HOT ROLLED HSLA STRIP STEELS FOR AUTOMOTIVE AND CONSTRUCTION APPLICATIONS

Jitendra Patel, Christian Klinkenberg and Klaus Hulka

NIOBIUM Products Company GmbH
SteinStr. 28 - Düsseldorf
40210 - Germany

Abstract

High strength low alloy (HSLA) steels offer the advantage of weight and cost savings compared to mild steel. Therefore they are widely used in the automotive and the construction industry. The hot strip mill typically hot rolls gauges ranging from about 2 to 10mm. Processing on a hot strip mill is especially favourable to maximise the strength during thermomechanical rolling. The retardation of recrystallisation, responsible for grain refinement, occurs naturally in niobium microalloyed steel at the typical rolling temperatures found in the finishing train. The high deformation speed and short interpass time allows for about 50% of the total niobium content to remain in solid solution, thus adding to retardation of transformation during accelerating cooling, which also supports grain refinement, and permits additional precipitation hardening in the coil. As the final product often undergoes a cold forming operation, the required ductility is obtained by producing low carbon (<0.08%) and low sulphur (<0.005%) steel, including sulphide shape control. With the additions of microalloys and other alloying elements, HSLA strip steels up to a minimum yield strength of 690MPa (Grade 100) is widely applied, even substituting traditional quenched and tempered steels. All these modern steel grades are based on niobium as a first choice microalloy. The (semi)-continuous rolling on a hot strip mill asks for specific efforts to guarantee a high uniformity of properties over the width and length of the coiled hot band. Thus the processing parameters and their influence on the final properties are analysed in detail.

Introduction

Twenty years on from Niobium '81, the hot strip mill (HSM) and its related products have advanced markedly. In particular, the growth and application of high strength low alloy (HSLA) steels in both the automotive and construction industry has been spectacular. This is highlighted in that the modern automobile makes use of steels that have been developed within the last 10 years. Table I highlights typical commercial HSLA strip steel grades that have been available since the 1970s.

Table I Typical chemical composition of HSLA strip

Minimum yield strength (MPa)	**%C**	**% Mn**	**%Si**	**%S**	**%Nb**	**%Ti**	**%V**	**%Mo**	**%B**	**Remarks**
380	0.07	0.60	0.25	0.005	-	0.10	-	-	-	1970's
380	0.07	0.60	0.25	0.005	0.03	-	-	-	-	typical since 1980's
500	0.07	1.10	0.25	0.005	-	0.15	-	-	-	1970's
500	0.07	1.10	0.25	0.005	0.02	0.08	-	-	-	1980's
500	0.07	1.10	0.25	0.005	0.04	-	0.04	-	-	typical since 1990's
500	0.07	1.10	0.25	0.005	0.07	-	-	-	-	alternative solution
690	0.07	1.30	0.25	0.005	0.05	0.12	-	-	0.0025	typical since 1980's
690	0.04	1.80	0.25	0.005	0.06	0.02	-	0.30	0.0020	alternative solution

The application of microalloyed high strength low alloy steels is now well established in today's market place for both the automotive and construction sectors. Of the two, it is undoubtedly the automotive sector, which has seen the greatest high profile developments. However, it must be noted that both sectors continue to place high demands on the quality and material performance delivered by the steel product and therefore the producer. Today, as then, the application of hot rolled high strength steels permits the down-gauging of otherwise heavy components whilst not compromising material performance. In return considerable cost savings can be realised from not only weight savings but from the entire process route from material delivery to final component application. This can be seen in figure 1 (1), were examples are given for automotive and construction applications.

The aim of this paper is to outline some of the key stages when hot rolling strip steels that are destined for the automotive and construction industry and to give some examples of their applications. Particular attention is given towards the processing conditions and the intertwined relationship that exists between the steel chemical composition, the physical metallurgy and the significant processing stages on a HSM. Although modern HSMs are capable to roll and coil heavy gauges up to 25mm (2"), in this paper consideration will only be given to strip gauges from 2 to 10mm, which are typical for the applications being considered. Nevertheless, it is worthy to note that many HSMs are also experimenting rolling to thinner gauges near 1.8mm, whilst heavier gauges (>10mm) are preferably being produced via plate mills.

For the automotive/heavy transportation industry, these steels are primarily used for under-body components, which require good press formability and ductility as well as acceptable surface appearance despite in most cases being hidden away. In addition to developing steels that satisfy customer requirements, the additional challenge facing strip steel producers of today is in the production of a hot rolled coil with optimum mechanical properties that satisfy the demands of the final application (i.e. *fitness for purpose*), whilst causing minimal disruption to rolling practices or increasing costs. The hot rolling of strip steels is an intensive process, and whilst rolling plain carbon steels is a relatively straightforward task, the successful hot rolling of high strength microalloyed steel grades can posse a somewhat different challenge. Furthermore, with the development and introduction of modern fabrication techniques such as laser welding and tube hydroforming, there is a clear need for strip producers to supply hot rolled coils with consistent properties. This applies to the properties both along the coil length and across the full width, but also from coil to coil.

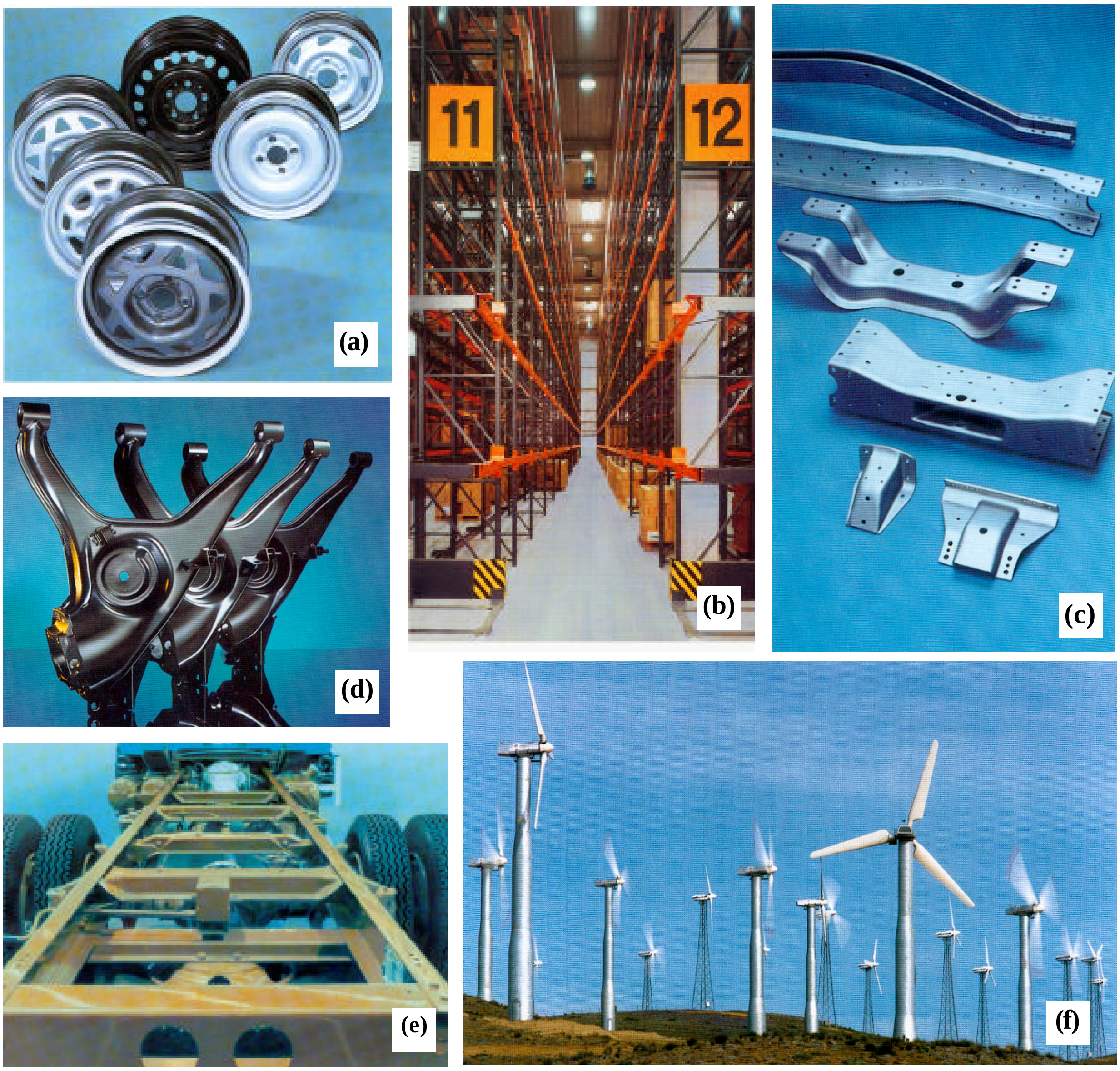

Figure 1: Examples of hot strip steel applied in the automotive and construction industry: (a) Passenger car wheels; (b) High level racking system; (c) Various profiles for automobiles; (d) Semi-trailing arm; (e) Truck frame; and (f) Masts for wind powered generators.

Applications, Property Requirements and Alloy Concepts

As mentioned previously, the choice of any material is based upon fitness for purpose. The main characteristics in selecting a steel grade are; the yield strength, the tensile strength, (uniform) elongation, low temperature impact-toughness, work-hardening, hole-expansion ratio, fatigue performance and weldability. Today several alternative steel grades are available, relying on different combinations of microstructures, the typical HSLA strip showing a microstructure of fine-grained ferrite plus pearlite, with precipitation hardening of the ferrite matrix. Figure 2 (2) outlines some of the relationships between the microstructural phases and mechanical properties of alternative high strength strip steels, indicating, that there is an optimum solution for each property combination, and the rather traditional HSLA strip still maintains its relevant position, especially when considering the rather easy processing route.

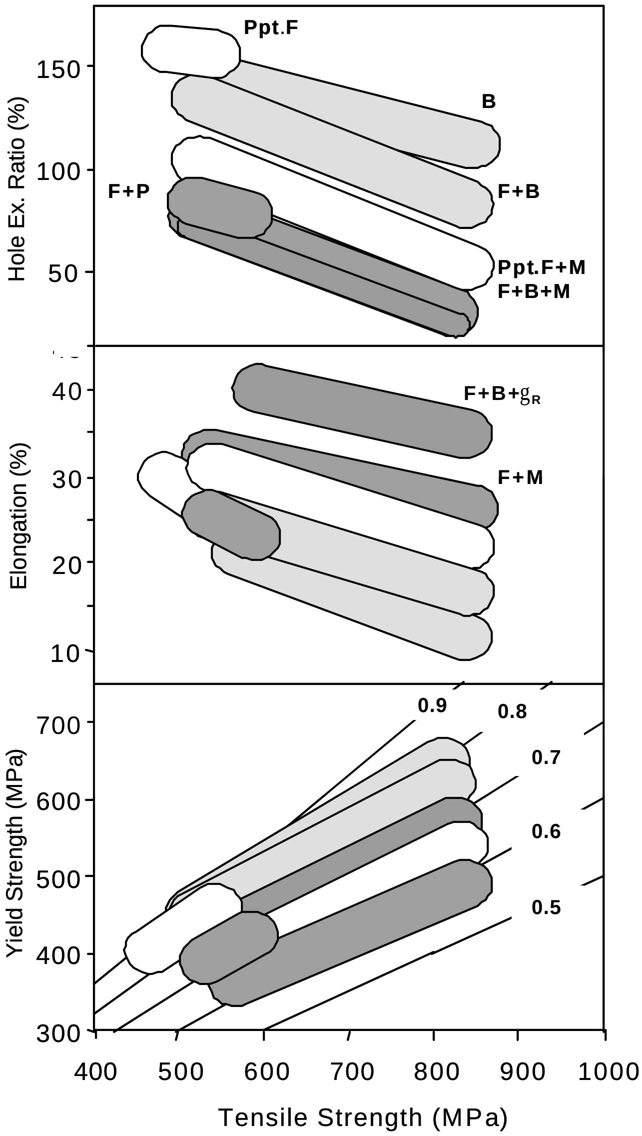

Figure 2: Relationship between microstructure and properties. Key: F = ferrite; P = pearlite; B = bainite; M = martensite; $?_R$ = retained austenite; p_{pt} = precipitates.

