NIOBIUM CONTAINING STEELS FOR SPIRAL AND ELECTRIC RESISTANCE WELDED LINE PIPE PRODUCTION

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Abstract

Niobium containing thermomechanical treated steels have been used as line pipe materials for several decades. These steels combine high strength, high impact toughness and outstanding weldability. There are basically two different processes to produce pipes from hot strip. Both processes have specific needs that have to be considered during hot strip production. Thermomechanical rolling might cause anomalies called separations in the fracture behaviour. Separations might be distinguished in several categories. Cleavage fracture separations can be avoided by controlled rolling above Ar_3 and grain boundary separations by coiling at low temperatures.

Introduction

The use of microalloyed steels for gas transmission pipes has led to improved weldability, particularly in field welding, higher operating pressures and a decrease in wall thickness of pipes (1). Thinner pipe walls facilitate the handling on the construction site and reduce the amount of steel needed. These steels show high impact toughness and the capability to arrest cracks assuring high safety standards of operating pipelines.

Metallurgical Principles of Hot Rolling

Four temperature regions of hot rolling have to be distinguished (Figure 1) (2):

a) Region of recrystallisation of austenite ($T > T_R$)
b) Region of non – recrystallisation of austenite ($T_R > T > A_3$)
c) Region of austenite to ferrite (α/γ) - transformation ($A_3 > T > A_1$)
d) Ferritic region ($T < A_1$).

A forming process induces the generation, movement and blocking of dislocations. At high temperatures the work-hardening in rolled material is removed by static recrystallisation, static recovery and sub-grain formation (3). The forming process in a certain temperature range leads to dynamic recrystallisation at a threshold rolling force. Dynamic recovery and dynamic recrystallisation enhance the removal of work-hardening (4).

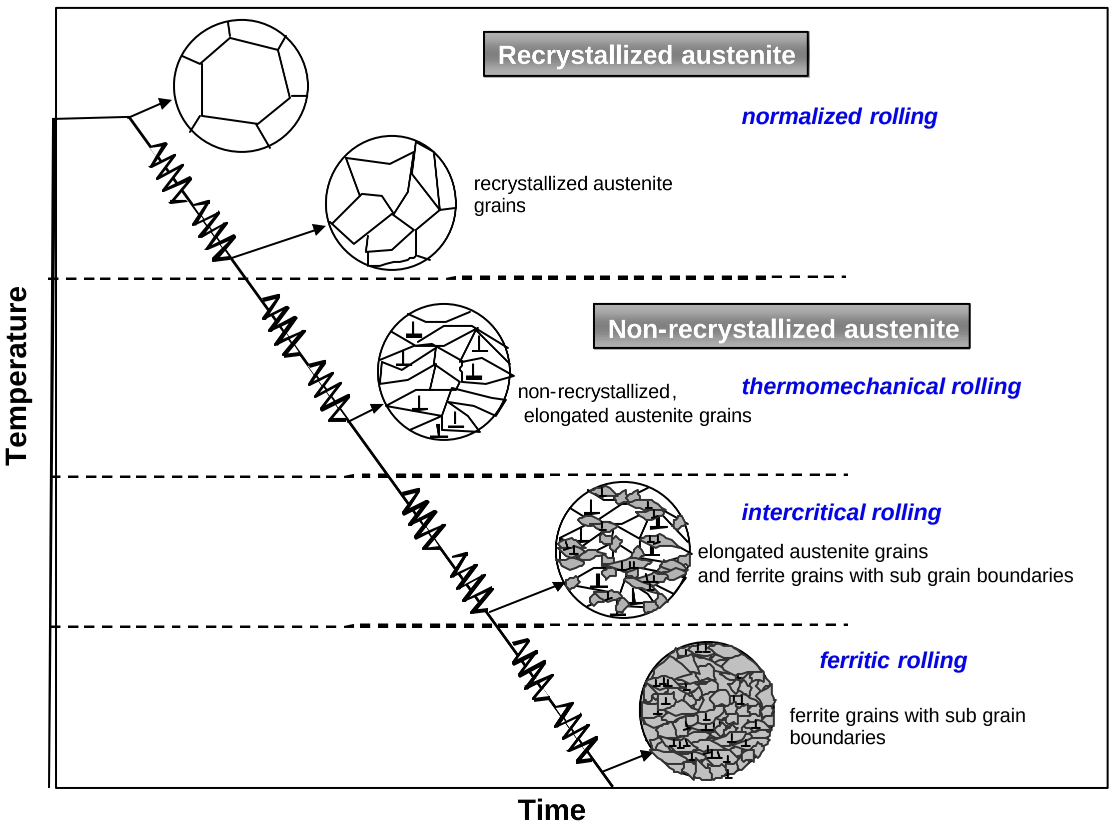

Figure 1: Temperature regions of the hot rolling process and the resulting microstructures.

