantage of the extra strength offered by the high strength low alloy grades, the limiting design factor being elastic deflection. It could be argued that the minimum yield stress of 250 N/mm^2 specified for the C-Mn grades is too low because the stress due to the mass of the section itself becomes a significant proportion of the maximum allowable design stress and therefore the beam has a very limited load bearing capacity. The HSLA grades are widely used for such applications as piling, bridges, ships, road and rail transport, mobile cranes etc. where a high strength to weight ratio is of prime importance. In recent years, structural sections in HSLA steels have also been used in the construction of accommodation modules for offshore oil production platforms where the cladding material is steel plate (Figure 1).

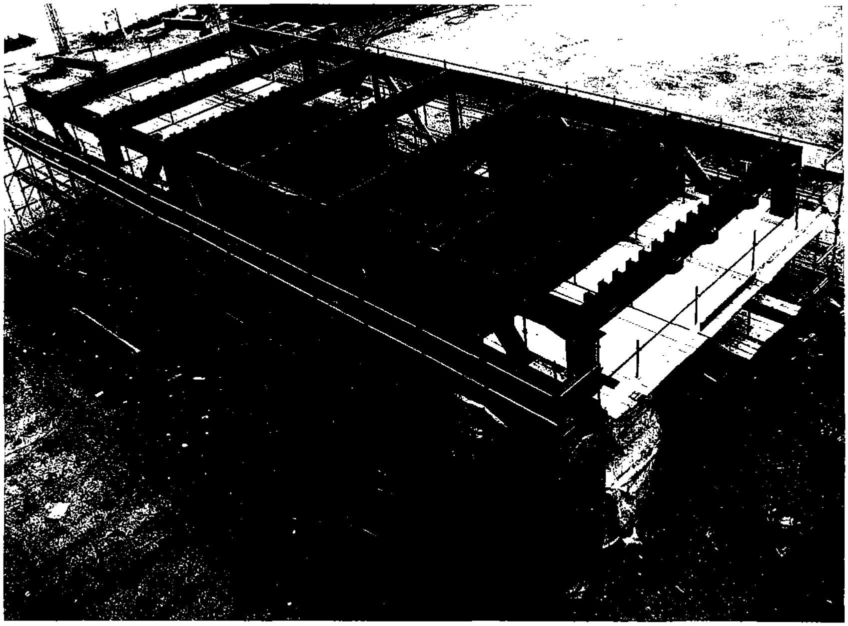


Figure 1 - Construction of an acommodation module for an off-shore oil production platform utilizing low C, Nb-treated steel sections (Arctic 355).

Sections are subject to a variety of rolling conditions depending on mill characteristics and rolling procedures. Rolling may terminate at temperatures as high as 1100 C or continue well into the $\gamma + \alpha$ range. The influence of Nb on the mechanical properties is related to rolling conditions and is optimum when rolling temperatures are relatively low. Impact properties in particular deteriorate when finish rolling temperatures (FRTs) are above about 1000 C. There are major advantages, therefore, associated with controlling the rolling schedule and controlled-rolling, already widely practiced in plate production, is now finding a limited use in section production. A parallel development, also similar to that in plates, is the trend towards lower C levels which leads to a tougher, more weldable product.

Structural Factors

Structure/Property Considerations

The major benefits of Nb in the hot rolling of sections are related to its ability to reduce the rate of recrystallization and grain growth of austenite thus contributing to the refinement of the microstructure. It has been shown quantitatively by Petch (4,5) that strength and toughness are optimized by minimizing the ferrite grain size. For example the strength of a HSLA section can be calculated utilizing an equation based upon controlled-rolled plate data. (6)

$$\sigma_{LYS} = \sigma_o + \sigma_S + \sigma_p + k_Y d^{-1/2} \qquad (1)$$

where σ_{LYS} = lower yield stress

and σ_o, σ_s, σ_p and $k_Y d^{-1/2}$ are contributions from the friction stress, solid solution, precipitation and grain size strengthening respectively.

We can take the example of a C-Mn-Nb steel rolled to different ferrite grain sizes, the general microstructure being ferrite plus pearlite. Table I shows the various contributions to the strength of this steel. The contribution from NbCN precipitation strengthening is based on average values taken from the literature (6). The importance of refining the ferrite grain size is apparent and this is true not only for strength but also for impact properties. The fine-grained steel would have an impact transition temperature about 50 C lower than that of the coarse-grained steel. One of the assumptions made in the calculations given in Table I is that the steels have a ferrite/pearlite microstructure. In practice, as a result of the influence of Nb on the transformation characteristics of a steel in the hot-rolled condition, a coarse-grained steel will often contain substantial amounts of Widmanstatten ferrite or bainite which can make a significant contribution towards the strength (while usually impairing impact properties) (7,8) so that there is often little difference in strength between fine and coarse-grained Nb-treated as-rolled sections. Table II illustrates the effect of Widmanstatten ferrite on the mechanical properties of sections rolled from the same cast but to different FRTs. The results in the table show that for a similar grain-size an increase in the volume fraction of Widmanstatten ferrite leads to a higher strength and poorer impact properties.

Table I. Calculated Contributions to the Strength of a Typical HSLA Steel of Composition 0.18% C, 0.30% Si, 1.40% Mn, 0.03% Nb.

STRUCTURE	σ_o N/mm^2	σ_s N/mm^2	σ_p N/mm^2	G.S. μm	$k_y d^{-1/2}$ N/mm^2	LYS N/mm^2
Coarse Grained	70	70	45	25	105	300
Fine Grained	70	70	45	8	202	387

Table II. The Influence of Widmanstatten Ferrite on the Mechanical Properties of Piling Sections of Composition 0.15% C, 0.01% Si, 1.40% Mn, 0.028% Nb.

FRT °C	FLANGE THICKNESS mm	PS* N/mm^2	UTS N/mm^2	el %	27J ITT °C	G.S. μm	WIDMANSTATTEN FERRITE %
1000	17	344	499	27	-20	14.2	32
1040	17	376	543	21	0	13.2	53

* 0.2% proof stress

In section rolling, the feedstock, which is usually in the form of a rectangular or square-section bloom is heated to a fixed temperature and then undergoes a series of shaping passes until the final shape is obtained. The FRT is influenced mainly by the reheating temperature and the total rolling time, the latter being related to mill characteristics and also to the type of section being rolled. It is possible for the FRT to vary from about 1100 C to 800 C. Some examples of the FRTs of different types of sections rolled in the same mill from the same reheating temperature are given in Table III. Note also the variation in FRT between the web and the flange.

Widmanstatten Ferrite

As previously indicated the combination of Nb in solution and a high FRT which gives a coarse austenite grain size, can result in a structure of polygonal ferrite and Widmanstatten ferrite or bainite. A typical strucutre is shown in Figure 2 which suggests that in a duplex austenite grain structure the large grains form Widmanstatten ferrite. Nb in solution in austenite is known to depress the Ar_1 and Ar_3 temperatures of a C-Mn-Nb steel (9,10) but generally an additional hardenability effect from a coarse austenite grain size or extra alloying elements is required for Widmanstatten ferrite or bainite to form. The bainite formed in Nb treated sections with C and Mn levels above certain values (> .12% C and > 1.0% Mn) tends to give poor impact properties (7,8) (approximately 2°C increase in impact transition temperature per percent bainite, Figure 3). Although it is possible to reduce the bainite volume fraction in a Nb treated steel section by reducing the Mn level (see for example Figure 4) it has been found that this does not necessarily lead to improved impact properties. This apparent anomaly is due to the fact that grain boundary carbide thickness tends to increase as Mn decreases and impact properties deteriorate as carbide thickness increases (12).