The main driving force to apply steel with higher strength than mild steel is the possibility of weight savings, which not only results in reduced fabrication costs, but in case of automotive application also improves fuel economy. Figure 3 (3) shows that under tensile stresses weight savings as high as 50 percent can be obtained, when doubling the yield strength. When applying tension or bending stresses the weight savings are somewhat lower, but still remarkable.

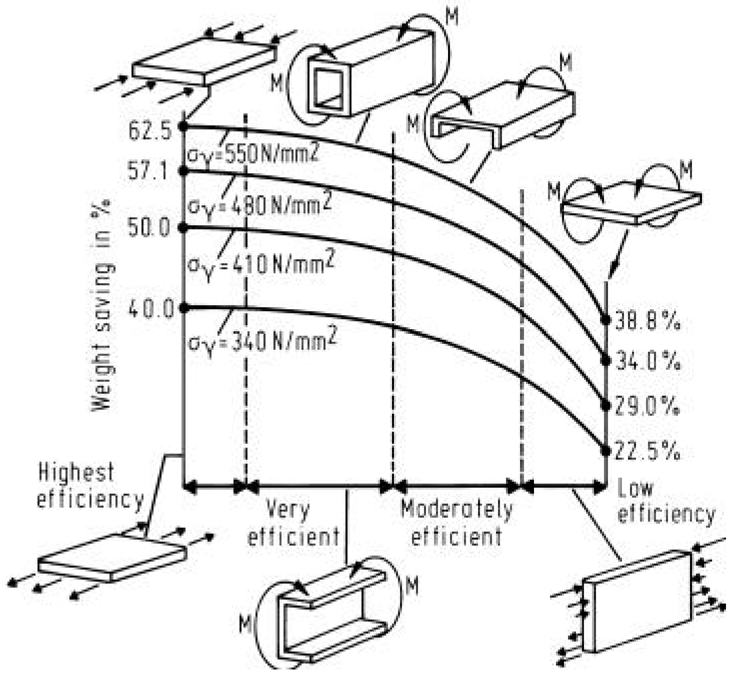

Figure 3: Potential weight savings when substituting a 200MPa yield strength steel.

For automakers, the vast majority of these cold-formed high strength steels are applied in chassis parts such as suspension arms, cross-member tunnels and longitudinal beams. Moreover, some grades have found widespread application in wheels, thus making the hole-expansion ratio and fatigue properties an important factor (4) and the HSLA strip with a minimum yield strength of 690MPa is widely applied for mobile cranes, substituting the traditional quenched and tempered steels. Although toughness requirements are a prerequisite for thick HSLA plate (e.g. beams, heavy plate, pipeline plate), it is normally not a major requirement for thinner strip products. However, it must not be overlooked that automobiles/trucks can experience long periods of sub-zero temperatures in cold climate countries, where average temperature as low as –30°C is not uncommon.

Good toughness can be achieved through grain refinement (the Hall-Petch relationship) and a reduction of second phase microsconstituent. Furthermore, a reduction in the latter also improves the cold formability. Figure 4 (5) shows that a reduction in the sulphur content significantly improves the uniform elongation, and a high uniform elongation equates directly to good cold forming properties. The presence of sulphur will cause the formation of manganese-sulphide (MnS) inclusions, which will elongate during the hot rolling process. The presence of a large number of MnS inclusions (as well as alumina particles - Al_2O_3) will cause cracking or splitting during component forming, especially when the bend axis is parallel to the rolling direction due to the creation of voids at the particle-matrix interface. To retain the original globular shape of the inclusion, additions of elements such as calcium (Ca) can be made, which form sulphides of reduced plasticity at higher temperatures and allow the globular-type inclusions, which are considerably less prone to nucleate voids, to be maintained in the final product.

Nevertheless, achieving low sulphur content from steelmaking should be practised and this is possible with modern steelmaking equipment including pig desulphurisation and ladle metallurgy, resulting in regular production of low sulphur containing steels, figure 5 (6). Applying such processing route for steel desulphurization, sulphide shape control by calcium appears also naturally: Thus the historical solution to use titanium, which acts as microalloy and also guarantees a certain sulphide shape control, has actually become insignificant.

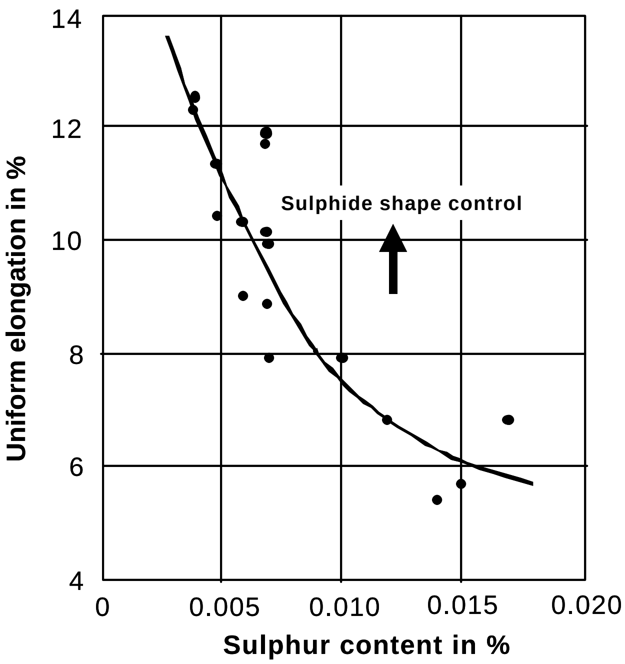

Figure 4: Influence of sulphides on uniform elongation.

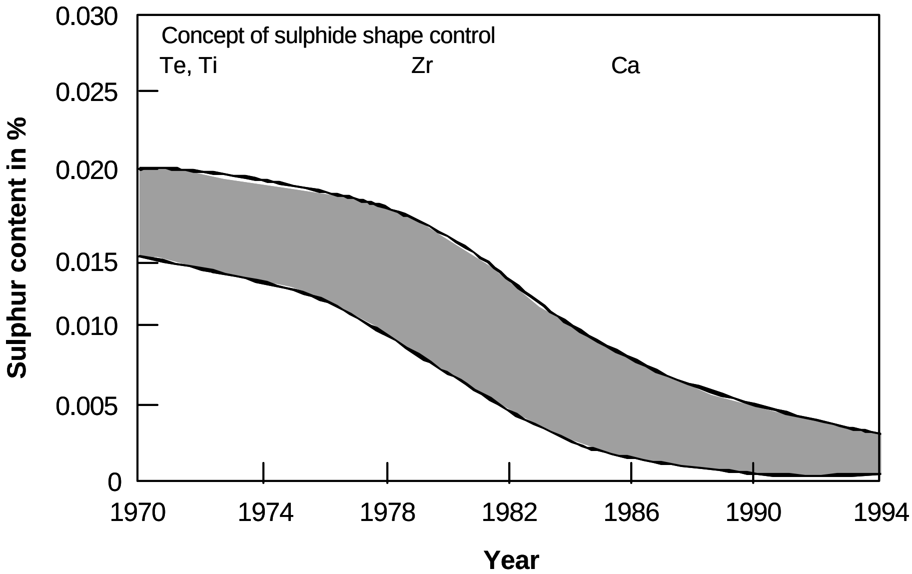

Figure 5: Sulphur concepts for HSLA strip in the last decades.

However, it is not only the amount of non-metallic inclusions, which impair ductility, but also the presence of a higher volume fraction of pearlite will limit ductility, as shown in figure 6 (5). Thus, a low sulphur and low carbon steel are prerequisites for modern HSLA strip development.

The vast majority of HSLA strip steels produced today are hot rolled from a continuously cast slab. There are a range of chemical compositions (7-12) that could be used to make a similar final strength product and the steels listed in table I are just possible examples. Part of the reason for this variation is due to specific customer requirements and another part depends on the capability of the respective hot strip mills. But all of the actually applied steels are based on a low C-Mn-Al philosophy. The relatively low carbon content permits good ductility properties and weldability. The manganese acts as a solid solution strengthener whilst also lowering the austenite-ferrite transformation temperature (Ar_3). However, the manganese content is usually restricted as a solid solution element to levels <1.80wt.%. The main microalloying element employed in these steels is niobium. Niobium additions up to levels of 0.06-0.07wt.% will generate yield strengths of up to 500MPa. Although, it must be noted that at heavier strip gauges, above 6mm, niobium is usually supplemented with additions of vanadium to guarantee the 500MPa yield strength. Nevertheless, the use of niobium as the first choice addition element is due to its ability to act as a grain refiner, which is well known to increase both strength and toughness. It is caused by the fact, that niobium is far superior to the other microalloying elements in its ability to raise the temperature at which austenite recrystallisation effectively ceases (13). Furthermore, niobium also provides a further increase in strength via secondary precipitation hardening, as will be discussed later.

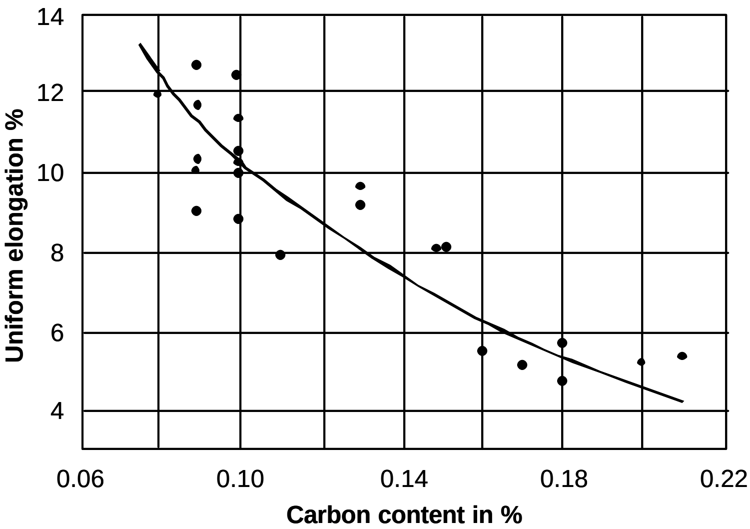

Figure 6: Influence of carbides on uniform elongation.

For strengths greater than 420MPa, the supplemented additions of vanadium will provide strength via additional secondary precipitation hardening in the ferrite matrix. Alternatively, titanium additions can also be made which will result in precipitation of TiC particles. However, titanium is normally added in small amounts <0.020wt.% with the aim of precipitating fine TiN particles which are useful in the weld heat affected zone (HAZ). Secondly, the titanium combining with nitrogen makes niobium more effective by avoiding the enhanced formation of Nb(CN) and promoting NbC formation, thus further increasing the strength. Figure 7 (14) summaries the effect of the three commonly used microalloys, niobium, titanium and vanadium on the strength and the ductile to brittle transition temperature. Niobium is seen to exhibit the strongest effect. For example, in order to raise the yield strength of mild steel by 150MPa from a single alloying addition, then 0.03%Nb, or 0.08%V or 0.10%Ti is required.

It is important to remember that each of the microalloys are unique and therefore are used depending upon suitability of the process route and final product. For conventional hot strip rolling, niobium mainly acts as a grain refiner, vanadium mainly as a precipitation hardener and titanium's effect can be considered to lie between the two. Hence, niobium has the ability to provide a dual effect in developing high strengths and also improving toughness.