Normalized Rolling

Normalized rolling is a controlled rolling process in the region of recrystallisation of austenite. The rolling generates dislocations that nucleate new austenite grains. These new austenite grains are smaller than before. The recrystallised globular austenite grains transform into a globular, fine ferrite grain structure.

The temperature control combines the conventional process route of rolling and annealing. The obtained microstructure corresponds to that of the conventional process.

Thermomechanical Rolling

At lower rolling temperatures recrystallisation of the austenitic phase is impeded (5, 6). Rolling at these temperatures produces an elongated grain structure with a high dislocation density. Grain boundaries and dislocations are nuclei for new ferrite grains. The elongated austenite grains transform into small ferrite grains (7). The high dislocation density enhances the formation of small ferrite grains by nucleation and growth. It also facilitates the diffusion and precipitation of microalloying elements. The carbides and nitrides of the elements niobium, titanium and vanadium are isomorphs and carbon can be found in nitrides and nitrogen in carbides. They are referred to as carbonitrides.

The temperature region of non-recrystallised austenite (temperature region of thermo-mechanical rolling) can be extended by the addition of microalloying elements. Solute microalloying elements restrict the movement of dislocations, sub-grain boundaries and grain boundaries. They create a solute drag effect, meaning that the velocity of the dislocation or sub-grain boundary equals the diffusion velocity of the alloying element (8). Carbide and nitride precipitations impose a particle drag effect on dislocations, sub-grain and grain boundaries. These precipitations also hinder post-dynamic recrystallisation (grain coarsening). Niobium has the most pronounced effect on the retardation of recrystallisation (Figure 2) (9, 10, 11).

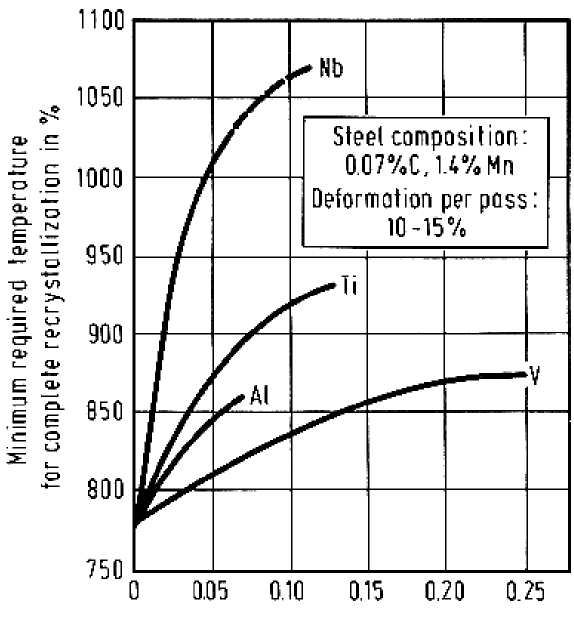

Figure 2: Influence of microalloying elements on the recrystallisation of the austenitic phase (11).

Intercritical Rolling

Intercritical rolling is performed in the temperature region where austenite and ferrite co-exist (between Ar_3 and Ar_1). In the rolling process austenite grains are elongated similar to the thermomechanical treatment and ferrite grains with sub grain boundaries are produced.

Ferritic Rolling

Ferritic rolling is undertaken in the ferritic phase (below Ar_1). The resultant is a ferritic microstructure with sub-grains. Less is understood of microstructure formation and mechanical properties in the intercritical and the ferritic temperature region. Rolling in the intercritical region is known to be susceptible to grain coarsening leading to a detrimental effect on the material toughness (12).

The most common rolling process is normalized rolling for the low strength grades and thermomechanical treatment for grades X60 and stronger.

Hot Strip Production

Modern high strength line pipe steel grades are usually thermomechanically treated. Special requirements such as a low carbon equivalent or a high percentage of ductile fracture surface in the Drop Weight Tear Test can only be obtained using thermomechanically rolled steels. Thermomechanical rolling is a complex combination of a number of process steps (Figure 3). Micro-alloying elements precipitate in the melt and nucleate fine-grained austenite during the casting process.