Table III. Finish Rolling Temperatures of Various Types of Sections

SECTION	FLANGE THICKNESS mm	WEB THICKNESS mm	FINISH ROLLING TEMPERATURE °C FLANGE	WEB
432 mm Bulb Flats 70.53 kg/m	14.7		920	
4N Piling	14.0	10.4	980	930
305 x 305 mm U.C. 97 kg/m	15.4	9.9	1000	890
305 x 305 mm U.C. 137 kg/m	17.8	17.8	1050	
305 x 305 mm U.C. 283 kg/m	44.1	26.9	1100	

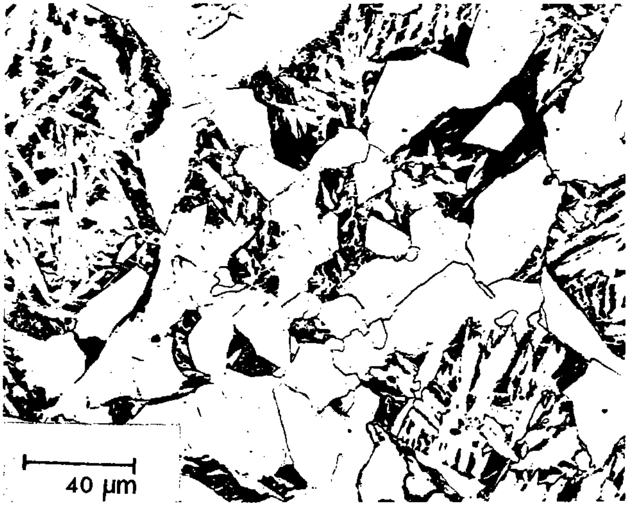


Figure 2 - Coarse-grained Widmanstatten ferrite

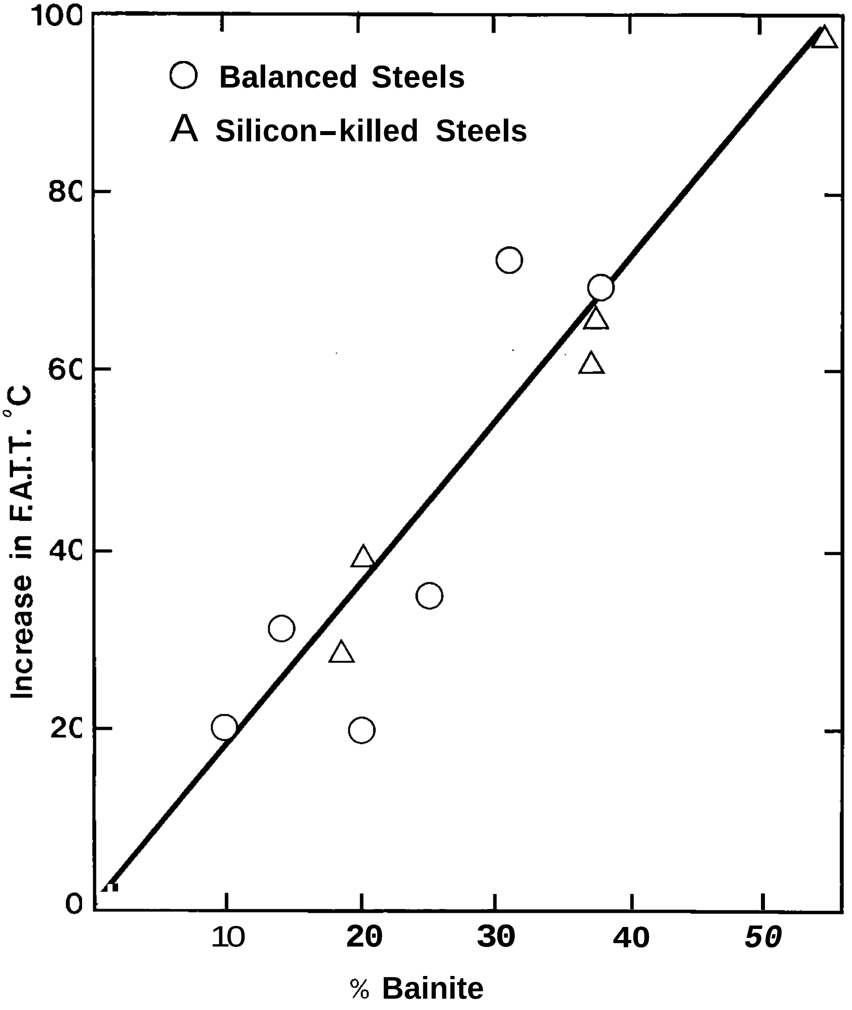
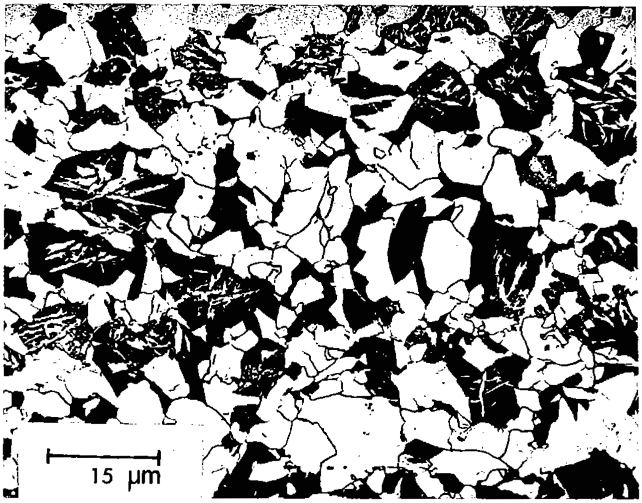
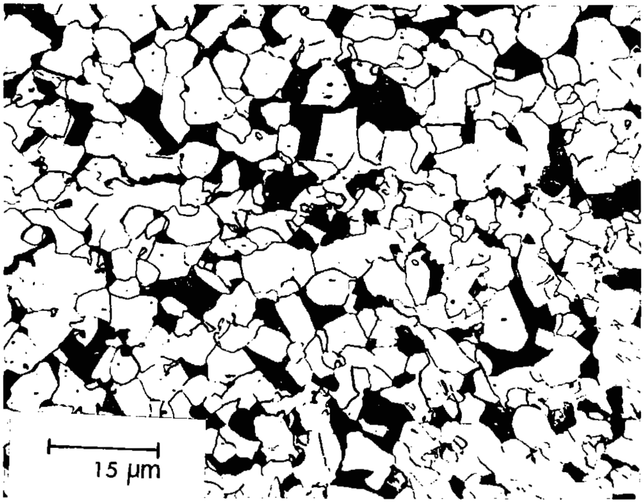


Figure 3 - Relation between % bainite and Charpy V-Notch 50% fibrous appearance transition temperature of steels with a base composition 0.18% C, 1.40% Mn, 0.03% Nb.



(a)



(b)

Figure 4 – Influence of Mn on the occurrence of Widmanstatten ferrite (a) 1.4% Mn-Nb (b) 1.0% Mn-Nb-V.

The influence of Widmanstatten ferrite or bainite on impact properties as indicated in Figure 3 is an over simplification since it is known that factors such as C content and bainite colony size or prior austenite grain size are important (13, 14). Therefore, even if low FRTs and austenite grain refinement are not sufficient to completely remove the bainite, the smaller colony size per se should improve impact properties.

In Nb-treated steels finish-rolled below about 1000 C the impact properties are improved (15) (Figure 5), not only as a result of the virtual absence of Widmanstatten ferrite or bainite, but also as a result of two other factors discussed below.

(a) a refinement in ferrite grain size

(b) a reduction in the precipitation strengthening effect of NbCN

Grain Refinement

To maximize ferrite grain refinement it is important that during rolling there is sufficient total deformation (about 70%) and deformation per pass (> 10%) within the recrystallization temperature range to significantly refine the austenite grain size. When rolling is continued at lower temperatures, a Nb addition aids the retention of deformed austenite grains which leads to further ferrite grain refinement. For example the addition of 0.04 percent Nb can delay the static recrystallization of austenite by about 2 1/2 orders of magnitude (16) and greater additions of Nb, if previously taken into solution at the reheating temperature, can delay recrystallization even further (17). Thus at temperatures below about 1000 C the austenite grain shape in a Nb-treated section is closely related to the rolling deformation. Since ferrite grains nucleate mainly at austenie grain boundaries there is very nearly a 2:1 relation between the austenite boundary spacing in the through-thickness direction and the ferrite grain size (18). This relation holds true for small deformed austenite grains but for larger austenite grain sizes deformation bands can also act as nucleation sites thus effectively increasing the ratio (19).

Strain-Induced Precipitation

In the absence of deformation the precipitation kinetics of NbCN in austenite are sluggish (20). However significant NbCN precipitation occurs during rolling particularly at temperatures around 950 C which approximates to the temperature of the nose of the C curve (21,22). The precipitates thus formed in the austenite are too large to play a significant role in the strengthening of the ferrite so that rolling in the range 900–1000 C effectively reduces the precipitation strengthening contribution from the Nb addition.

Another consequence of the strain-induced precipitation of NbCN is that there is less Nb in solution to influence transformation characteristics. This effect together with the influence of retained austenite deformation on the kinetics of the ferrite reaction gives a structure relatively free of acicular, low-temperature transformation products. It is observed that although the impact properties are improved with a decrease in FRT the strength of steels with Nb contents around 0.03 percent is not markedly changed (15). This arises from the trade-off between the reduced precipitation strengthening and the increased strength from grain refinement.