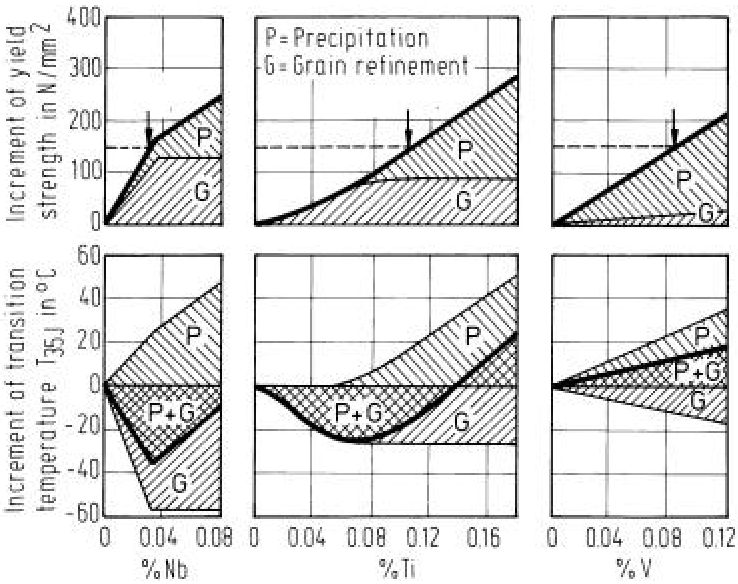

Figure 7: The effect of microalloy additions to the properties of mild hot strip steel.

Historically, a large percentage of HSLA strip steels made greater use of titanium, this was primarily because titanium forms sulphides at high temperatures and this adds to ductility improvement by sulphide shape control. However, with improved steelmaking practises and hence lower sulphur levels, this role for titanium became of minor importance. Additionally when employing titanium as the principal microalloy, a greater spread in mechanical properties is observed. Figure 8 (15, 16) shows production data for a titanium microalloyed Grade 70 (>500MPa yield strength), confirming earlier data (17) indicating that deviations in the finish rolling temperature of ±30°C from an aim of 910°C and in the coiling temperature (aim 700°C) results in a yield strength level ranging from 500 to 700MPa. Even when restricting the processing temperature to ±15°C, the scatter in yield strength remains above 100MPa. As a result of titanium's capability in being a strong oxide, nitride and sulphide former, before forming titanium-carbide, its effectiveness for austenite processing and precipitation hardening is limited.

Figure 9 underlines that for effective austenite processing in the finishing train where approximately 0.20%Ti is required (18). Therefore, for typical titanium levels, in the range of 0.02 to 0.15%, the status of the austenite and thus the amount of titanium in solid solution are not defined and are strongly dependent on the deformation rate and temperature. Consequently, the potential for strength increase by precipitation hardening is rather uncertain and highly dependent on the coiling temperature. It was this rather uncertain condition during austenite processing of titanium steels, which led to the preferred application of niobium as microalloy, since it completely retards austenite recrystallisation in the finishing sequence with as little as additions of 0.03%. The optimisation, as indicated in table I, led via a partial to a total substitution of titanium in HSLA strip, with the result of more homogeneous mechanical properties and better toughness in the heat affected zone, as shown in figure 7.

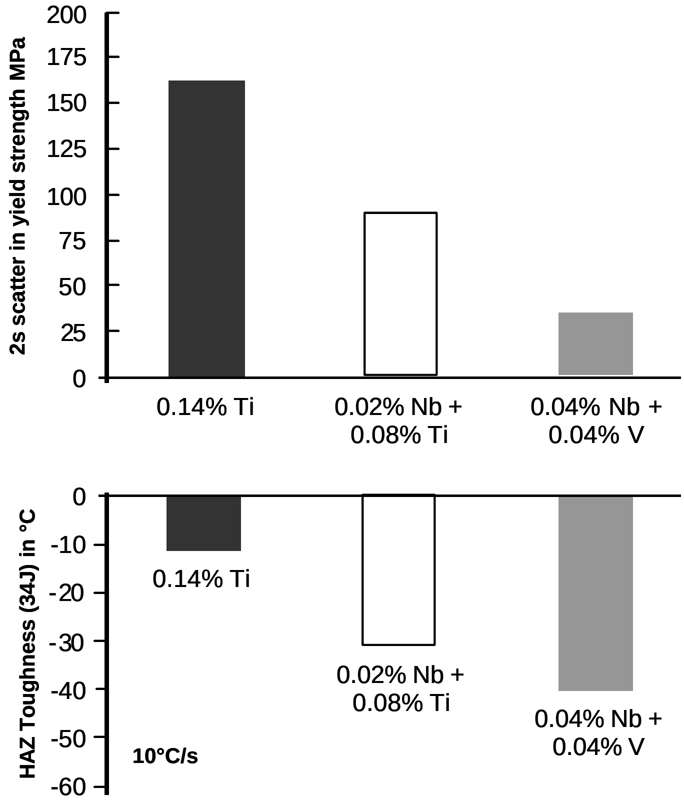

Figure 8: Different microalloy concepts in the production of HSLA strip Grade 70 ($R_{e\ min}$=500MPa) and resulting properties with regard to scatter in yield strength and toughness in the heat-affected zone. Base composition: 0.07%C, 1.10%Mn.

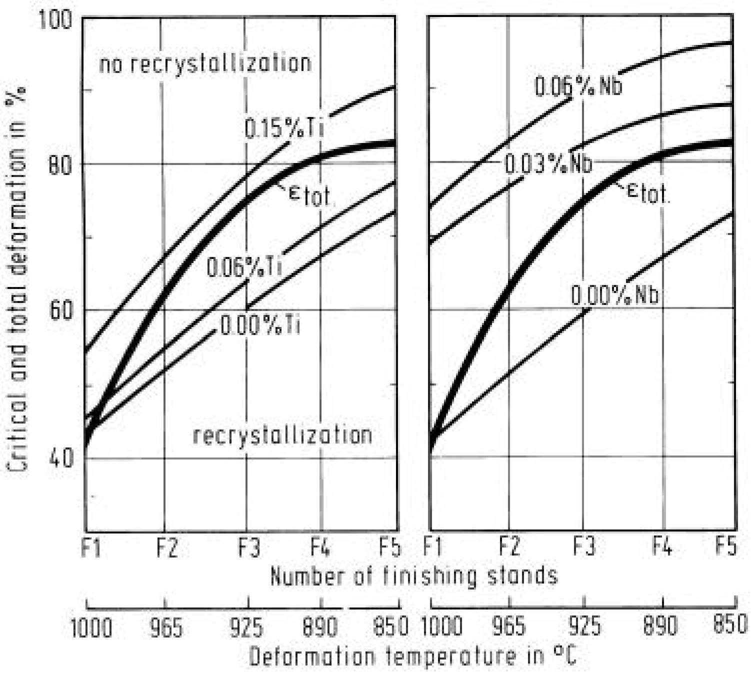

Figure 9: Critical deformation for dynamic recrystallization of Ti or Nb microalloyed steel compared to the total deformation in the finishing train of a hot strip mill.

Based upon a niobium microalloyed variant, which will easily generate a minimum yield strength of 420MPa (equivalent Grade 60), figure 10 further highlights the contributions of various strengthening mechanisms via alloy designs and thermomechanical treatments to achieve yield strength levels up to 700MPa in hot rolled strips (11). Thermomechanically rolled pearlite-reduced steels with around 500MPa minimum yield strength (equivalent Grade 70) ask for additional strength increase in addition to grain refinement and more precipitation hardening is commonly used. Either higher niobium levels in combination with a high finish rolling temperature can achieve this, or additions of vanadium or titanium to such a niobium based steel. Higher strength steel grades such as Grade 100 (minimum yield strength of 690MPa) require a fine-grained ferrite-bainite microstructure, which exhibits ultra-high strength and good toughness. For a bainitic microstructure and increased hardenability, the manganese content is usually increased and additions of molybdenum and or boron can be made. These ultra-high strength steels have been commercially introduced for quite some time and have specifically found use in truck bodies, car brackets, crane booms and structural tubings, permitting weight reductions whilst delivering enhanced strengths (19).

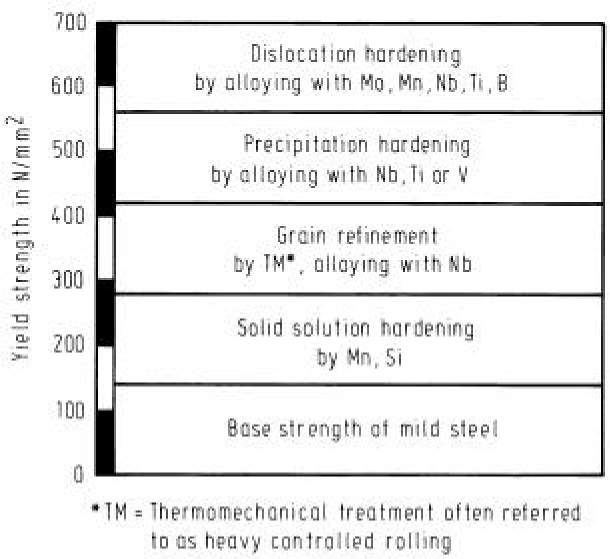

Figure 10: Contribution of various strengthening mechanisms via alloying and processing to achieve 700MPa yield strength in hot strip.

Processing Conditions and Physical Metallurgy

To aid understanding of the following section, figure 10 shows a schematic layout of a hot strip mill and the accompanying metallurgical processes.

Slab reheating

Following casting, the slab is reheated or soaked within a furnace to permit hot rolling to strip. Overall there are three ways by which the continuously cast slab can be charged into the reheating furnace:

i) Cold charging;
ii) Hot charging; and
iii) Direct charging

Out of the three, cold charging practices are the most popular due to the ease of handling cold slabs and the requirement of scheduling slab grades and dimensions. Conventional charging practices are such that slabs corresponding to a single grade and the required widths are rolled in a continuous sequence. Besides charging the slabs from cold, they can also be hot charged or directly charged. Hot charging is whereby slabs are introduced into the furnace at around 700 to 900°C, this not only saves in reheat time but importantly saves energy. For direct charging, slabs are transferred straight from the caster to the furnace. However, for an efficient set-up the continuous caster must be relatively close to the furnace. In addition, both hot and direct charging does not permit examination of the slab surface for defects, and thus does not allow for any scarfing.

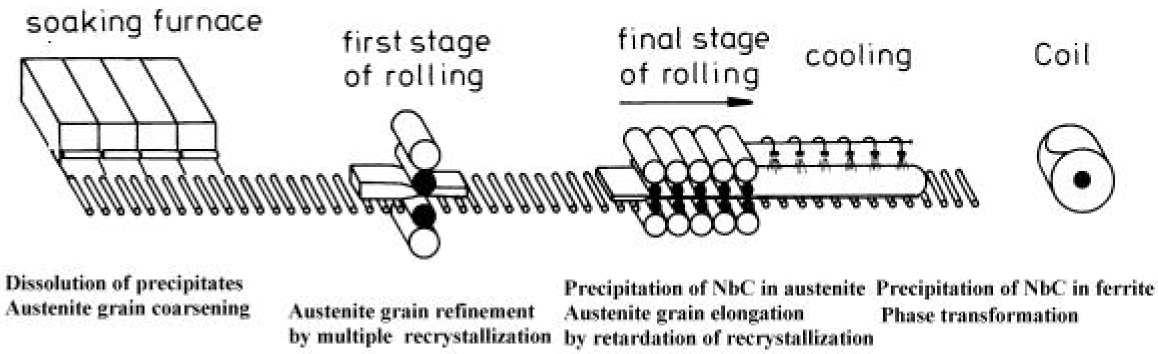

Figure 11: Metallurgical processes during hot strip rolling of HSLA steel.