The first production step in a hot rolling mill is the reheating of the slabs in a furnace in order to increase the plasticity and also to re-introduce the added microalloy into solution. During reheating, a phase transformation from ferrite to austenite occurs and grain growth takes place. The temperature and duration of the slab in the furnace is crucial in order to bring the microalloying elements in solid solution. Only microalloying elements in solid solution lead to a precipitation hardening in the latter process. Increasing the duration of the slab in a furnace (>1180°C) from 100 to 190 minutes causes an increase in the yield strength of up to 90MPa. Furthermore, these elements cause a retardation of both, the recrystallisation of austenite and the transformation of austenite to ferrite (13). In the latter process this leads to grain refinement and work-hardening. A detrimental effect of high furnace temperatures and long duration times on the impact transition temperature is described in the literature; this is attributed to grain coarsening in the slab. However, according to Cuddy (14), this effect is negligible.

Experimental data displayed a relationship between the furnace temperature and the rolling temperature in the roughing mill. Using a furnace temperature of 1200°C to 1250°C (in the core of the slabs) a fine grained micro-structure can be obtained, if the rolling in the roughing mill starts at a temperature <950°C. Practically, this is achieved by introducing an air cool (delay) in front of the roughing mill. However, overall prudence must be given to the developed rolling loads.

Precipitation of microalloy carbonitrides during the TM-rolling may occur during deformation and/or the low rolling temperature (15). Deformation induced precipitation can take place in the roughing or the finishing stands and has to be controlled by draught per pass and interpass time. A temperature controlled process commands precipitation due to supersaturation effects. Different precipitates can be obtained in every process step depending on the alloying concept being employed. The precipitates in the austenite phase have an effect on the nucleation of the ferrite grains in the austenite to ferrite transformation, the retardation of recrystallisation and the impeding of grain growth. The mechanical properties are effected by precipitation hardening and grain size control (Hall-Petch relationship).

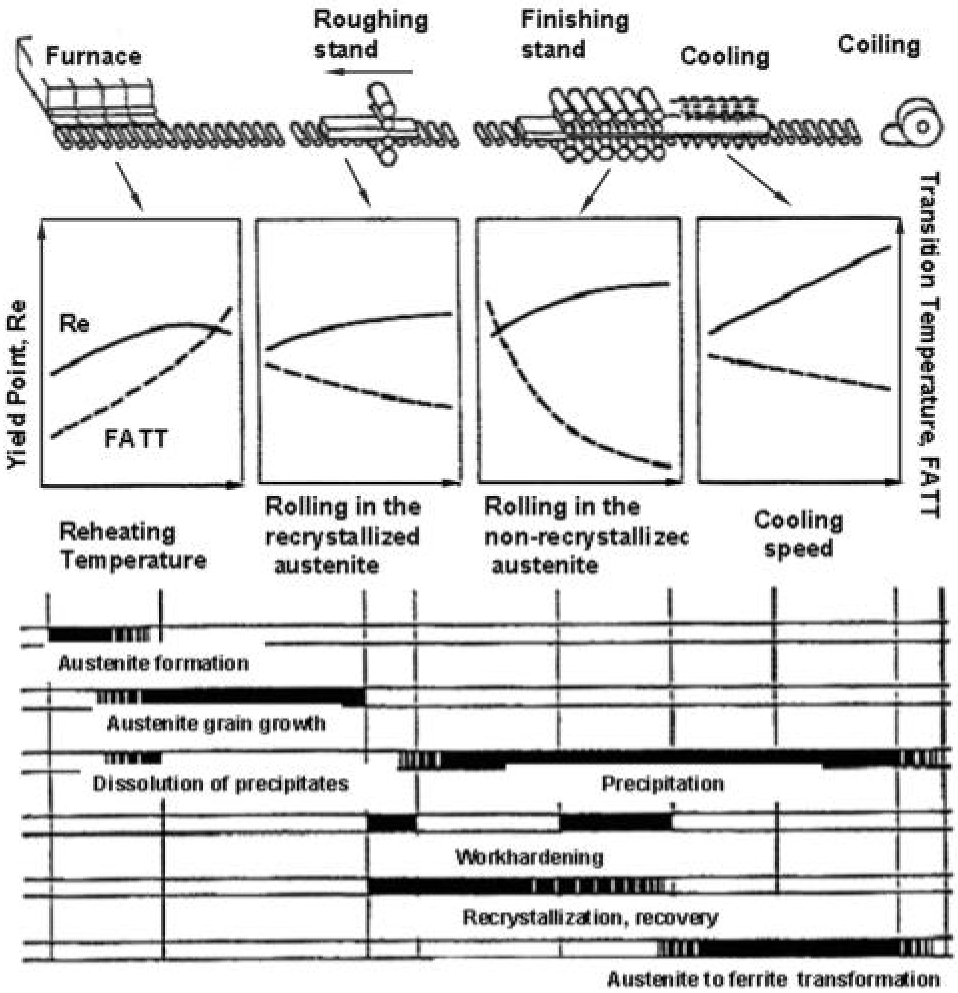

Figure 3: Influence of the rolling scheme on the mechanical properties (8).