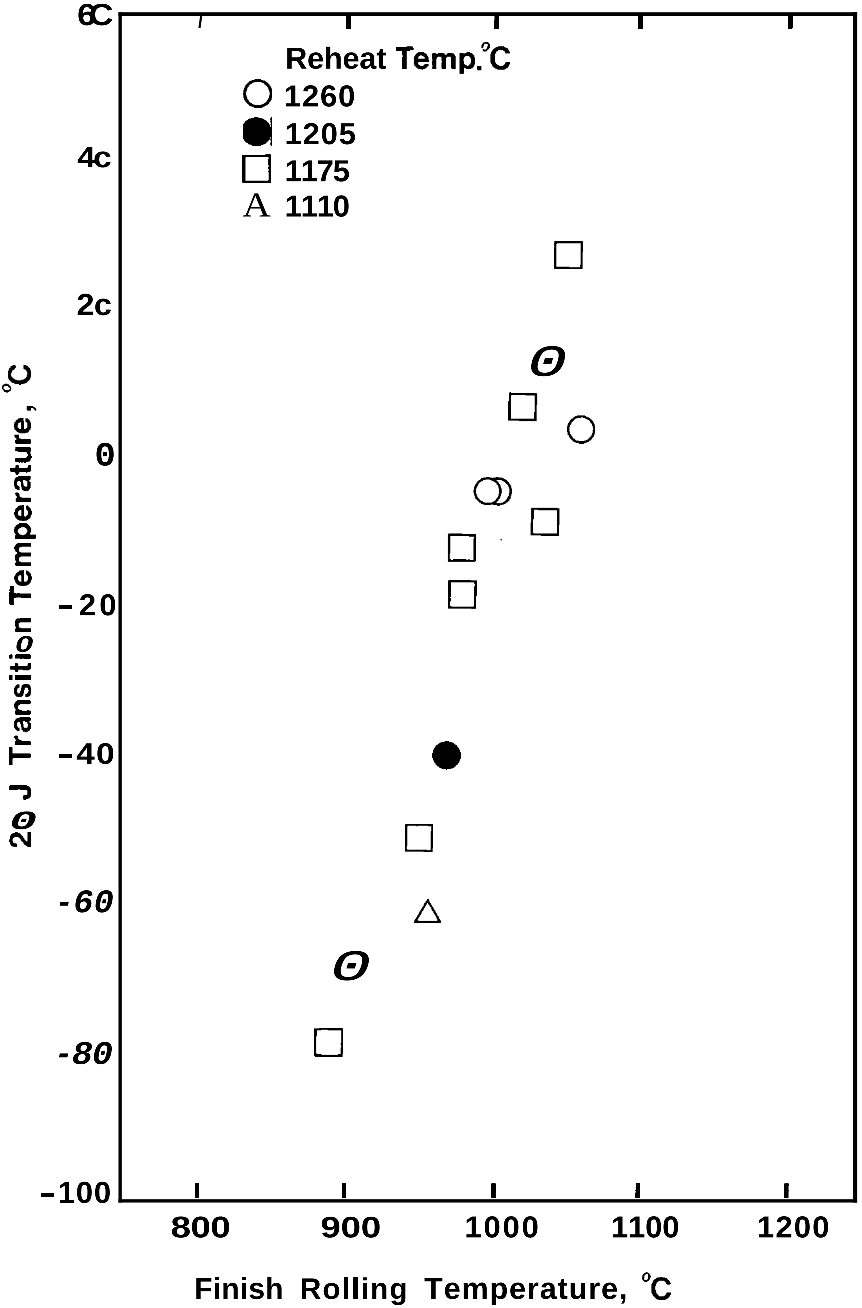


Figure 5 - Influence of finish rolling temperature on impact transition temperature for steels containing 0.11% C, 1.30% Mn and 0.08 to 0.12% Nb (15).

Controlled Rolling

It has been shown that an excellent combination of strength and impact properties can be obtained in Nb-treated sections if rolling can be controlled in such a way that a significant amount of deformation occurs in the lower austenite region. For example a simple two stage rolling process can be utilized similar to that used in the controlled rolling of plates (23, 24). In such a process the austenite is deformed in a temperature range above 1050 C in order to refine the austenite grain size. If given a total deformation of around 70 percent a fine austenite grain size is formed by static recrystallization after each pass (16, 18).

This partially-rolled section is then held until the temperature is below about 900 C when the finishing passes are given. Since recrystallization is sluggish in a Nb-treated steel the austenite grains become pancaked leading to significant grain refinement as discussed earlier. If rolling is continued into the $\gamma + \alpha$ region sub-structured ferrite is formed giving further strength increases with little deterioration in impact properties (23, 25).

Although controlled rolling of sections leads to an attractive combination of strength and ductility there are important reasons for the relative lack of activity in this area. When the rolling temperature is reduced the rolling loads are increased and many mills are not designed to resist the additional stresses. Additionally the presence of Nb in a temperature range in which the recrystallization rate is reduced can significantly increase rolling loads above those of C-Mn steels (26-29). In such situations passes may not be filled and shape problems can occur. Because a delay is incorporated in the rolling procedure, controlled rolling can increase rolling times and thus reduce productivity. This disadvantage can largely be overcome by utilizing off-line holding of partially-rolled sections as in the controlled rolling of plates (30). Finally there has been little commercial incentive to control roll since it is mainly the notch toughness which is improved and the demand for notch tough sections is at present relatively small. However, controlled rolling can allow a reduction in the CEV for the same level of mechanical properties and this can be advantageous to fabricators (31).

Descriptions have appeared in the literature of systems installed in section mills by which the temperature of the stock is controlled so that the finishing passes are given in the lower austenite region (30, 32, 33). The principle involves the use of pyrometers which measure the temperature of the steel before its entry to the finishing stand. If the temperature is above some predetermined value the partially-rolled section is held (preferably off-line) until the required temperature is reached and then it enters the finishing stand. Figure 6 shows the layout of a British Steel Corporation mill in which controlled rolling is practiced (32). After the material leaves the roughing stand, which may be either on the east or west side depending on the number of passes given, it enters the holding area. During the last pass on the roughing mill and its transfer to the holding area, the temperature is measured by a pyrometer which scans the roller table. The micro-processor-controlled pyrometer locks onto the steel and the temperature is recorded. As the material passes into the hold area its movement is detected by optical sensors and a signal passed to the computer. The temperature is then calculated by the computer using a known cooling rate and when it reaches a certain value rolling is re-commenced.

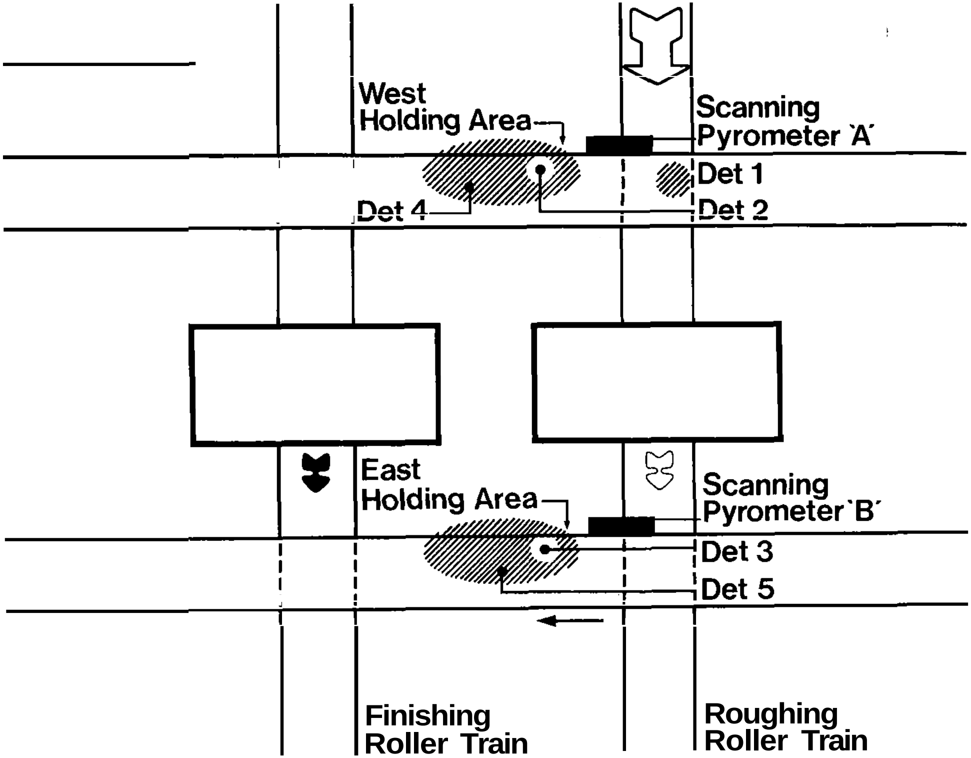


Figure *6* - Plan view of mill showing the fields of view of the pyrometers and of the hot metal detectors (Det 1–5) which are used to "track" the progress of sections through the mill (32).