Besides giving the metal adequate plasticity for hot rolling, for HSLA steel grades the slab reheating temperature must be high enough to also ensure the following:

i) That the microalloying addition has gone into solution (however, for Ti/N treated steel grades, the existence of fine TiN particles is aimed for to limit the austenite grain growth during reheating), and
ii) The temperature at exit of finishing will be above the start of the austenite-to-ferrite (Ar_3) transformation temperature.

Incomplete dissolution of the microalloying elements will mean their exclusion to participate in any grain refinement and/or secondary precipitation hardening. Although a reheating temperature of 1200°C would suffice for the vast bulk of microalloyed grades, a reheating temperature of 1250°C is commonly applied in modern strip mills, thus guaranteeing an appropriate finish rolling temperature. Figure 12 (20,21) shows the temperatures required for complete dissolution of the carbides and carbonitrides of niobium that were formed during the cooling of the cast slab. As shown, the minimum temperatures required for complete dissolution are determined by the niobium, carbon and nitrogen content and a higher alloy addition will thus require a higher reheating temperature. To reduce reheating fuel costs, refractory degradation and also increase productivity, some researchers have suggested reducing the soaking temperature. However, an investigation into the reduction of slab soaking temperature found that it substantially reduced the amount of available solute microalloying alloying addition, resulting in lower strengths (22). The minimum soak temperature of the slab is also governed by the power of the roughing stands, as a colder slab will require much higher rolling loads.

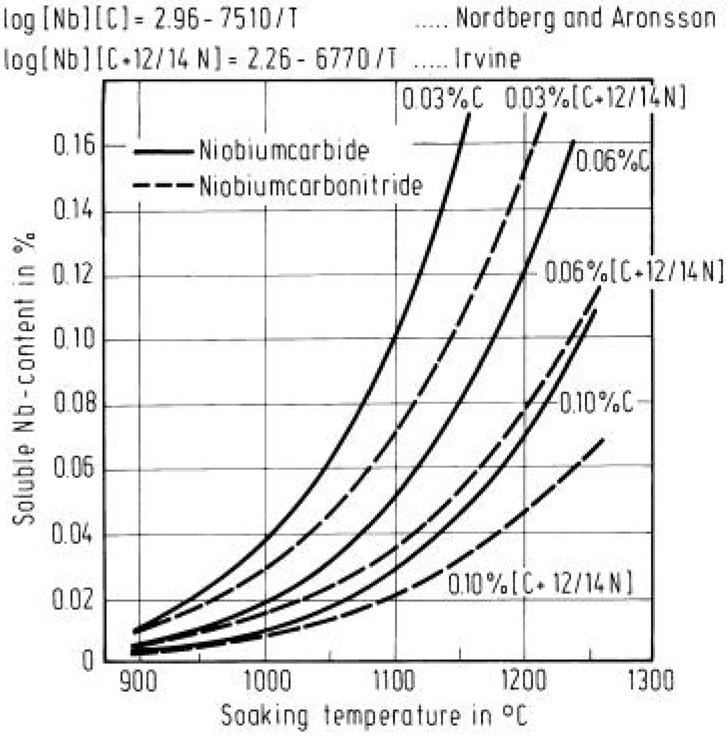

Figure 12: Solubility of niobium carbides and carbonitrides in low carbon steel.

In addition, figure 13 (23) highlights the affect of temperature on the austenite grain growth characteristics. Although the process of roughing should result in a smaller austenite grain size, it is not desirable to have a very large starting grain size. Therefore, to limit the grain size and as mentioned above, the addition of small amounts of titanium to niobium microalloyed steels is sometimes made to pin the austenite grain boundaries. As the titanium will also scavenge the available free nitrogen also the slab surface will be improved and deplete levels there will be a tendency to form more NbC precipitates during hot rolling.

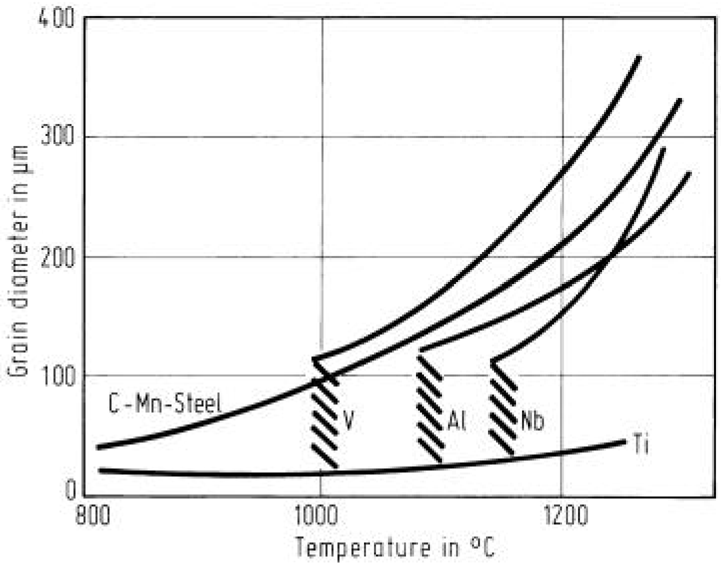

Figure 13: Austenite grain growth characteristics in steels containing various microalloy additions.

In general there are two types of reheating furnaces that are in operation throughout the world:

i) Walking beam, whereby the slabs are transported via a series of moving arms which lift the slab from below and move it forward, and the second; and
ii) Pusher-type, where the introduction of one slab will force the exit of another.

Although both furnaces should result in the drop-out (exit) of a homogenised soaked slab, the pusher type furnaces have a tendency to impart some degree of localised chilling effect due to the skids, which are water-cooled. Indeed, a recent investigation (24) highlighted the loss in final strengths that can be expected at the skid chill positions. However, it must be noted that pusher furnaces are widely used throughput the world, and with regular maintenance the skid chills should not have a great impact upon the through coil consistency in mechanical properties.

Roughing, the Delay Table and Coil Box

On exiting the furnace, the slab will continue to cool and so the process of reducing it to the final hot rolled coil must be undertaken with the least delay for both metallurgical and processing reasons. Before entry into the roughing stands, the slab passes through a set of vertical and horizontal scale breakers. Here the scale formed during reheating is effectively cracked off through the application of a light load assisted by the use of high-pressure water sprays. During the passage through the roughing train the slab is reduced in thickness from about 250mm to 35mm in several reductions of typically 20% or more. During the roughing complete recrystallisation is expected for all steel grades. The primary metallurgical aim of the roughing process is to destroy the as cast structure and through repeated recrystallisation, finish with a homogeneous austenite grain size.

Following roughing the bar emerges onto either a delay table, or enters a coil box. At this stage the temperature of the bar will typically be around 1050°C. The aim of the delay table, or coil box, is to 'hold' the bar as it is fed into the finishing train. The coil box also allows homogenisation in temperature, catering for the natural temperature run that develops along the bar length. In order to reduce the temperature loss on the delay table, heat reflecting panels are often used. It is interesting to note that it was only after the 1980's that the coil-box technology (invented by Stelco) was applied to hot strip mills, in addition to the introduction of the Generation IV mills, which were specifically designed as a response to new economic priorities (25). The delay can also be used to lower the entry temperature of the bar. This would occur when one or two stands in the finishing train are dummied to produce a thick final hot rolled gauge, typically >10mm. It is important to ensure that the bar condition prior entry into the finishing train is of homogeneous grain size, since any discrepancy in the uniformity of the grain size will be carried through to the final product and is likely to have an impact upon the uniformity of final mechanical properties.

Finishing Train

Prior entry into the finishing train the head end (nose) of the bar is cropped via a flying shear to square the bar. Again a set of high-pressure water jets are used to remove any secondary scale formed on the bar. The finishing train typically consists of 6 to 7 stands, each which can be independently controlled in terms of roll gap, roll speed, work roll shifting and bending. In practice, for hot rolled gauges up to 10mm, all seven stands can be used. During rolling, the bar will be in all the stands at the one time with peripheral roll and coil speed synchronised to maintain strip tension with the aid of inter-stand balanced looper rolls. In addition, inter-stand cooling can also be applied to aid rolling and also to cool the bar.

The reduction pattern employed is designed to reduce the developed rolling loads in the mill, as the strain rate will substantially increase due to the increased roll speed. The lower the bar temperature, the higher will be the loads. Furthermore, as the austenite is conditioned and strain induced precipitation takes place in the mill the loads will increase. Table II (26), provides an example of the temperatures, strains, strain rates etc. that could be experienced when hot rolling a typical low carbon niobium microalloyed strip steel. The time taken to hot roll the entire bar is usually limited to 60 to 70 seconds, and this is achieved by accelerating the mill (sometimes referred to as mill zoom), which also preserves the temperature of the strip. However, even with mill acceleration a degree of temperature run down will exist along the bar length. It is important to note that unlike Steckel or plate mills, the reduction pattern employed within the finishing train is somewhat restricted. This is mainly due to the sequential nature of the rolling operation, the power and torque of each individual stand, the rolling velocity etc.

Table II Example of hot strip mill finishing conditions in processing 3mm HSLA strip

	Stand 1	**Stand 2**	**Stand 3**	**Stand 4**	**Stand 5**	**Stand 6**	**Stand 7**
Temperature (°C)	1020	990	960	935	910	890	865
Strain	0.57	0.41	0.43	0.34	0.27	0.28	0.14
Strain Rate (s^{-1})	9	15	29	46	66	101	98
Roll Speed (ms^{-1})	1.2	2.1	4.5	5	6.1	7.9	9.5
Force per unit width (tm^{-1})	1.7	1.6	1.7	1.3	1.2	1.1	1.0

The metallurgical benefits to be gained when finishing rolling for niobium microalloyed steels are well known (14, 23, 27-32) and therefore only the process related mechanisms for thermomechanical rolling will be briefly mentioned here. For niobium microalloyed steels (depending upon the steel composition) a stage will be reached, either before or during rolling, when no austenite recrystallisation will occur i.e., recrystallisation-stop temperature. From here, further hot deformation will 'pancake' the grains. It is widely recognised that the retardation of austenite recrystallisation is either due to solute drag and/or strain induced precipitation of Nb(CN). In either case the resultant being, with subsequent reductions, that the austenite grains become elongated and thereby develop a greater effective grain boundary surface area. Together with the formation of deformation bands within the grains, the ability to nucleate ferrite grains is substantially increased. It is this process of developing a pancaked or elongated, austenite that is referred to as 'conditioning' the structure and forms the characteristic part of thermomechanical process.

For niobium microalloyed steels, nucleation of Nb(CN) in austenite is expected to occur heterogeneously on preferential sites such as grain boundaries and dislocations, or more probably on subgrain boundaries as found in deformed austenite. It is considered that grain boundary precipitation will occur an order of magnitude quicker than matrix precipitation. Thus suggesting that grain boundary precipitation first delays the recrystallisation process and matrix precipitation is required to ensure the complete stoppage of recrystallisation (33). Any strain-induced precipitation that takes place in the austenite is incoherent with the final ferrite matrix since it had a cube-cube relationship with the former austenite microstructure. Furthermore it is considered to make little if any contribution in terms of precipitation hardening as result of its relative coarse particle size. Strain induced Nb(CN) precipitates in austenite have their major role in developing a fine ferrite grain via austenite conditioning, resulting in a much better combination of high strength, good toughness and ductility than possible via precipitation hardening.