The remaining solute microalloys that do not precipitate in austenite cause retardation in the recrystallisation of ferrite and induce solid solution hardening. The ferrite grain size and the texture of the ferritic phase are influenced by the retarded recrystallisation. The cooling of the strip induces the precipitation of carbonitrides in the supersaturated ferrite phase and causes precipitation hardening (16).

Work-hardening is caused by the deformation process in both the recrystallised and the non-recrystallised austenite. This work-hardening is partially removed by recrystallisation and/or recovery. An increase in the level of deformation in the recrystallised austenite region has only a minor effect impact on the yield point and the transition temperature. However, an increase of deformation in the non-recrystallised austenite leads to an increase in yield strength and a drastic decrease in the transition temperature. An additional elegance of the thermomechanical treatment is rolling in the non-recrystallised austenite region in both, the roughing and the finishing stands. It is necessary to carry out at least 70% of the forming in this temperature region.

An increase in the final rolling temperature reduces the degree of forming in the non-recrystallised austenite and causes a drop off in yield strength and a rise in the transition temperature.

The final microstructure of the steel is also influenced by the cooling rate after rolling. Accelerated cooling improves both the yield point and transition temperature. On the run-out-table the elongated austenite grains transform into ferrite-pearlite or acicular ferrite (17, 18) (depending upon steel make-up and level of cooling applied).

Line Pipe Production

The production of line pipe can be undertaken via four different process routes:

1. Spirally welded pipe from heavy plate
2. Longitudinally welded pipe from heavy plate
3. Helically or spirally welded pipe from hot strip
4. Longitudinally welded pipe from hot strip

For the pipe production from hot strip only the latter two options are significant.

Spiral Welded Pipe Production

Spiral pipes are produced from forming and welding plate or strip material (19). Some pipe producers may use a tack welding operation, whereby the pipes are formed and tack welded in one step and the submerged arc welding is done in another operation.

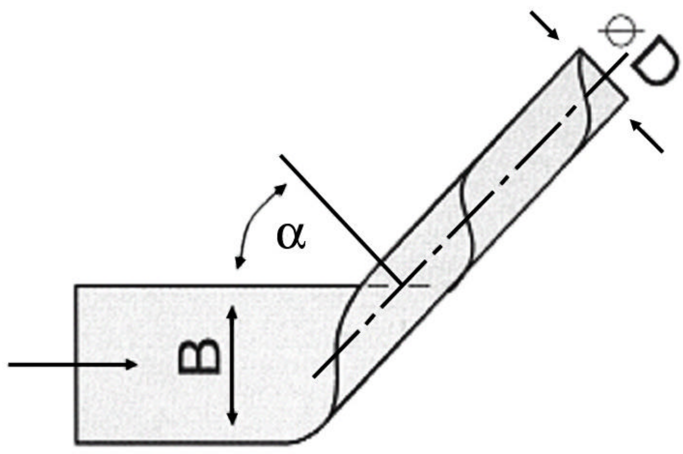

Figure 4: Forming process and relationship between strip width and pipe diameter.

A major advantage of spiral pipe production is its high versatility. Various pipe diameters can be produced from the same strip width by changing the forming angle α (Figure 4). The forming angle is defined as the angle between the incoming strip and the leaving pipes:

$$\sin \alpha = \frac{B}{Dp}$$

where: D = pipe diameter B = strip width
α = forming angle.

A skelp weld joins one coil to the other in order to produce a continuous pipe. Rolling stands (usually a three roller bending unit) form the strip material into a continuous pipe that is cut to length in a later process step.

The two step manufacturing process with continuous tack welding is used to obtain a higher productivity and improved quality since welding is the most time consuming operation (Figure 5). At Salzgitter Großrohr GmbH, the operations run one production line for forming and tack welding and three submerged arc welding stations (Figure 6). The tack welding has no influence on the latter pipe properties since it is completely re-molten. The welding stations are equipped with two welding heads (2-3 wires) on the outside and three on the inside (3-4wires) in order to perform the submerged arc welding outside and inside the pipe at the same time.