Variability of Temperature/Deformation Within a Section

During the rolling of a section, unlike a plate, different deformation and temperature conditions are normally experienced over the cross section. This often leads to a variability in mechanical properties and, although not a major problem since test piece locations are generally specified, it is nevertheless a topic worth of study. Figure 7 shows the finishing temperature distribution in two H sections at two finishing temperatures *(33)*. This illustrates the generally recognized variations. The flange, except at the edge, is hotter than the web and the highest temperature occurs at the web/flange junction. The ferrite grain size at various positions within an H section has been related to the amount of deformation and the FRT *(33)*. Thus, the flange edge has the finest grain size followed by the web and then the flange while the coarsest grain size occurs in the web/flange junction. The web/flange junction temperature can be approximately 100 C higher than that of the web or flange during the finishing passes. In a Nb-treated steel, therefore, there is a tendency for Widmanstatten ferrite or bainite to form at the web/flange junction due to the increased hardenability as a result of the coarse austenite grain size. It would be necessary to apply differential cooling using water or air jets, particularly during the later stages of rolling if the aim is to attain uniform properties over the cross section.

The mechanical properties are usually enhanced if the section is allowed to cool efficiently on the cooling banks, for example by having the section lengths well separated and enhancing the natural air cooling rate by using some form of controlled forced cooling *(34)*.

Property Improvement in Conventionally-Rolled Sections

Attempts have been made to refine the grain size of steel finish rolled at a relatively high temperature by utilizing a high Nb content (⩾ *0.06%)* *(35, 36)*. Grain refinement can occur from (a) the presence of fine undissolved particles and/or (b) an increased level of Nb in solution which raises the temperature at which recrystallization becomes sluggish. Figure *8* shows that the austenite grain size at the soaking temperature can be considerably reduced at high Nb levels (15). However, there is evidence that the advantage of starting the rolling schedule with a relatively fine austenite grain size is largely lost after a rolling reduction of approximately 70 percent. Figure 9 from the work of Cuddy *(18)* illustrates this point with data from steel containing various grain refining elements although other results reviewed by Sellars (16) indicate that it should still be advantageous to start with a fine austenite grain size since this tends to give a finer grain size after deformation.

Smith et al *(37)* noted that there appeared to be no advantage in starting rolling with a fine austenite grain size in a low C, high Nb steel. They concluded that the larger amount of Nb in solution obtained by soaking at a higher temperature was more important, despite the large starting austenite grain size, since it raised the temperature range within which recrystallization became sluggish. Nevertheless the available evidence indicates that low C, high Nb (⩾ *0.06%)* sections must undergo controlled rolling in order to optimize the mechanical properties (15, *38)*. This is illustrated in Figure 9 and also in Figure 10 which shows the impact properties obtained from different positions in the flange of a beam of low C, high Nb steel after controlled rolling (finishing temperature < 1000°C) and conventional rolling (finishing temperature > 1000°C) *(38)*.

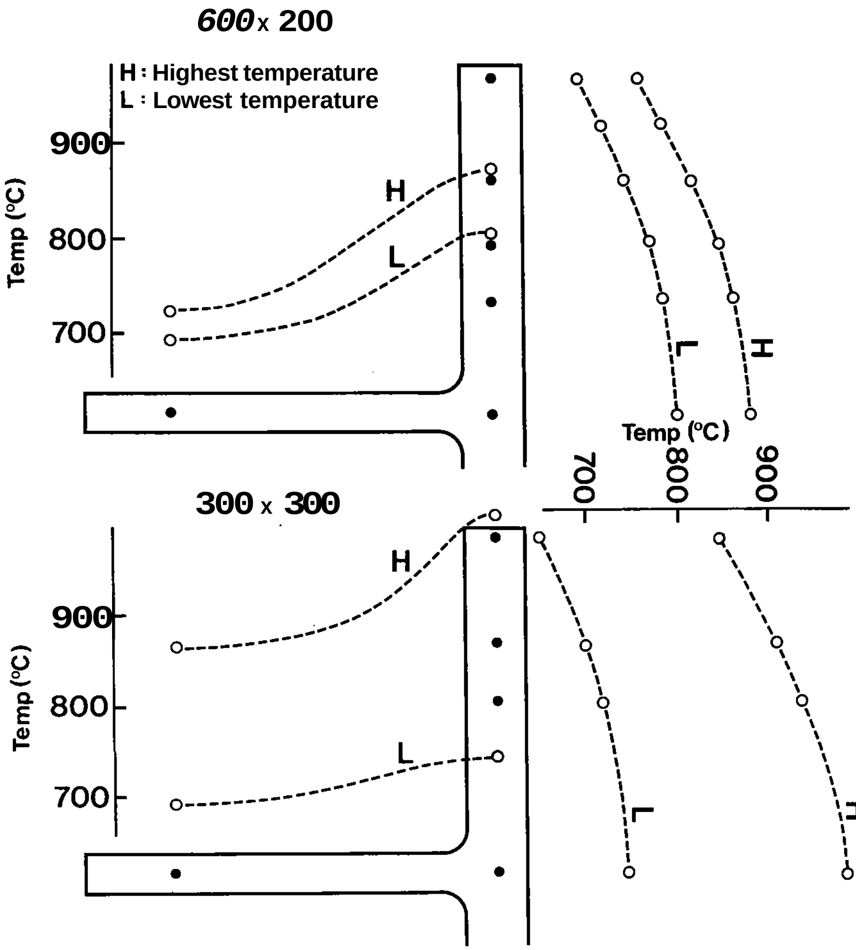


Figure 7 – Finishing temperature distribution within two sizes of H section (33).