In addition to developing an optimum conditioned structure, it is also important that the finishing temperature is kept above the Ar_3 point, even at the strip edges. When hot rolling wide strip there is a tendency to develop a cold edge, which could be up to 20°C lower than the mid-width temperature, which is normally used as the control measure. Thus, if during rolling the edges cool below the Ar_3, then the formed ferrite will be deformed, which will lead to inconsistent properties. Although it is possible to control roll into the intercritical range to increase the final strength through substructure and/or subgrain hardening of the ferrite, this type of rolling will generate a mixed grain structure, which has a toughness impairing effect. Since, on the other hand, the finishing temperature influences the level of strain imparted in the microstructure below the recrystallisation temperature, it is not surprising to find that a reduction in temperature will lead to improved toughness values, as long as the finish rolling is carried out in the metastable austenite.

Furthermore, it must be noted that the aim final hot rolled gauge will also have an impact upon the mill processing parameters in addition to the final mechanical properties. The general trend observed, for an identical steel composition and processing conditions, is a reduction in final strengths with heavier gauges. This is particularly observed when moving to gauges above 6mm and can be explained by:

i) A reduced imparted total strain for the heavier gauges resulting in a 'less' conditioned austenite structure, and hence a reduction in ferrite nucleation sites, and;
ii) The fact that a heavier final gauge will naturally experience a slower cooling rate on the run-out-table, thus affecting the ferrite nucleation rate and thus grain size.

The amount of solute niobium at entry and exit of the finishing sequence is important for austenite processing and potential precipitation hardening as well. Under practical rolling conditions almost no niobium will have been precipitated out during the roughing process (34). Although a number of proposals exist, the exact mechanism and development of Nb(CN) precipitation during multi-pass finishing is still under investigation, but taking into account the high deformation rate and short inter-pass time of hot strip finish rolling, the NbC precipitation in austenite will be much less complete with regard to the equilibrium, than in plate or even Steckel mill rolling and one can assume, that about 50% of niobium will remain in solid solution (35).

Run-Out-Table (Accelerated) Cooling and Coiling Temperature

On exit of the finishing train, the strip thickness gauge and width is accurately measured via an X-ray device, and is then cooled by water sprays from above and below the strip. The cooling of the strip is probably one of the most important stages HSLA steels hot strip rolling, requiring accurate control as it is a very flexible and powerful tool of the hot strip mill. Once the coiler captures the head-end of the strip, tension is applied to the strip and the mill will accelerate to maintain the finishing temperature. Such variations in the strip velocity will result in different rates of cooling to be applied and result in inconsistent mechanical properties if the cooling rates are not controlled along the entire strip length.

There are a large variety of cooling profiles that can be employed on a modern commercial hot strip mill. The application of an early cool is finding increased use in the production of niobium-HSLA strip steels, as this permits maximum exploitation of the conditioned austenite structure. However, if a late cooling is applied, then some degree of recovery will occur in the austenite, but no recrystallisation. Furthermore, the presence of niobium in both precipitate and solute form will significantly retard the restoration process and thereby assist in the preservation of the dislocation structure for longer.

As discussed, it is the essence of controlled rolling to increase the nucleation sites for ferrite grains, by giving a large amount of deformation to the steel in the non-recrystallised austenite region and accelerated cooling is to inherit the potential ferrite nucleation sites and make full use of them (35). The application of an accelerated cool will promote further grain refinement, since the lower transformation provides more nuclei in the undercooled austenite. The type of microstructures that can be developed from controlled cooling can be predicted from a continuous cooling temperature (CCT) diagram. Such diagrams chart how the mechanical properties can be tailored accordingly to the cooling strategy employed. In practice for low carbon microalloyed steel grades the cooling is interrupted at temperatures ranging from 650°C to 550°C, or lower for some products.

The applied cooling rate has a significant role to play in determining the final ferrite grain size, and this is shown in figure 14 which demonstrates, for the same steel gauge and composition, the enhancement of the cooling rate (via an applied early cool and 75°C lower coiling temperature) increased the yield strength through a finer ferrite grain size, additional benefits were also seen in a noticeable narrowing of the grain size distribution (36).

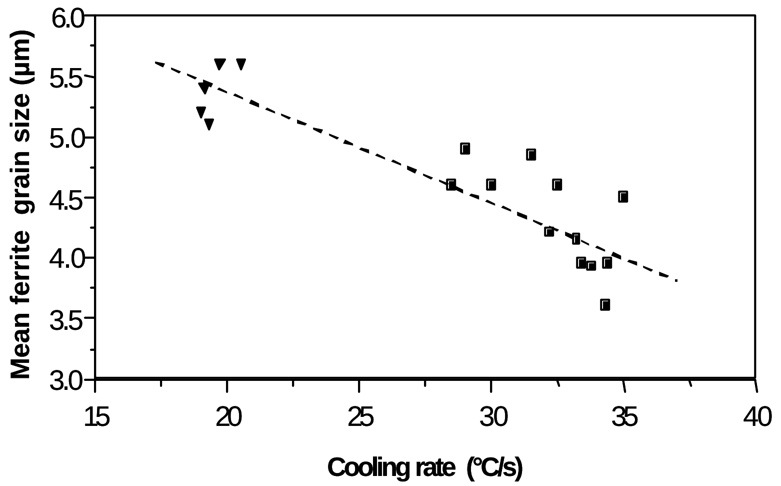

Figure 14: Influence of cooling rate in the run-out table on the ferrite grain size of HSLA strip.

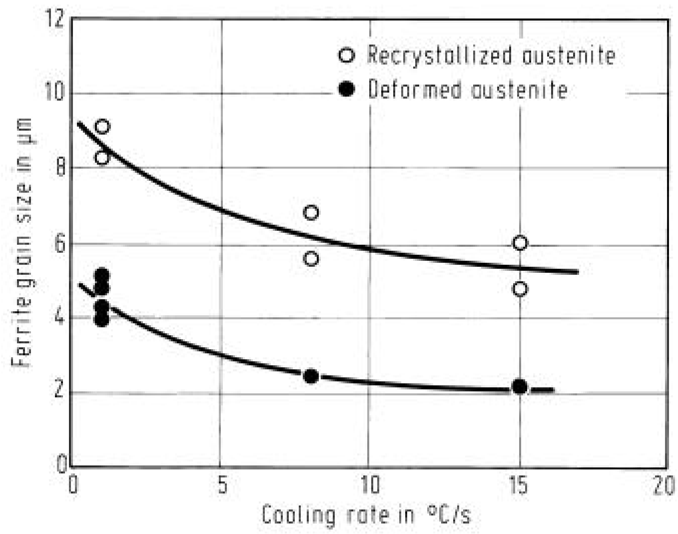

Figure 15: The effect of austenite processing and cooling rate on the final ferrite grain size.

The effectiveness of a deformed austenite structure to that of a recrystallized structure with the application of an accelerated cool is also clearly demonstrated in figure 15 (37). Although in reality the cooling rates experienced for strip processing will be in excess of 15°C/s, the trend is clear to see. Here, the ability to exploit the highly conditioned structure, rich in 'potential' ferrite nucleation sites is realised.

If the accelerated cool exceeds a critical level and the interrupt temperature is low, then an acicular ferrite (carbide free bainite) structure can be produced. Besides the cooling rate also a high alloy content promotes such bainitic transformation. Steel of such microstructure achieves high strengths (>700MPa TS) and adequate elongation and toughness, thus this type of product is finding increased use in the automotive industry for wheel disc, drum applications and anti-intrusion frames.

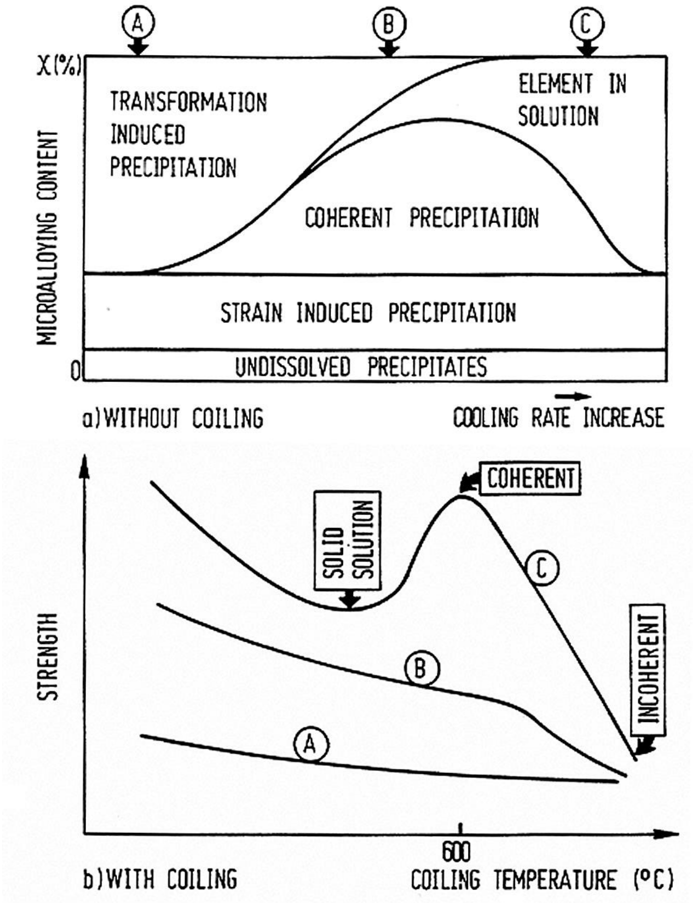

Figure 16: Influence of processing conditions on the nature of precipitates and the resulting strength – schematically.

The solute niobium level after finish rolling will determine, in conjunction with the cooling rate and final coiling temperature, the degree of precipitation hardening via fine Nb(CN) particles that will occur. This is schematically shown in figure 16 (38). During accelerated cooling, in addition to the ferrite grain refinement, interphase precipitation of the microalloying element can occur. However, this is dependent upon the level of cooling and with very high cooling rates suppression of interphase precipitation has been suggested (39). For niobium microalloyed steels, under prevailing conditions, fine Nb(CN) precipitates will form on the austenite-to-ferrite transformation front, giving the characteristic row-type distributions (planar array). These fine particles, typically a few nm in diameter and with row spacing of about

100nm (dependent upon cooling rate), will further increase the strengths via the mechanism of particle cutting. The distinctive rows of particles that are associated with microalloyed interphase precipitation are seen when only imaged at a certain orientation using a transmission electron microscope. When imaged from another incident angle, the particles will appear to be randomly distributed within the matrix. The niobium precipitates which form in the ferrite can be identified from the orientation relationship between the ferrite and the precipitate reflection in the electron diffraction pattern and it is well established that Nb(CN) precipitates in the ferrite with the Baker-Nutting orientation relationship (40).

Application of a high coiling temperature may result in incomplete transformation to ferrite, see figure 17 (26). For the steel composition given in the figure, any remaining austenite will transform slowly to ferrite and pearlite; as the austenite will be rich in carbon rejected from the surrounding ferrite. The pearlite/carbides morphology will be strongly influenced by the coiling temperature. Coarse lamellae will form with high coiling temperatures while lowering the temperature will result in a degenerated pearlite aggregate of ferrite and carbide. The presence of grain boundary carbides and coarse pearlite will lead to poor toughness values. It is likely that faster cool rates and a low coiling temperature will in fact lead to more second phase due to the rapid undercooling of the austenite leading to a finer pearlite/carbides with a lower carbon content. It also possible that if incomplete transformation occurs on the run out table, then the austenite which transforms relatively slowly may promote coherent or interphase precipitation of Nb(CN), although a too high coiling temperature may lead to a loss of coherency.