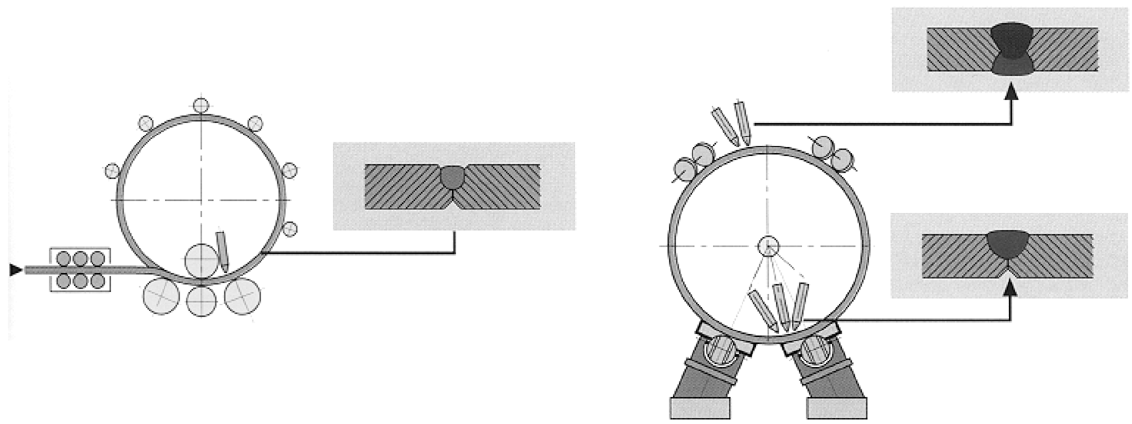

Figure 5: Tack welding (left) and final welding operation (right).

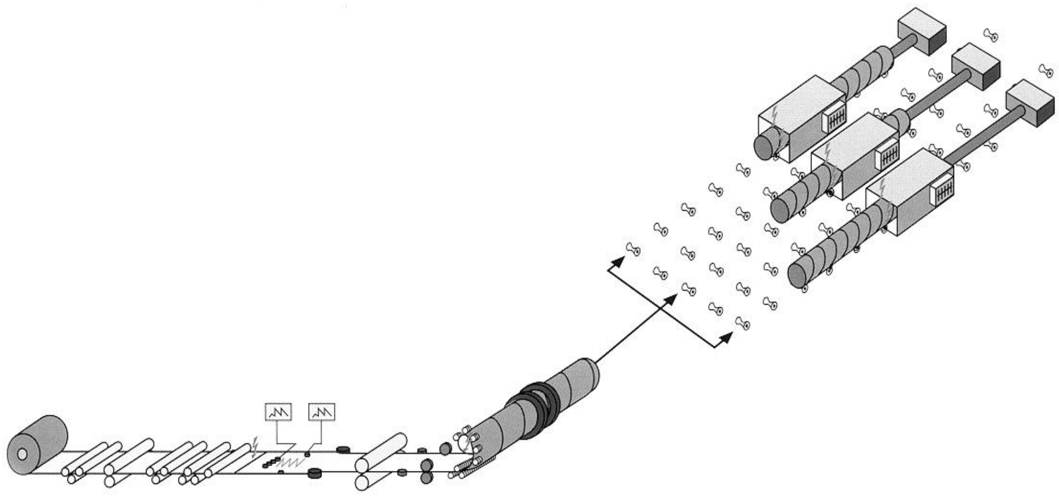

Figure 6: Set up of a spiral pipe plant.

Electric Resistance Welded Pipe Production

Production of Electric Resistance Welded (ERW) pipes is carried out in a continuous forming and longitudinal welding operation (20). The most common welding process is the High Frequency Induction (HFI) welding. A major advantage is the high productivity attainable due to the high welding velocities of HFI process. The pipe diameter depends critically on the strip width and very tight tolerances apply:

$$D = \frac{B}{p}$$

where: D = pipe diameter B = strip width

The transverse edge of a coil is welded to the other in order to obtain a continuous strip. This runs into a loop tower. The continuous strip is rolled in several rolling stands to a circular shape (Figure 7).