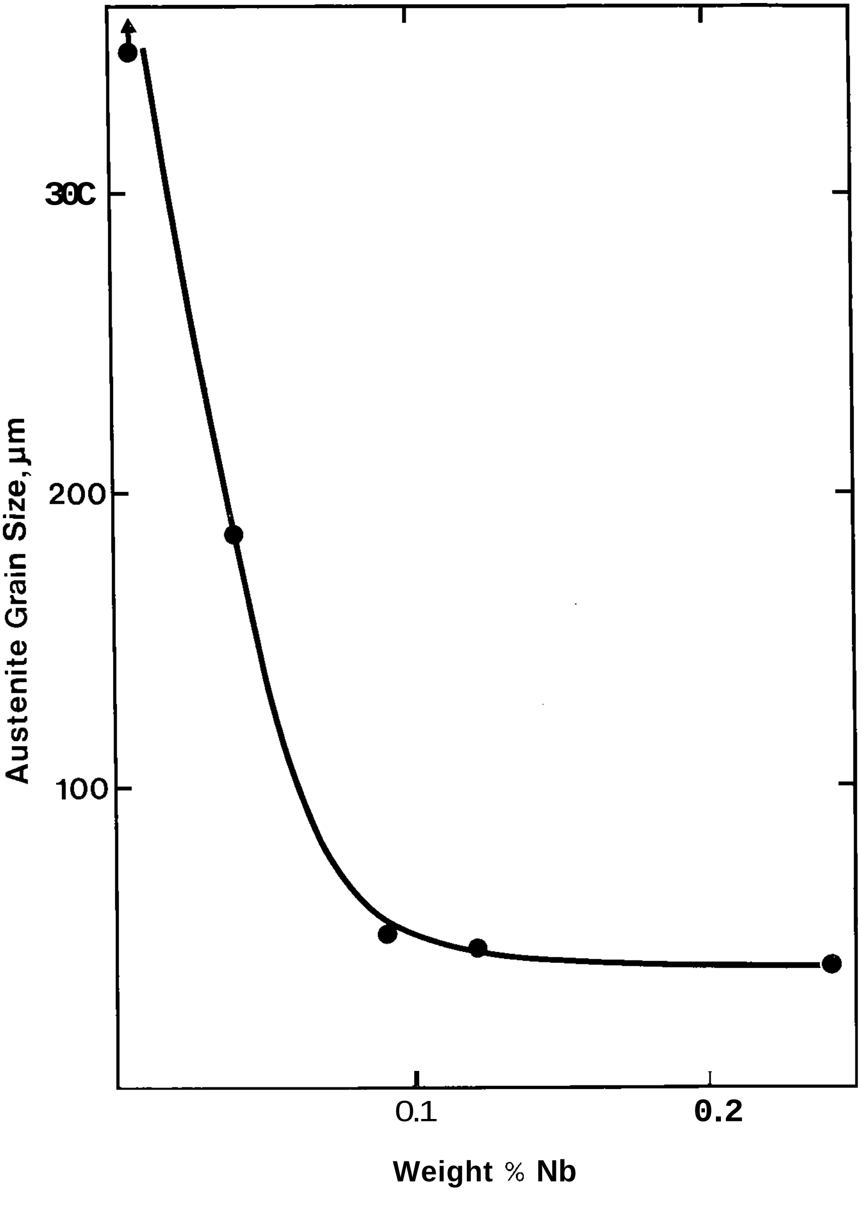


Figure 8 - Influence of Nb content on austenite grain size at *a* reheat temperature of 1175 C. Base composition 0.11% C, 1.30% Mn, 0.30% Si, 0.03% Al (15).

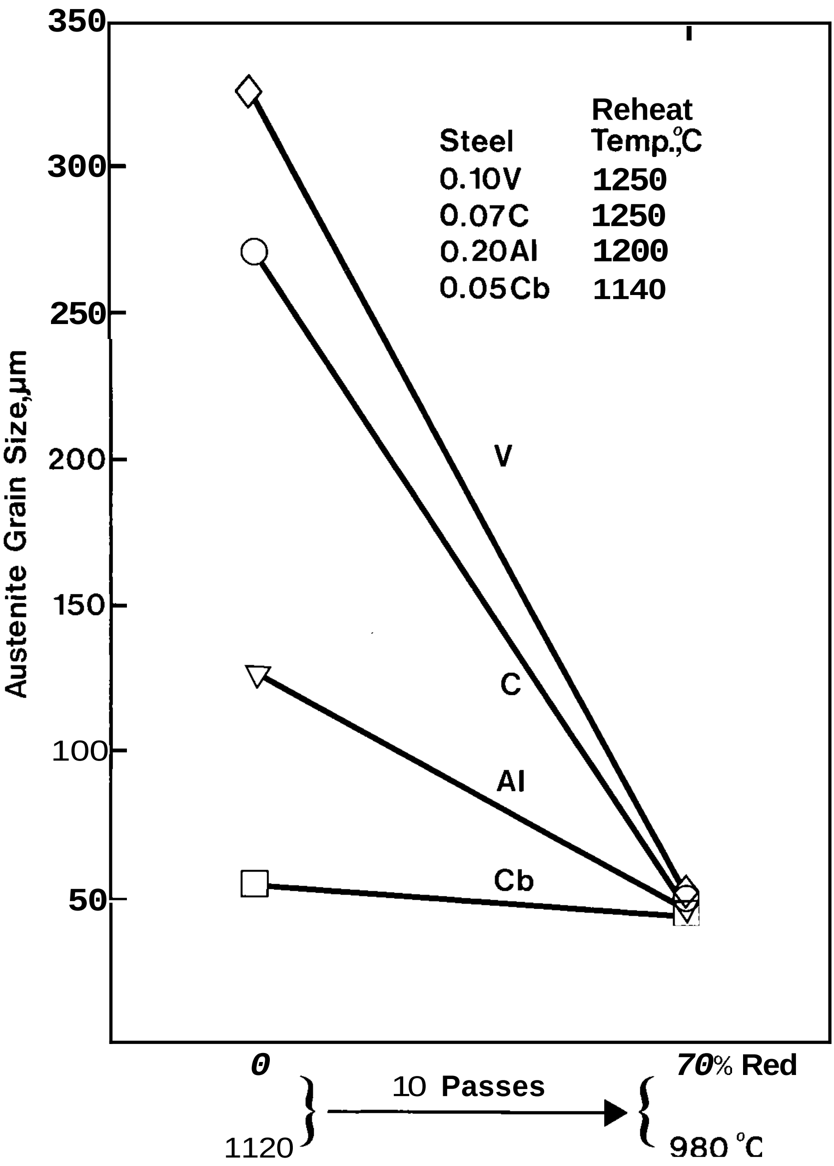


Figure **9** – Refinement of the initial grain sizes **in** four steels **by** a 10 pass roughing schedule. 70% reduction between 1120 and 980 C.

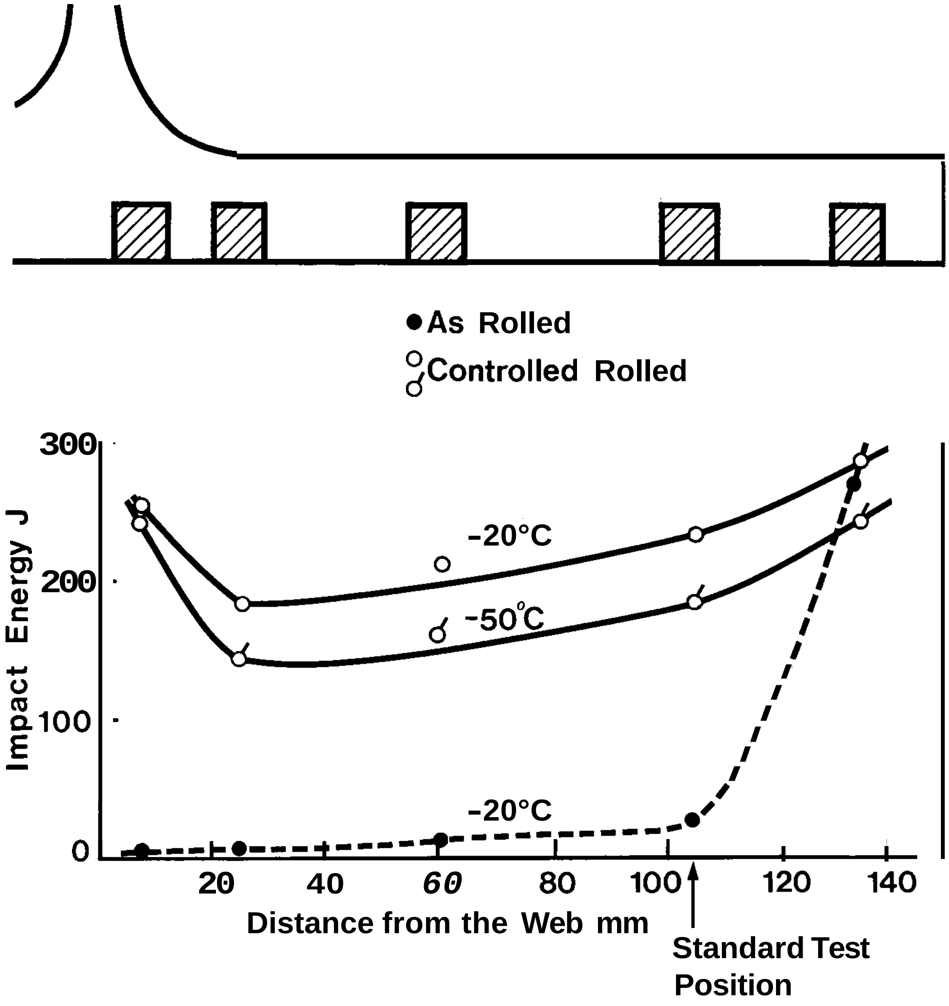


Figure 10 - Influence of rolling procedure on the impact properties at different positions within the flange of a beam of composition .051% C, 1.66% Mn, 0.42% Si, 0.018% S, 0.017% P, 0.0051% N, 0.035% Al, 0.138% Nb (38).