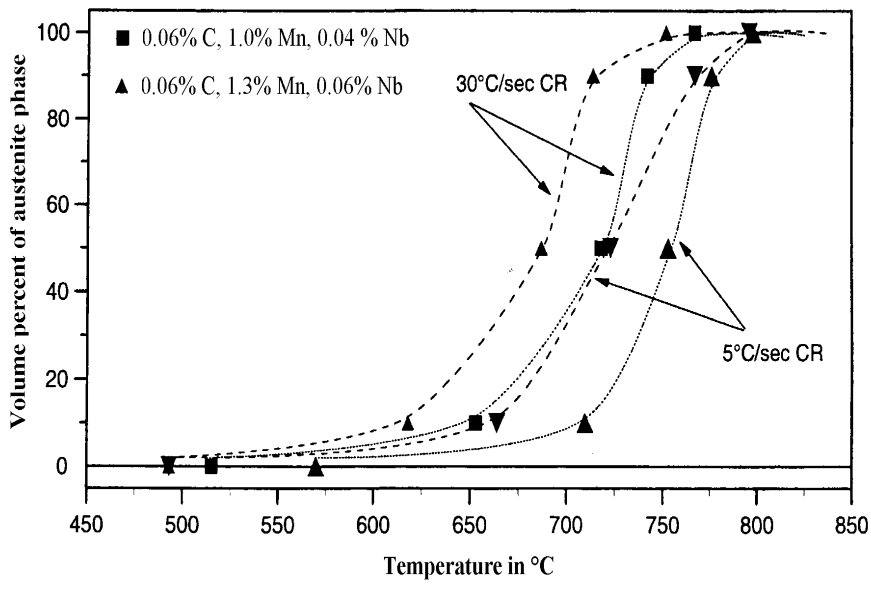

Figure 17: Phase transformation curve of two steels and two cooling rates (reheated to 1000°C and linearly cooled).

From the early developments on accelerated cooling in the late 1950s and early 1960s, through to the introduction of laminar cooling and water curtain devices on hot strip mills, current research is focusing on the application of ultra-fast cooling (UFC) technologies (41). Studies have so far shown that compared to conventional laminar devices, where cooling rates of 20 to 40°C/s can be readily achieved, UFC units can deliver cooling rates over 300°C/s. Early studies on a low carbon niobium microalloyed steel has shown that the strength is further enhanced through a combination of developing a very fine equi-axed ferrite grains and an increase in precipitation hardening. Consequently, optimisation of the total alloying content can be considered (as discussed below). Furthermore, and equally important, the studies have indicated that the uniformity in mechanical properties is also improved.

Coiling and Coil Cooling

Once cooling has been interrupted, further precipitation of Nb(CN) will occur within the ferrite matrix at favourable sites such as dislocations. As the hot rolled coil slowly cools, some degree of particle ripening will occur for all existing precipitates. The ripening process is commonly termed Ostwald ripening, were the particles will undergo cannibalistic growth. (31). As the particles coarsen, the strengthening mechanism changes from one of particle cutting to dislocation looping. According to the Orowan-Ashby relationship the ideal situation is to create a large volume fraction of particles having a small particle size, thereby developing a large contribution to the overall yield strength. The advantage of using niobium as a microalloying element is seen from the fact that it not only refines the ferrite grain size and increases the strength and toughness, but also contributes to the strength via secondary precipitation effects. Niobium is also able to provide a greater increase in yield strength when precipitating as a coherent particle in the ferrite matrix in comparison to vanadium and titanium, figure 18 (42). It can be explained by the larger difference in the lattice parameter of NbC to a-iron compared to TiC or VC and VN.

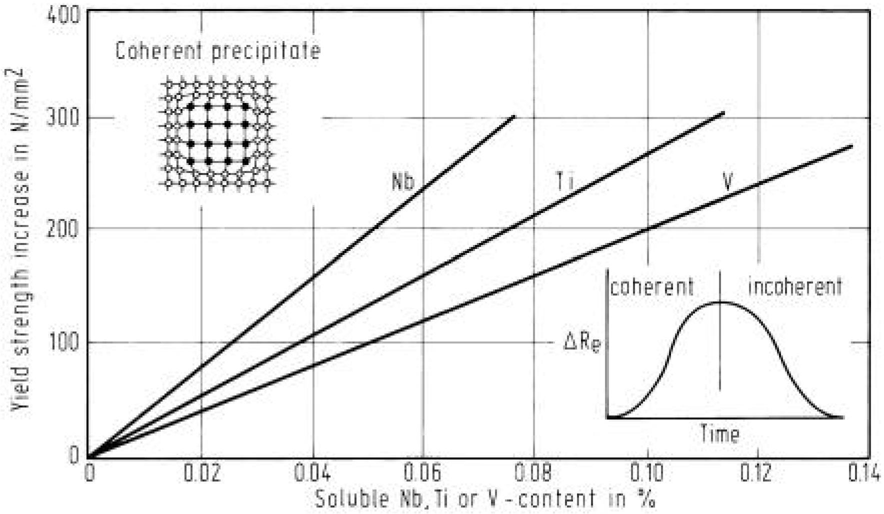

Figure 18: Maximum yield strength increase by precipitation hardening for a wide range of steel compositions, solution treated at 1300°C and isothermal holding at 600°C.

It is clear that the interrupt (or coiling) temperature is important in not only determining the microconstituent type, but also the degree of precipitation strengthening that can be expected from the remaining solute niobium exit finishing. It has already been discussed, that the precipitates formed in the high temperature austenite state will not contribute towards any secondary hardening effects. This is because they will be relatively coarse in comparison to the coherent particles. However, their contribution was generated when pinning the austenite grain structure during hot rolling in the finishing train. In general, a lower coiling temperature (<600°C) will limit the opportunity for particles to coarsen and thereby maintain a high strength. However, if the coiling temperature is too low, <450°C, then precipitation is likely to be suppressed thereby leaving a quantity of microalloy in solution. Ultimately, the correct choice of coiling temperature will depend upon the final property requirements and also the power of the coiler to be able to coil a cold strip. In some hot strip mills, the latter is sometime found to be the limiting factor. A recent laboratory based investigation confirmed the existence of an optimum coiling temperature for generating high strengths whilst maintaining ductility levels (24,36).

The results of the investigation led to an industrial trial where, for a given niobium microalloyed steel, the average cooling rate on the run out table was increased and the coiling temperature was reduced from 650°C to 575°C. The resultant change in the ferrite grain size was shown earlier in figure 14, whereby increasing the cooling rate from 20°/s to 32°C/s reduced the average ferrite grain size from 5.5µm to 4µm, resulting in a yield strength increase of about 25MPa. In this instance, the use of a reduced coiling temperature also gave higher contributions from secondary hardening and subgrain strengthening; estimated at 80-90MPa in total, in comparison to 40MPa when coiling at 650°C. Furthermore, in examining a series of niobium microalloyed steels another investigation confirmed, that for a constant finish rolling temperature, an increase in the niobium content did not help to further increase the level of precipitation hardening and the optimum solution was to adjust the coiling temperature, figure 19 (26).

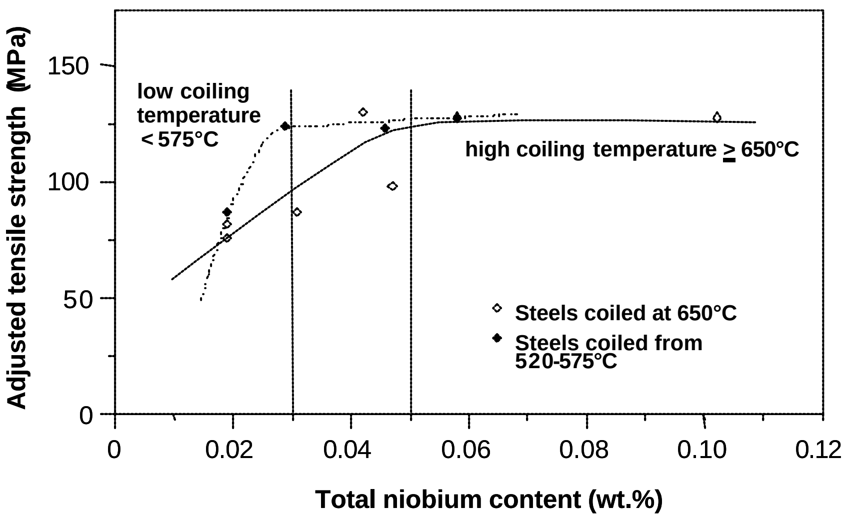

Figure 19: Adjusted tensile strength as result of the niobium content and coiling temperature.

It is noteworthy to mention, that reducing the coiling temperature can also have a positive effect of the level of cold formability. Figure 20 shows the strength and hole expansion values for three different coiling temperatures (43). The resulting microstructures comprised of 80% ferrite with a second phase of either pearlite, bainite or martensite. When coiling at 450°C the precipitation hardening effect of niobium was observed to diminish and only the positive effect of refining the microstructure prevailed. Nevertheless, the strength is not impaired compared to the 650°C coiling temperature as a result of the higher dislocation density in the bainitic constituent. The enhanced cold formability is directly attributable to the elimination of pearlite bands. From figure 20, the hole expansion value is also much higher than for dual phase steels, which were coiled below the martensite start temperature and therefore exhibit a ferrite plus marteniste microstructure. Although these steels show an even higher strength than the ferrite plus bainite steel, the higher internal stresses caused by the martensite transformation at low temperature lowers the ductility. Therefore, HSLA steels with a microstructure of ferrite plus bainite are often applied to applications such as passenger car wheel discs where a minimum tensile strength of 600MPa is required. The typical chemical composition of this steel would be 0.08% carbon, 0.25% silicon, 1.45% manganese and 0.03% niobium (12).

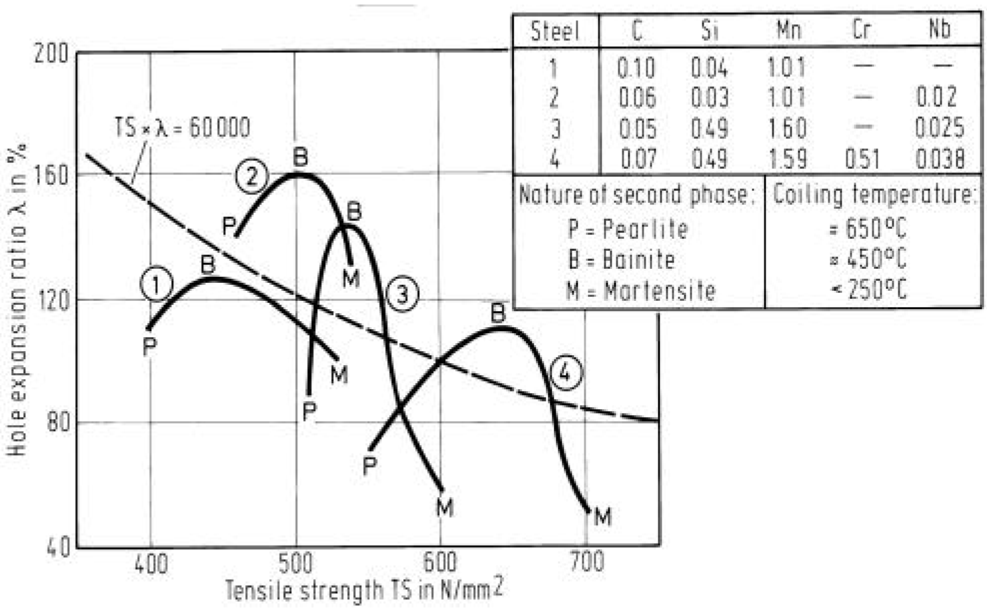

Figure 20: Influence of coiling temperature and alloy design on the microstructure and properties of HSLA strip.