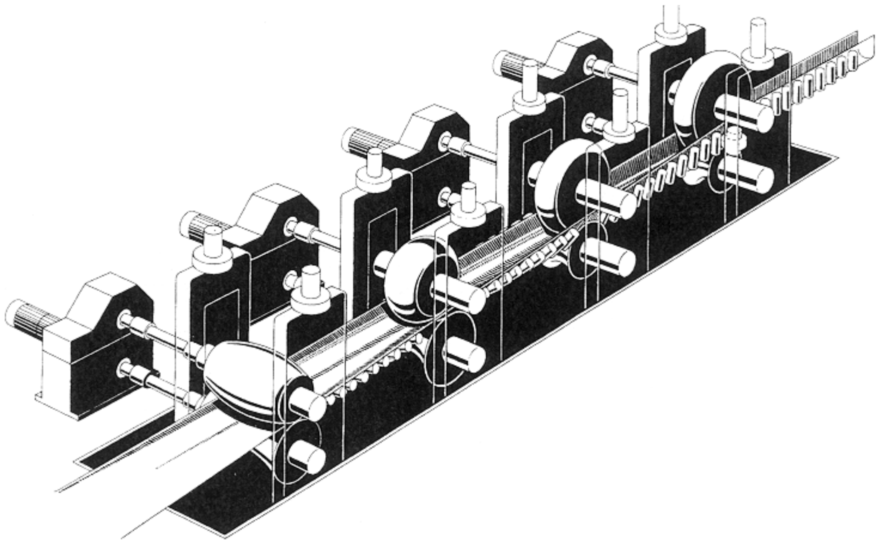

Figure 7: Continuous forming process (21).

The longitudinal strip edges are heated electrically and pressed together to achieve binding. Two kinds of electrical welding can be distinguished: low frequency welding in the range between 50 to 400Hz and high frequency welding from 150,000 to 500,000Hz. High frequency welding can be performed as a conduction or an induction process (Figure 8) (22). In the conduction process the electrodes are in contact with the future pipe. The current flows from one electrode to the other using the skin effect. The same welding occurs at the induction process but the current transmission takes place without a contact. This is carried out using a ring inductor.

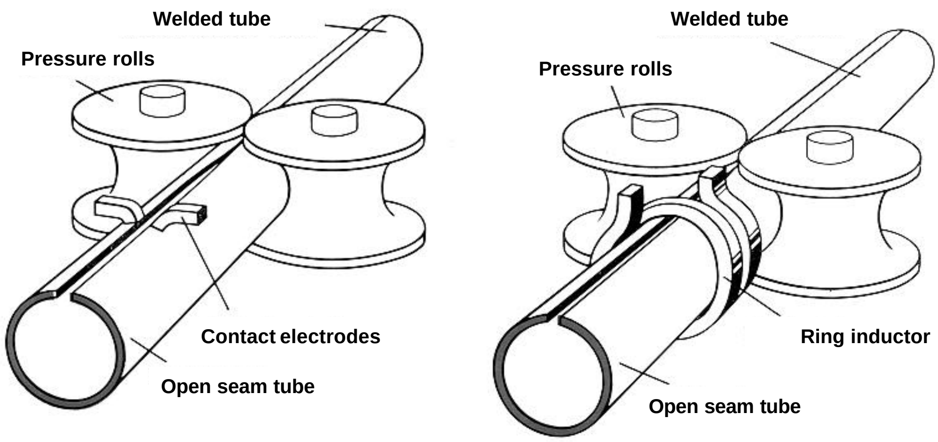

Figure 8: Conduction (left) and induction (right) welding (24).

The longitudinal weld can be annealed and controlled cooled (water or air cooling) after welding (23).

Differences of the Pipe Production Processes

Thermomechanically treated hot strip displays anisotropic mechanical properties. This phenomenon can be explained by the elongated grain structure in the austenitic phase that transforms into a textured ferritic phase. The ferrite nucleates on the austenite grain boundary and, although the ferritic grains are globular, the former austenite grain boundary remain in the microstructure. Therefore, thermomechanically rolled material possess long grain boundaries in rolling direction.

Another reason for the anisotropy is the elongation of non-metallic inclusions like manganese sulphide. At high temperatures the sulphide inclusions are harder than the matrix material, but in the temperature regime of the thermomechanical treatment the inclusions are softer. During the rolling process they stretch in the rolling direction and elongate resulting in anisotropic toughness behaviour, particularly the Charpy notch impact toughness (25, 8). As a consequent, the Charpy impact values in the transverse direction are usually inferior to those in the rolling direction. However, modern steelmaking techniques using calcium-silicon desulphurisation can reduce the effect of inclusions in the steel. The addition of elements (titanium, zirconium, rare earth metals) that influence the hardness of the sulphide also have a beneficial effect on the toughness.