Heat Treatment of Sections

Sections may be heat treated to improve the mechanical properties. The main type of heat treatment is normalizing which is usually carried out to improve impact properties. When a Nb-treated section is normalized, the presence of a fine dispersion of NbCN allows the formation of a fine grain size. However, if the Nb content is very low or if the as-rolled grain size is particularly fine there may be little or no grain refinement after normalizing. Table IV compares the as-rolled and normalized properties of a universal beam containing 0.01 percent Nb and no Al addition. In this example the grain size actually increases from 7.1 to 10.0 μm after normalizing, and the yield stress shows an unexpectedly large decrease of 170 N/mm^2. Approximately half of this decrease in strength can be related to increased grain size (~ 40 N/mm^2) and the loss of precipitation strengthening (~ 40 N/mm^2). The remainder of the strength loss can be accounted for by the removal of the ferrite sub-structure which had resulted from a low FRT in the $\gamma + \alpha$ range. Such low temperature deformation has been shown to give a significant strength increase with little effect on impact properties (23, 25). It is thought that the embrittling effect of dislocation strengthening is partially counteracted by the occurrence of fissuring in the test piece during fracture (25). Therefore, since the effect on impact properties of an increase in the grain size is balanced by the influence of a reduction in precipitation and dislocation strengthening, the overall effect of normalizing in this particular example is to cause no change in the Charpy V-notch transition temperature.

The benefits to the impact properties of normalizing an initially coarse-grained, as-rolled section can be seen from the results contained in Table V. The results are taken from the investigation into the effect of normalizing on the mechanical properties of two sizes of bulb flats, 160 x 7

Table IV. The Mechanical Properties of a 457 x 152 mm Universal Beam (Flange Thickness 11 m) in the As-Rolled and Normalized Conditions. Steel Composition 0.16% C, 0.01% Si, 1.32% Mn, 0.01% Nb.

HEAT TREATMENT	CODE	YS N/mm^2	UTS N/mm^2	el %	CHARPY ITT	GRAIN SIZE μm
As-rolled	415	548	634	16	275 at -45 C	7.1
Normalized	428	378	541	24	273 at -45 C	10.0

Table V. The Influence of Normalizing on the Mechanical Properties of Two Sizes of Bulb Flats. Steel Composition .18% C, 0.21% Si, 1.26% Mn, 0.006% P, 0.020% S, 0.027% Al, 0.031% Nb.

	AS-ROLLED				NORMALIZED			
SECTION SIZE	YS N/mm^2	UTS N/mm^2	345 ITT C	GRAIN SIZE μm	YS N/mm^2	UTS N/mm^2	345 ITT C	GRAIN SIZE μm
220 x 12 mm	437	606	+10	13.2	397	530	-65	7.3
160 x 7 mm	486	600	-42	6.5	409	531	-76	6.3

mm and 220 x 12 mm which contain grain refining additions of both Nb and Al. The as-rolled structure of one of the sections (220 x 12 mm) was relatively coarse with areas of Widmanstatten ferrite and the impact properties were poor. Normalizing caused significant grain refinement. However in the case of the smaller section size the initially fine structure was essentially unchanged by normalizing.

These results show that to obtain an improvement in impact properties of an already fine-grained Nb-treated section by normalizing it is necessary to accept a substantial decrease in strength. However, if the as-rolled structure of the section is coarse grained and contains bainite or Widmanstatten ferrite a dramatic improvement in impact properties can be obtained by normalizing without reducing the yield stress by a large amount.

Some data exist to show the influence of normalizing on the mechanical properties of low C, high Nb (> .06%) sections. Table VI gives the mechanical properties of the 9 mm thick flanges in channels in the as-rolled and in the normalized conditions. Normalizing caused a larger decrease in the yield stress than observed in the lower Nb sections presumably due to a larger precipitation strengthening effect from the higher Nb level in the as-rolled condition. As expected, normalizing caused a major improvement in the impact properties. Table VII shows the influence of normalizing on the mechanical properties of some wide flange beams which had been rolled to finish about 1000 C (38). These had a Nb content of 0.138 percent. Again normalizing caused a significant decrease in the yield stress and a large improvement in impact properties. In general, the mechanical properties of the normalized low C, high Nb sections tend to reflect the influence of C on the strength and impact properties i.e. they tend to have a slightly lower strength but better impact properties than sections with higher C levels.

It has been observed that after normalizing there is some distortion in most sections and the distortion is greater the lighter the section. However, roller straightening machines can satisfactorily correct any distortion arising from heat treatment.

Steel Development

Although present useage of notch-tough sections is small it is recognized that the requirement will grow and that there is a need to develop easily weldable, notch-tough structural sections preferably without recourse to controlled rolling, normalizing or expensive alloying additions. The important effect of processing, inter-related with composition, on the structure and properties has already been discussed and the present section deals in more detail with the influence of C, Si, Mn and Nb on mechanical properties.

It is well known that major advantages are associated with reducing the C content, such as improved weldability and notch toughness. Figure 11 shows that lowering the C level of an as-rolled, ferrite/pearlite steel leads to a progressive loss in both yield and tensile stress (39) while Figure 12 shows that the energy absorbed in a Charpy impact test, at a given temperature, is significantly increased as the C content is decreased. In order to maintain the tensile properties of low C hot-rolled sections above certain specified levels it has been shown that adjustments can be made to the Mn, Si, Nb and Al contents to develop the finest possible ferrite grain size and an optimum amount of precipitation strengthening for the leanest possible composition (37).

Table VI. Mechanical Properties and Metallographic Data from PRS Steel in the As-Rolled and Normalized Conditions. Steel Composition 0.09% C, 0.34% Si, 1.30% Mn, 0.008% P, 0.015% Al, 0.061% Nb, 0.008% N.

		AS-ROLLED					NORMALIZED				
PRODUCT SIZE mm	THICKNESS mm	CODE	YS N/mm^2	UTS N/mm^2	CHARPY ITT	G.S.	CODE	YS N/mm^2	UTS N/mm^2	CHARPY ITT	G.S. µm
152 x 76	9	277	463	564	185 at -20 C	9.0	230	361	458	185 at –75 C	7.0
Channel		412	453	543	185 at –10 C	13.2	236	342	441	185 at –90 C	8.2

Table VII. Mechanical Properties of Wide Flange Beams in the As-Rolled and Normalized Conditions (38).
Steel Composition 0.051% C, 0.42% Si, 1.66% Mn, 0.017% P, 0.018% S, 0.035% Al, 0.139% Nb, 0.005% N.

FLANGE THICKNESS mm	CONDITION	YS N/mm^2	UTS N/mm^2	El %	IMPACT ENERGY J -20 C	-50 C
10	AR	435	540	31	210	
	N	385	480	36	280	
20	AR	435	550	28	30	
	N	380	480	35	280	265
30	AR	400	530	30	105	
	N	380	490	35	290	280
40	AR	430	570	26	35	
	N	375	475	33	290	280

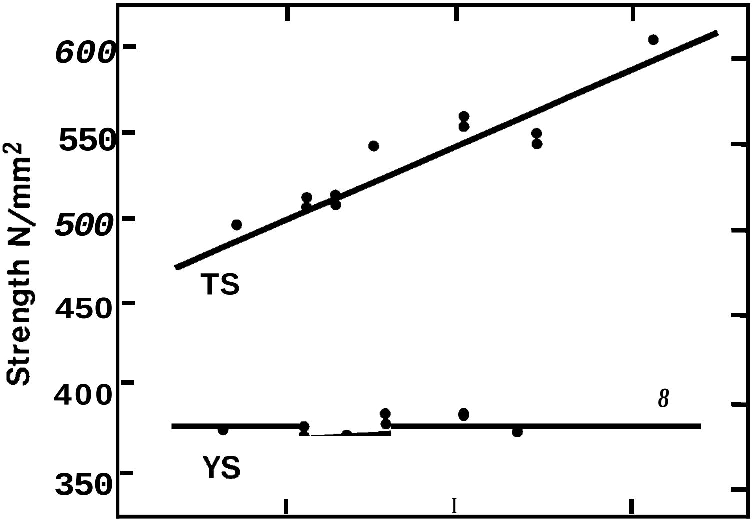


Figure 11 - Effect of C content on the strength of hot-rolled (FRT 1000 C) 19 mm flats of 0.25% Si, 1.40% Mn, 0.032% Nb, 0.042% Al, 0.006% N steel.