Uniformity of Properties

The challenge however lies in achieving these ideal/optimum-processing conditions both along the entire hot rolled coil length and across the coil width. On removal from the coiler, the coil will cool very slowly to room temperature. However, during the cool there will be a tendency for precipitate ripening to mirror the cooling profile of the coil. This is observed from figure 21, which shows the topological yield strength developed from a section of a niobium HSLA strip steel (26). This particular steel coil exhibits softer strengths at the edges, suggesting that insufficient time at temperature was experienced to generate optimum secondary hardening from Nb(CN) particles, unlike the mid width of the coil that appears to have experienced the right cooling conditions. It is factors such as these that will also impart some degree of inconsistency within the coil. In general it has been found, for high microalloyed steels (niobium or vanadium), that the immediate coil ends will exhibit higher strengths than the body due to exposure related effects of the inner and outer laps (36,44). This is shown quantitatively in figure 22, where two cooling curves representing distinct parts of the coil are superimposed onto iso-hardness curves of a steel with 0.02% niobium in solid solution obtained for various annealing times and temperature conditions in the ferrite (44). The difference hardness increases at a certain annealing temperature is a result of the annealing time correlating with the volume fraction and particle size of the ferrite precipitates. As after a certain time, fine NbC precipitates are formed homogeneously throughout the matrix. With longer annealing times the amount of such precipitates increases and a hardness of up to 30HV (corresponding to 100MPa tensile strength) can be realised. With increased annealing times, the hardness is expected to fall due to particle coarsening effects.

This is something that is inherent to all hot-rolled coils. Although it is important to note that if the applied coiling temperature is well below the desired optimum, then the reverse will be true; i.e. the coil ends will be soft due to suppression of precipitation. Also, a change in the second phase microconstituent and volume fraction must also not be forgotten. To minimise this effect, and depending upon the response time of the run-out-table control system, it is possible to apply a catenary or U-pattern cool to the strip. The process involves a reduction in the level of cooling applied at the head and tail end of the hot-rolled strip and thus producing a coil with hotter ends. This will, to a degree, counteract the rapid cooling experienced by the exposed outer and inner laps and thereby balance the overall coil cooling rate.

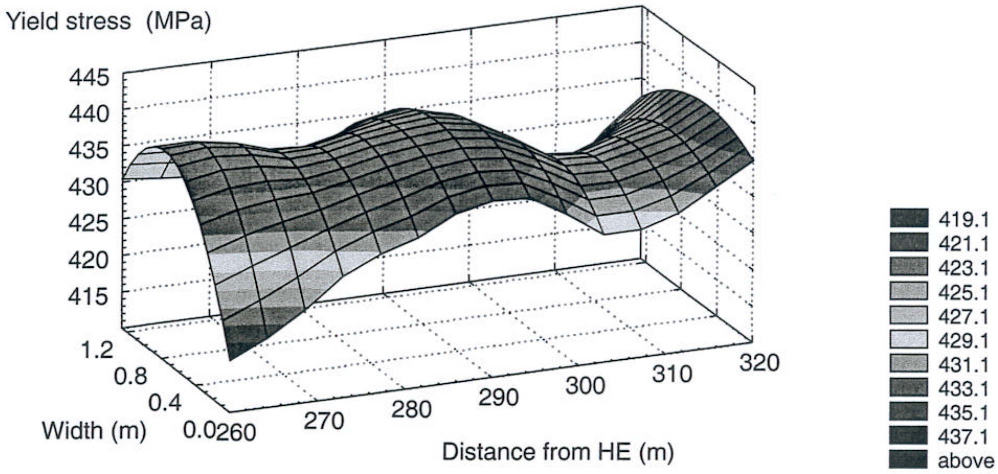

Figure 21: Topological yield strength distribution for a niobium HSLA strip.

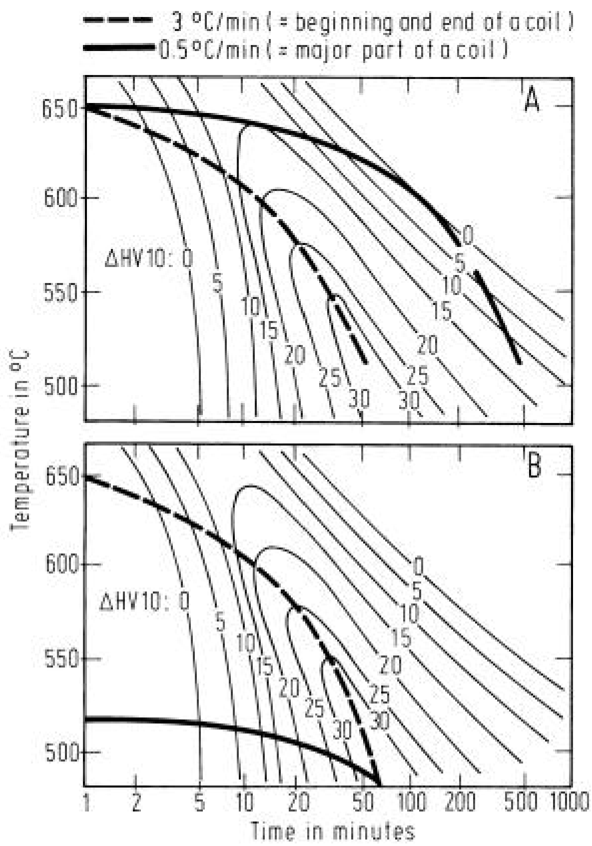

Figure 22: Iso-hardness curves as result of precipitation hardening by NbC of steel with 0.02% solute niobium with the cooling curves for different coil positions superimposed. a) Constant coiling temperature; b): Maximum and homogeneous strength.

Summary

The roles of niobium are summarised in figure 23 (46).

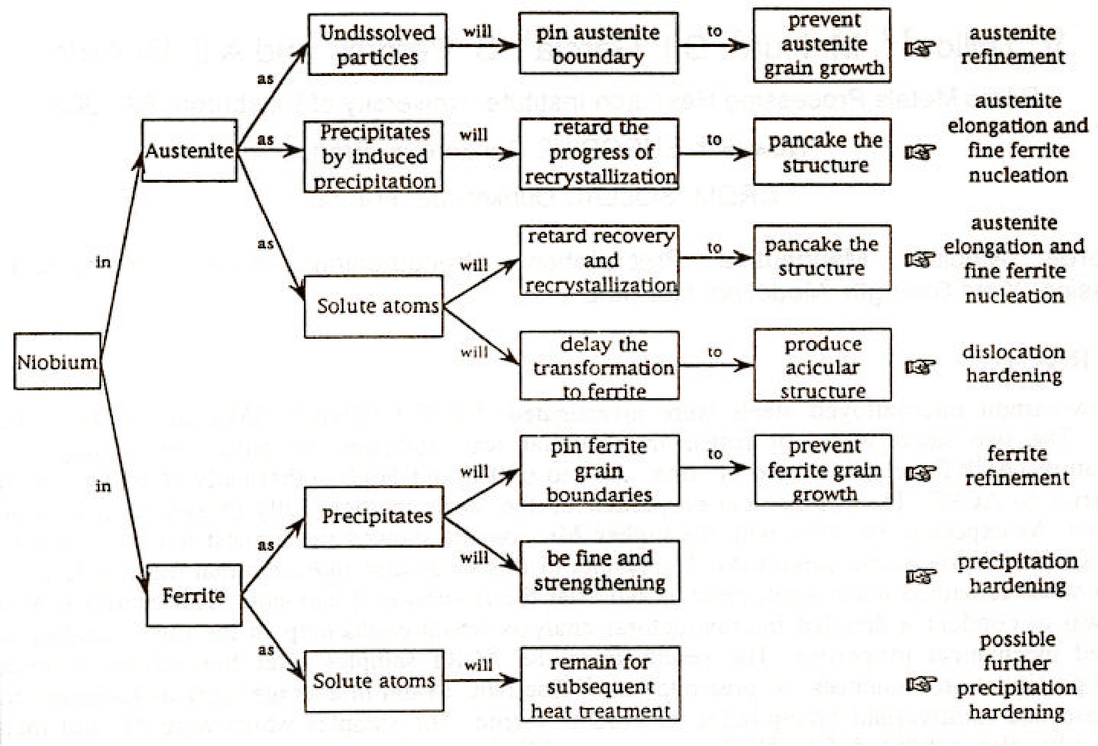

Figure 23: Schematics of the different roles of niobium during thermomechanical rolling.

The general and expected trend is that an increase of niobium to the base steel will result in higher strengths. This is shown in figure 24, which contains a range of industrial niobium HSLA strip steels with varying manganese levels (26). A conclusion that can be rapidly drawn is that achieving a maximum contribution from the niobium microalloying addition requires striking the right balance between:

i) Achieving sufficient levels of austenite conditioning below the recrystallisation temperature to aid generation of a finer ferrite grain size, and;
ii) To ensure favourable conditions for the precipitation of fine coherent Nb(CN) particles in the ferrite structure to generate a degree of secondary hardening.

The hot strip rolling of all microalloyed high strength steel grades require careful process control over the entire strip mill. It is clear that there is no one single important part of the process route that is key. By understanding the intertwined relationship between the process route and the physical metallurgy it is possible to develop a range of cold formable steel grades for the automotive industry. In addition, through knowledge of the process metallurgy it is possible to take corrective action further down the process stream if it is required.

The lion's share of the challenge evidently lies with good temperature control and management over the entire hot strip mill. Although all microalloyed steels can be considered more responsive to the surrounding process conditions, niobium has the added advantage over other elements such as vanadium, in that it imparts strengthening contributions at two different stages of the process i.e., grain refinement during finishing train rolling and secondary precipitation hardening, especially during coil cooling. Thus, even if the hot strip mill cannot apply a very low coiling temperature or a catenary cooling profile, the niobium microalloying addition, along with the steel composition and finishing schedule, can be tailored to generate a maximum conditioned austenite structure and hence, fine ferrite grains. The latter will not only provide high yield strength but also improve toughness properties. With the application of an optimum coiling temperature a further increase in strength can be realised via precipitation hardening. However, the relationship between the ferrite grain size and the secondary hardening contribution is a complex one and figure 25 shows the balance, which exists (26).

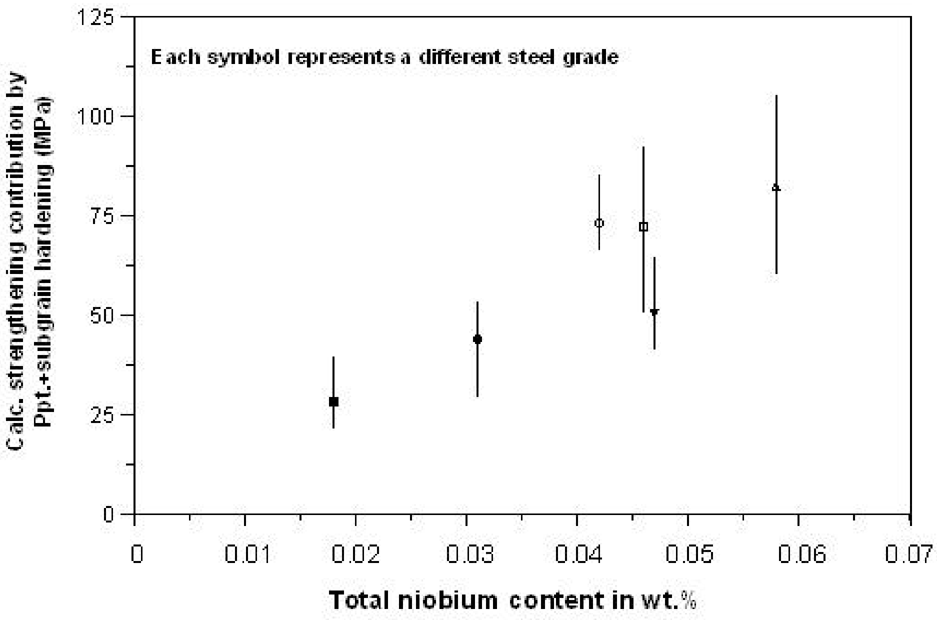

Figure 24: Relationship between niobium content and strength increase by precipitation and subgrain hardening.