Pipes are usually tested with samples from the circumference of the pipe. These specimens, transverse to the pipe axis, correspond to a completely different location within the strip material depending on the pipe production process used. A transverse or longitudinal sample in a ERW pipe corresponds with the transverse or longitudinal sample in the strip. However, the location of a transverse sample in a spirally welded pipe compared to the hot strip depends on the forming angle and the pipe diameter. In the hot strip a transverse sample in the pipe is located approximately in a 20 to 30° angle from rolling direction. Considering the anisotropic properties, at 30° from rolling (longitudinal) direction the yield point has a minimum (26) and the Charpy notch impact toughness a maximum (Figure 9).

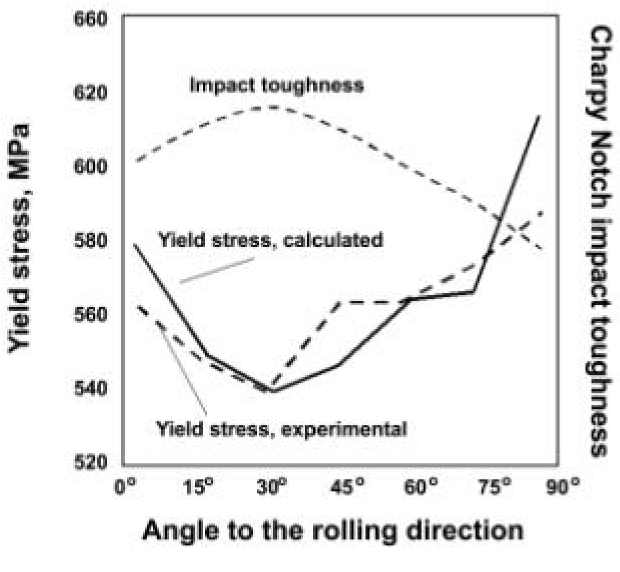

Figure 9: Anisotropic mechanical properties (26).

A pipe made from the same strip material will show different properties depending on the production process. The ERW pipe will display higher yield strength and the spiral welded pipe higher impact toughness. Another difference is the welding process. The weld of longitudinal welded pipes can be easily annealed in order to control the microstructure and properties. This is particularly advantageous in pipe production for sour service since residual stresses can be removed and the hardness of the weld can be reduced.

Fracture Behaviour and Separations

Thermomechanically treated steel is susceptible to the formation of separations (27, 28). Separations are cracks perpendicular to the direction of the major crack. They occur in both, tensile tests and Charpy impact tests. The direction of the separations is parallel to the strip surface (Figure 10). The tensile state is most unfavourable in the middle of the Charpy notch specimen thickness. A specimen will split in half due to the three-axial tensile state (1st. Order Separation). Each of these halves will face a similar situation and another splitting may occur (2nd Order Separation). This process might continue (3rd Order Separation) (29).

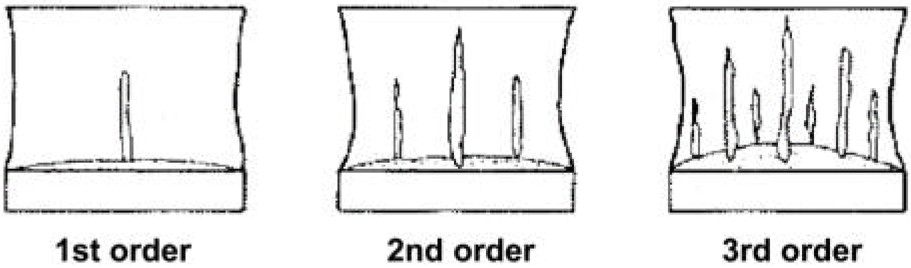

Figure 10: Classification of separations (29).

Separation formation reduces the Charpy impact toughness (Figure 11).