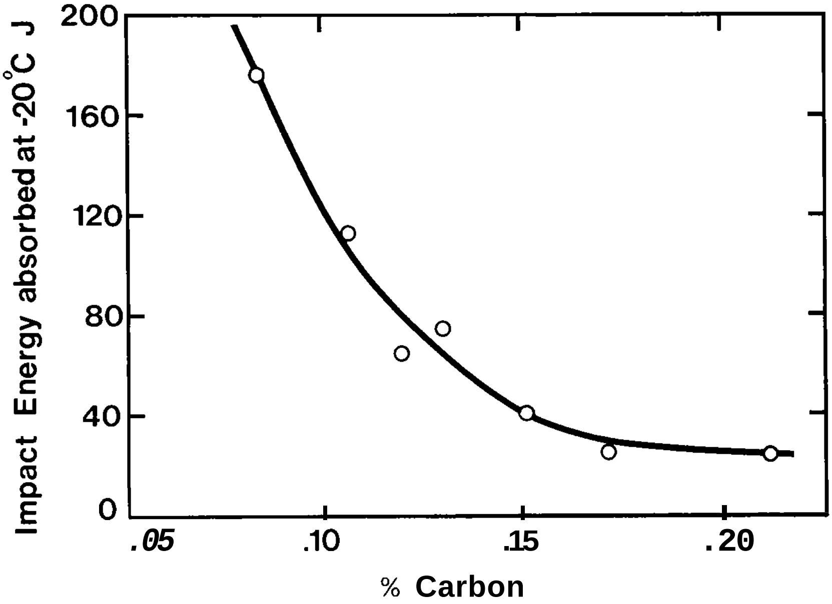


Figure 12 - Effect of C content on the Charpy impact energy absorbed at -20 C for the 19 mm flats in Figure 11.

Figure 13 shows the effect of Mn on the strength and impact properties of steels containing 0.05 percent C, 0.30 percent Si, 0.067 percent Nb and 0.028 percent Al hot rolled to 13 mm flats with a FRT of 860 C. It is clear that, as long as the microstructure remains ferrite/pearlite, increasing the Mn content leads to useful increases in both strength and notch ductility. However, for steels of the above composition, it was found that Mn levels in excess of 1.5 percent resulted in the introduction of regions of bainite into the microstructure which caused a loss of discontinuous yielding and reduced impact properties. Thus at these C and Nb contents and for relatively low FRTs Mn levels should be kept in the range 1.2 to 1.5 percent. However, with steels of lower C content there may be scope for the use of higher Mn levels.

Further strengthening can be obtained by increases in the Si content of the steel, Figure 14. However, this is limited by the fact that many current specifications limit Si levels to ≤ 0.50 percent, even although it is now known that higher Si levels can be tolerated with little effect on impact properties (40).

Any additional strengthening which may be required is usually obtained through a combination of grain refinement and precipitation strengthening by the use of small additions of Nb and/or V. The importance of processing conditions on the influence of Nb on the structure and mechanical properties has already been discussed. It was shown that optimum properties are obtained when substantial deformation occurs at temperatures below about 1000 C. Figure 15 shows the mechanical properties of 12 mm flats rolled to a schedule involving reductions of 18 percent per pass in the finishing stands with a FRT of 920 C. In this case the main influence of the Nb has been to cause grain refinement giving an improvement in strength and impact properties. Significant strain-induced precipitation of NbCN in the austenite has allowed only a relatively small amount of precipitation strengthening.

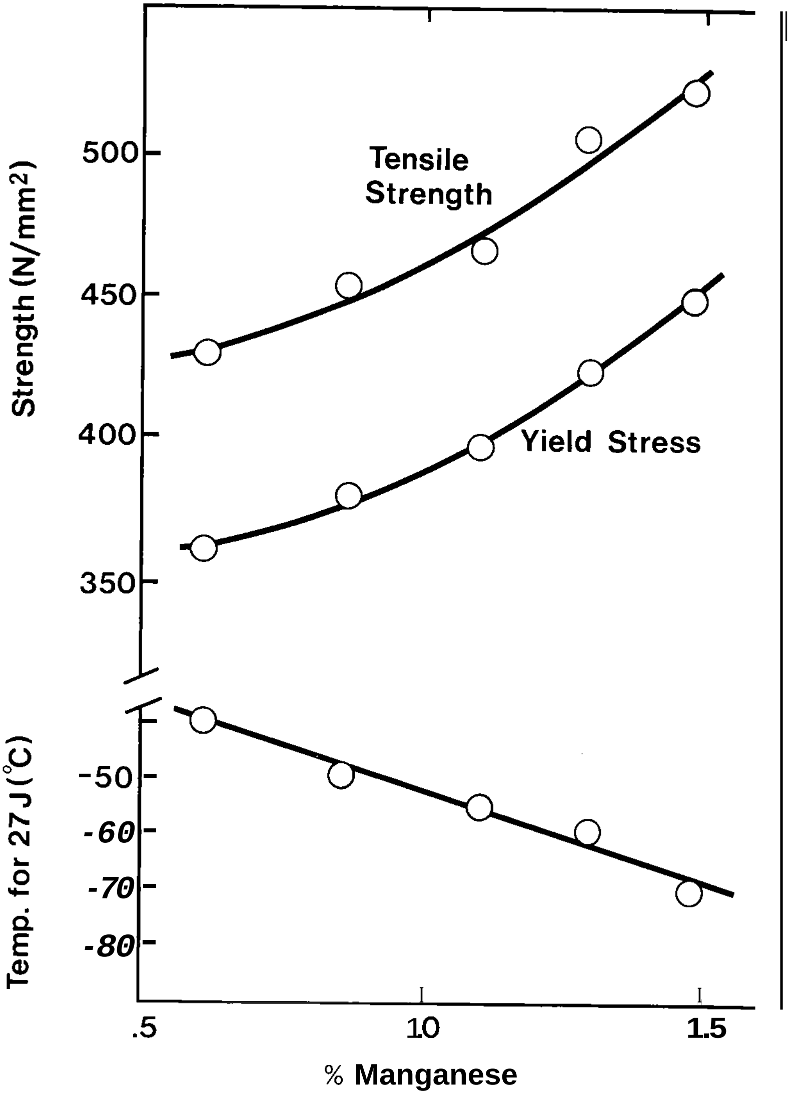


Figure 13 - Effect of Mn Content on the mechanical properties of hot rolled flats of 0.05%, 0.30% Si, 0.067% Nb, 0.028% Al steel.

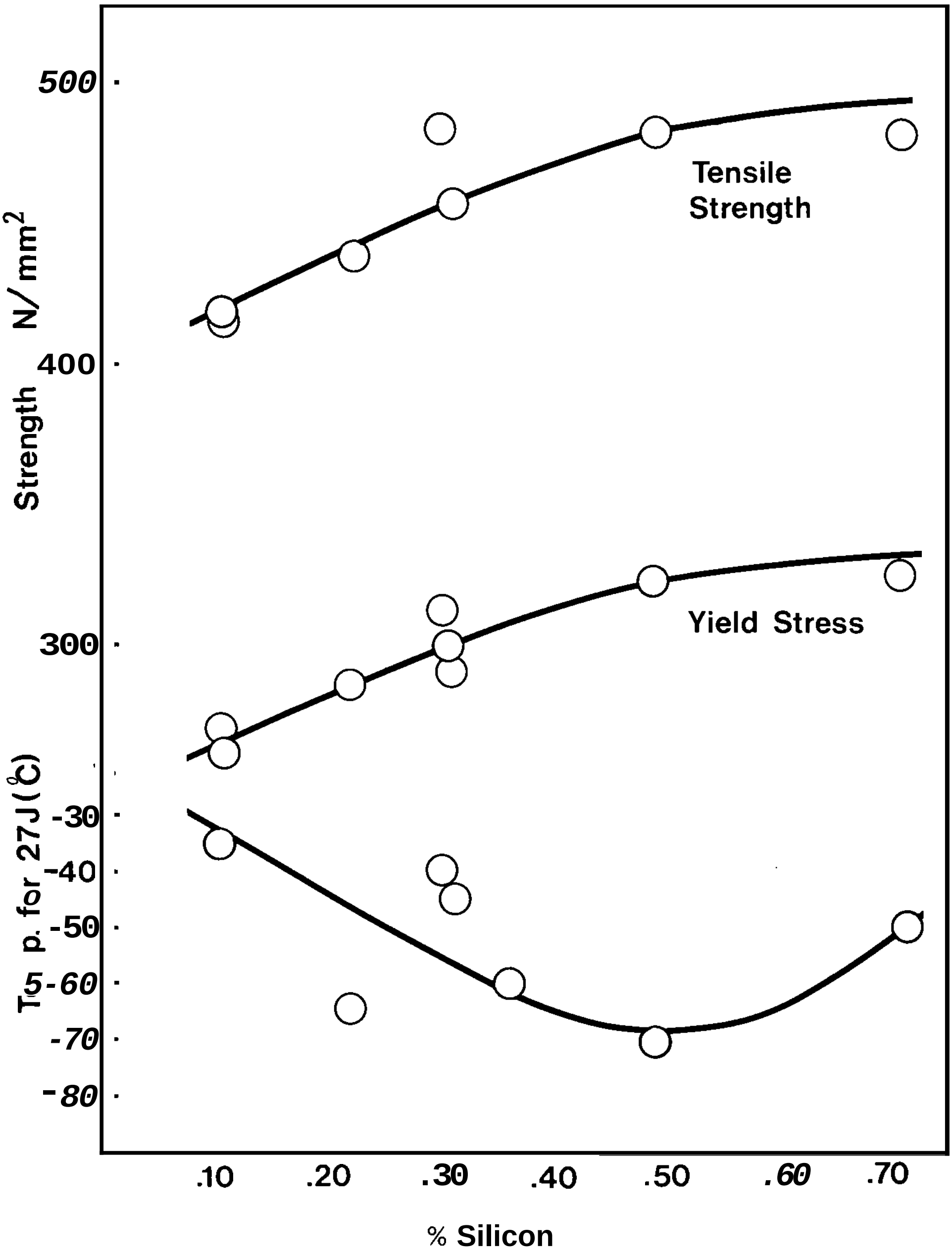


Figure 14 - Effect of Si content on the mechanical properties of hot rolled flats of 0.11% C, 1.16% Mn, 0.037% Al steel.