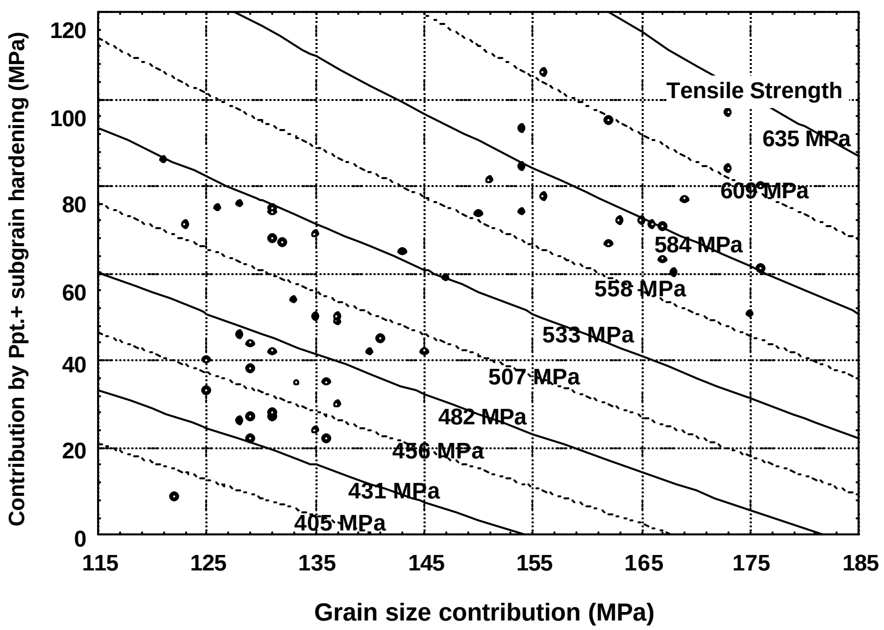

Figure 25: Contribution of various strengthening mechanisms on the strength of HSLA strip (0.055-0.075 %C, 0.4-1.5 %Mn, 0.02-0.06 % Nb.

The cold forming of hot rolled strip is a standard production step especially for the automotive and construction industries. For tensile strength levels above 500MPa microalloyed HSLA steels are quite acceptable for a wide range of applications. However, dual-phase steels are also now widely available for applications requiring superior formability. These steels, which have a dual or tri-phase microstructure, are produced by various processing routes or heat treatment, which are harmonised with the chemical composition. In the optimisation of all these steel types it has been established that - equally as in HSLA strip - microalloying with niobium further improves the mechanical properties, especially through refinement of the microstructure. This not only generates higher tensile properties, but also has no ductility impairing effect, thus resulting in an exponential increase of the characteristic product of tensile strength and elongation with higher niobium levels.

References

(1) Thyssen Stahl AG, Hot rolled coil and strip, brochure 6751 AE 39, August 1993.

(2) SHIRASAWA H, Recent developments of cold formable high strength hot rolled steels in Japan. In proceedings of the symposium on high strength sheet steels for the automotive industry, Baltimore, MD, October 16-19, 1994. The Iron and Steel Society.

(3) YOUNGER D.G, Metal Progress, 1975, No 5, p. 43-47.

(4) ONIK M, J Zijp and A Bodin, High strength steels for automotive applications. In 41st Mechanical Working and Steel Processing Conference proceedings, Baltimore, MD, October 24-27, 1999. The Iron and Steel Society.

(5) YAMAGUCHI, T and H. Taniguchi, Ductility in hot rolled steels (Japanese), Nippon Kokan Technical Report No. 45, 1996, p. 23-30.

(6) Niobium Information 19/01. Improved service performance of high strength low alloy strip and sheet steels for automotive applications. CBMM/NPC, Düsseldorf, 2001.

(7) TERACHER, P and G. Marron, Application of high strength hot rolled steels in wheels. In Proceedings of the symposium on high strength sheet steels for the automotive industry, Baltimore, MD, October 16-19, 1994. The Iron and Steel Society.

(8) FERON, S. et al., Development of new hot rolled high strength steel grades with improved formability for the transportation industry at Cockerill Sambre. In Proceedings of the symposium on high strength sheet steels for the automotive industry, Baltimore, MD, October 16-19, 1994. The Iron and Steel Society.

(9) PATEL J, Private communications, 2000.

(10) SPERLE, J-O and K. Olsson, High strength automotive sheet steel for weight reduction and safety applications. In Proceedings of the symposium on high strength sheet steels for the automotive industry, Baltimore, MD, October 16-19, 1994. The Iron and Steel Society.

(11) MÜSCHNBORN W et al., Recent developments in physical metallurgy and processing technology of microalloyed flat rolled steels. In Proceedings of the international conference, Microalloying '95, Pittsburgh, PA, June 11-14, 1995. The Iron and Steel Society, p. 35-48.

(12) RIGAUT G. and T. Teracher, Advances in producing microalloyed hot strip mill products. In Proceedings of the international conference, Microalloying ’95, Pittsburgh, PA, June 11-14, 1995. The Iron and Steel Society, p. 275-284.

(13) CUDDY L.J, The effect of microalloy concentration on the recrystallisation of austenite during hot deformation. In Themomechanical processing of microalloyed austenite. Warrendale (PA), USA, 1982. TMS of AIME, p. 129-140

(14) MEYER L, F. Heisterkamp and W. Müschenborn, Columbium, titanium and vanadium in normalised, thermomechanically treated and cold rolled steels. In Proceedings of an international symposium on HSLA steels, Microalloying ’75, Washington D.C., October 1-3, 1975, p. 153-167.

(15) HELLER T and J. ESDOHR, Stahl 1997/1, p.34-39.

(16) STRAßBURGER C, Thyssen Technical Report 1/1992, p.23-34.

(17) KAUP K et al., Stahl und Eisen 104, 1984, p. 1017-1024

(18) ROBILLER G and L. Meyer, 1st Risó International symposium on metallurgy and materials science, Risó – Denmark, 1980, p.311-316.

(19) MISRA R. et al., Role of structure and microstructure in the enhancement of strength and fracture resistance of ultra-high strength hot rolled steels. In 42nd Mechanical Working and Steel Processing conference proceedings, Toronto, Canada, October 22-25, 2000. The Iron and Steel Society.

(20) NORDBERG H and B. Aronsson, Solubility of niobium carbide in austenite, Journal of the Iron and Steel Institute, (206), 1968, p.1263-1266.

(21) IRVINE H. J, F.B. Pickering and T. Gladman, Grain refined C-Mn steels, Journal of the Iron and Steel Institute, (205), 1967, p.161-182.

(22) ABERNETHY K, Effect of hot charging on steel properties. In Conference proceedings of European steelmaking developments and perspectives in rolling and reheating, February 1-2, 1995. European Commission.

(23) SPEICH G.R. et al., Formation of ferrite from controlled rolled austenite. In Proceedings of an international conference in phase transformation in ferrous alloys. Warrendale Pa., USA, 1984. TMS-AIME.

(24) PATEL J.K, P.J. Evans and B. Wilshire, Optimisation of hot strip mill processing conditions for niobium HSLA steels. In Conference preprints of thermomechanical processing of steels, London, UK, May 24-26, 2000. The Institute of Materials.

(25) AYLEN ,. A technical history of the hot strip mill for steel. In Conference on the history of the wide strip mill in Europe, Manchester, UK, April 27-28, 2001.

(26) PATEL, J.K, Engineering doctorate thesis; Controlled hot rolling of HSLA strip steels to optimise properties. University of Wales, Swansea, UK, September 2000.

(27) GROSS J, Transformation characteristics of low-carbon Cb-containing steels. In Proceedings of the symposium; low alloy high strength steels, Nuremberg, Germany, May 21-23, 1970. The Metallurg Companies.

(28) KOZASU et al., Hot rolling as a high-temperature thermo-mechanical process. In Proceedings of an international symposium on HSLA steels, Microalloying '75, Washington D.C., October 1-3, 1975.

(29) TANAKA T., Science and technology of hot rolling process of steel. In Proceedings of the international conference, Microalloying '95, Pittsburgh, PA, June 11-14, 1995. The Iron and Steel Society.

(30) MEYER L, F. Heisterkamp and C. Straßburger, Alloying possibilities for increasing strength and toughness of weldable structural steels. In Proceedings of the symposium; low alloy high strength steels, Nuremberg, Germany, May 21-23, 1970. The Metallurg Companies.

(31) GLADMAN T, D. Dulieu and I.D. Mc.Ivor, Structure-property relationships in high-strength microalloyed steels. In Proceedings of an international symposium on HSLA steels, Microalloying '75, Washington D.C., October 1-3, 1975.

(32) FUKUDA M, T. Hashimoto and K. Kunishige, Effects of controlled rolling and microalloying of strip and plates. In Proceedings of an international symposium on HSLA steels, Microalloying '75, Washington D.C., October 1-3, 1975.

(33) DUTTA B and C.M. Sellars, Effect of composition and process variables on Nb(C,N) precipitation in niobium microalloyed austenite. Materials Science and Technology Vol.3, p. 197-206.

(34) HERMAN J.C., B. Donnay and V. Leroy, Precipitation kinetics of microalloying additions during hot-rolling of HSLA steels, ISIJ Int. 32 (1992), No. 6. p. 779-785

(35) GRAY J.M. and A.J. DeArdo, Austenite conditioning alternatives for microalloyed steel products, In HSLA steels metallurgy and applications, ASM International, p, 83-96

(36) PATEL J.K. and P.J. Evans, The effect of processing conditions on the consistency of mechanical properties for Nb-HSLA strip steels. In 40th Mechanical Working and Steel Processing conference proceedings, Baltimore, MD, October 24-27, 1999. The Iron and Steel Society.

(37) CUDDY L.J, In Accelerated cooling of steels, ASME, Warrendale (PA), 1986. The Metals Society of the American Society of Materials Engineering.

(38) LEORY V. and J. Herman, Contrôle de la cinétique de precipitation induite par laminage à chaud et refroidissement accéléré dans les aciers HSLA. ECSC Report EUR 15748 FR, Contract No. 7210-MA/201, 1996.

(39) ITMAN K, K. Cardoso and H. Kestenbach, Quantitative study of carbonitride precipitation in niobium and titanium microalloyed hot strip steel. Materials Science and Technology Vol.13, 1999, p. 49-55.

(40) BAKER, A.J and J. Nutting, In Iron and steel special report No.64, 1959, p.1.

(41) HERMAN J.C, J. Lacroix and P. Riche, Ultra-fast cooling in the hot strip mill. Technical steel research European Commission Contract No. 7215-CA/204, 205, 206. 1st July 1996 to 31st October 1998.

(42) Niobium Information 17/98. Characteristic features of titanium, vanadium and niobium as microalloy additions to steel, Düsseldorf, 1998.

(43) Niobium Information 15/97. Dual phase and TRIP steels. CBMM/NPC, Düsseldorf, 1997.

(44) HOOGENDORN Th., A. Bodin and P. Hekker, Accelerated cooling of strip: from coiling temperature control to heat treatment. In Proceedings of the international conference, Microalloying '95, Pittsburgh, PA, June 11-14, 1995. The Iron and Steel Society.

(45) Niobium Information 14/97. Thermomechanical rolling of hot strip for line pipe application. CBMM/NPC, Düsseldorf, 1997.

(46) THILLOU V et al., Precipitation of NbC and effect of Mn on the strength properties of hot strip HSLA low carbon steel. In Proceedings of the international conference on microalloying in steels, San-Sebastián, Spain, September 7-9, 1998. Trans Tech Publications.