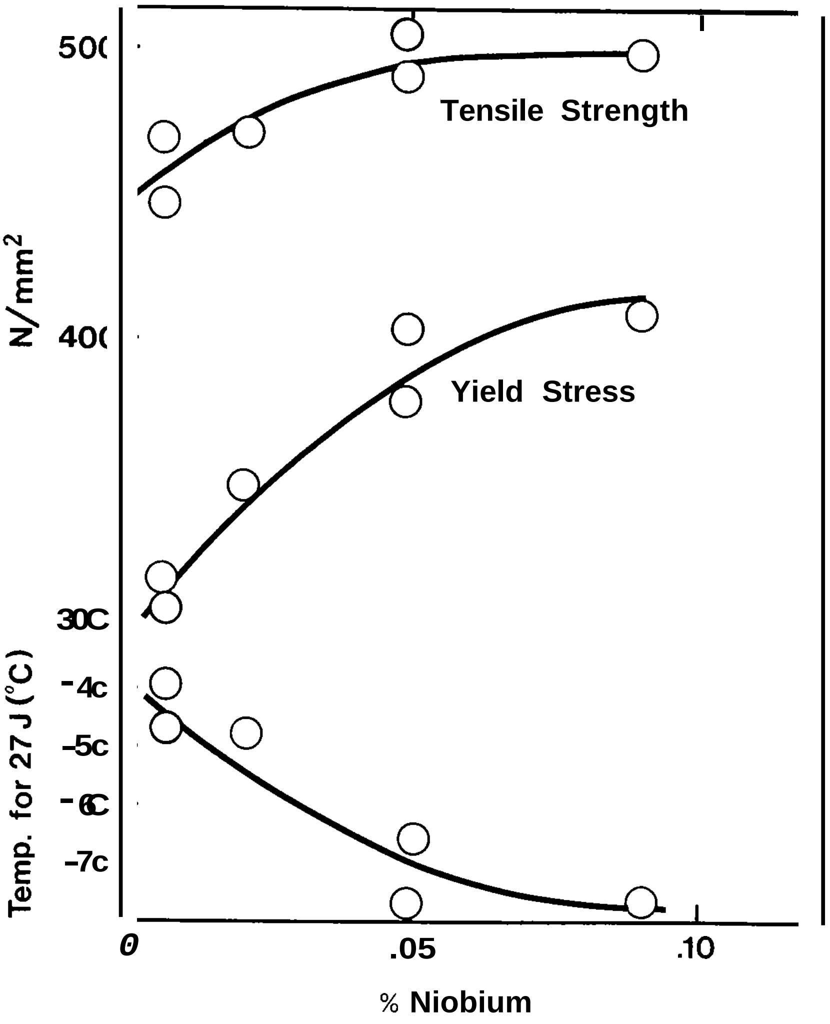


Figure 15 - Effect of Nb content on the mechanical properties of hot rolled flats of 0.09% C, 0.39% Si, 1.27% Mn and 0.01% Al steel.

Although the effect of increasing the Nb level in a hot rolled, low C steel is to refine the grain size and give rise to some precipitation strengthening, the extent to which each mechanism operates is governed by the rolling schedule. When heavy draughting is used during the last few passes (FRT < 1000 C) the grain size is markedly reduced by the Nb addition and it is possible to produce a product with a high strength and a low impact transition temperature (Figure 15). On the other hand, if light draughting is used during the final passes or if the FRT is relatively high (> 1000°C) then the grain refining action of the Nb addition is impaired and most of the increase in strength is due to precipitation strengthening with a resultant increase in the impact transition temperature.

Recent developments have also taken place involving Nb-treated sections of low C steel containing substantial alloying additions of Ni, Cr, Mo, Cu (41) and Cr (42). The high strength alloy steel IN-787 (41) has a good combination of strength and toughness and has been produced in the form of wide-flange beams which have found use in the construction of off-road truck frames. Table VIII details the mechanical properties of such sections in various heat treated conditions. Note that ageing is necessary to optimize the mechanical properties. Imacro (42) is a low C, Nb-treated steel which relies on approximately 4 percent Cr to obtain its properties. It has been shown that hot-rolled sections can be produced in this type of steel with the following mechanical properties at a thickness of 5-12 mm: - 0.2 percent PS, 650 N/mm^2 min, UTS 900-1000 N/mm^2, el 12 percent min., ITT (405) -40 C max.

The uses of such steels are restricted to specialized applications because of their significant cost disadvantage compared with normal HSLA steels.

Table VIII. The Mechanical Properties of IN-787 WF Beams 457 mm x 35 kg (41)
Steel Composition 0.04% C, 0.31% Si, 0.64% Mn, 0.010% P, 0.010% S, 0.90% Cr, 0.91% Ni, 0.22% Mo, 1.18% Cu, 0.04% Nb.

Test Condition	Web Thickness mm	YS N/mm^2	UTS N/mm^2	el %	J at -46 C average
AR + aged 620 C	12.7	600	737	18	45
AR + aged 700 C	12.7	568	667	19	19
N at 900 C	12.7	343	577	28	123
N + aged 620 C	12.7	467	574	27	235

Weldability

In Nb-treated steels, welding cycles which promote the formation of a coarse austenite grain size should be avoided in order to obtain good heat affected zone toughness. The embrittling effect of welding can be magnified in Nb-treated steels. However, it must be emphasized that adequate heat affected zone toughness has been obtained during welding trials on commercially rolled low C, Nb-treated sections (0.08% C, 0.06% Nb) (43). Samples up to 42 mm thick had impact properties better than 275 at -25 C in all test positions after multi-pass welding with heat inputs in the range 1.5 -

2kJ/mm. The results obtained on the low C, Nb-treated steels while not always satisfying 27J at -20 C at the fusion boundary were significant improvements over results recorded on higher C steels (i.e. 0.18% C, 1.40% Mn, 0.03% Nb) where frequently energies of 275 above room temperature have been recorded. In addition, welding trials on the 0.08 percent C, 0.06 percent Nb steels have shown that these steels have excellent resistance to hydrogen-induced cold cracking and can be welded without preheat in most situations. The subject of the weldability of Nb-treated steels is discussed in detail by Kirkwood (44).

Summary

Most Nb-treated HSLA sections are sold without impact requirements. These sections commonly have C contents up to about 0.18 percent with Mn and Nb levels typically around 1.3 percent and 0.03 percent respectively. They are widely used for applications such as piling, bridges, ships, road and rail transport etc., where a high strength to weight ratio is of prime importance. Improved weldability and impact properties at similar strength levels can be obtained by reducing the C level (≤ 0.10%) and increasing the Nb content (≥ 0.06%).

For optimum benefits from a Nb addition hot rolling should be completed in the lower austenite region and FRTs should be < 1000 C. Where the mill is capable of resisting the additional stresses such a controlled-rolling procedure can be adopted. This allows significant grain refinement and gives good impact properties. However, sections are more usually subject to a variety of rolling conditions depending on mill characteristics and local procedures and FRTs are often > 1000 C. This can give coarse bainitic structures and poor impact properties at similar strength levels to those sections with a lower FRT. Sections can also undergo normalizing to cause grain refinement and give guaranteed impact properties.

Steel composition can be tailored to the processing conditions and to the properties required and, although recent developments have concentrated on modifications to the C-Mn-Nb type of steel, more highly alloyed grades of Nb-treated steels have also been developed.

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