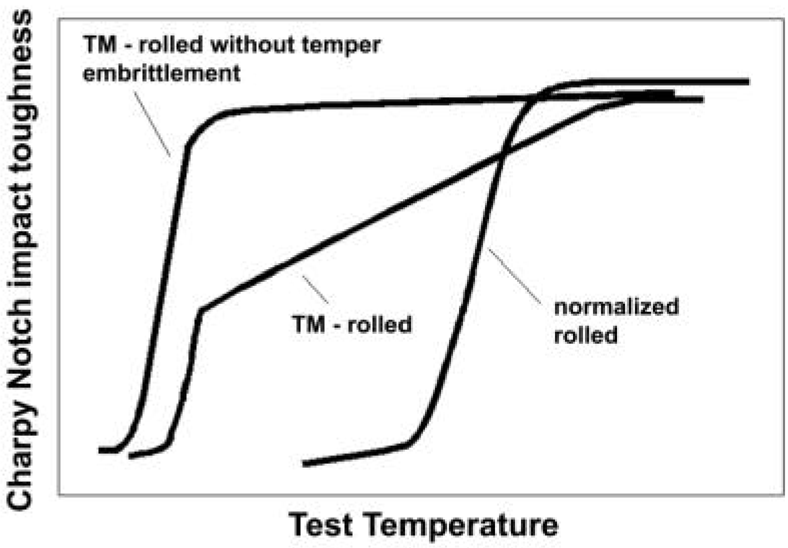

Figure 11: Influence of TM – rolling and separations on the impact toughness (29).

Two major groups of separations can be distinguished:

1. Inclusion type
2. Microstructure type

Separations of the inclusion type are cracks along the interface of an inclusion and the matrix material. This type of separation is negligible due to improved cleanliness of modern steel. Microstructural separations can occur as cleavage fracture and at the grain boundary.
The Characteristics for cleavage fracture separations are transcrystalline fractures on crystallographic cleavage planes parallel to the rolling plane. These crystallographic cleavage planes are generated by rolling in the intercritical temperature region. The grain boundary separations are characterized by a combination of reversible temper embrittlement and an elongated grain structure. Rolling in the temperature region of the non-recrystallised austenite might cause this temper embrittlement, which can be explained by phosphorus segregation on the grain boundaries. This segregation is enhanced by a slow cooling rate and explains the detrimental effect of higher coiling temperatures on the Charpy notch impact toughness (Figure 12).

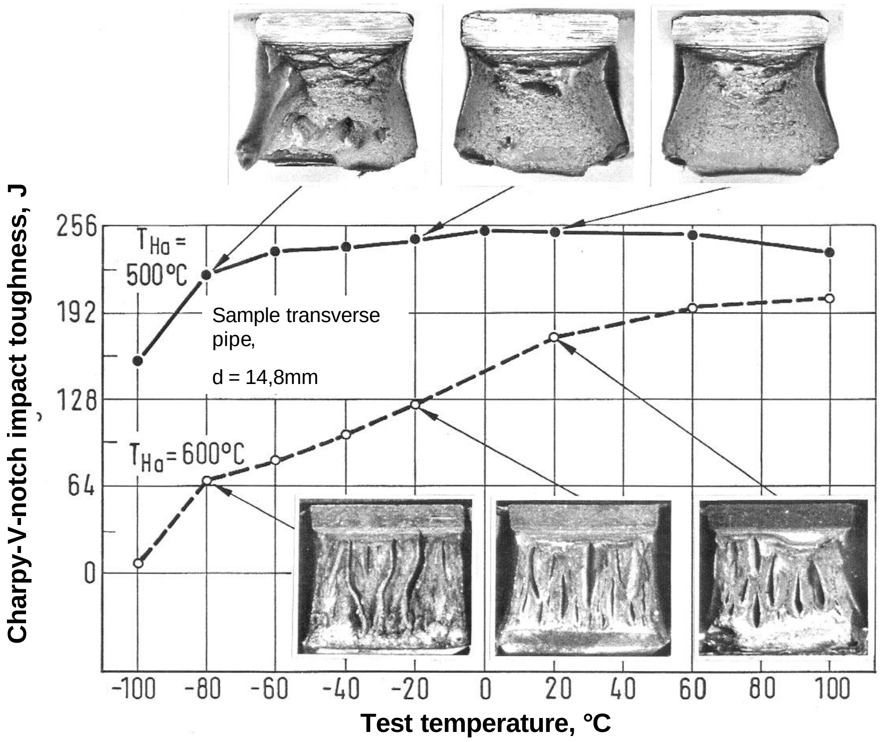

Figure. 12: Influence of the coiling temperature on reversible temper embrittlement (30).

There are two ways to prevent grain boundary separation formation (30, 31):

1. Reducing the amount of phosphorus
2. Reducing the coiling temperature

At coiling temperatures of 590°C the impact toughness can be improved by reducing the phosphorus content from 0.014% to 0.006%. Although achieving a low phosphorus content requires expensive steel making technology, most modern steel mills are well equipped to meet this requirement.

By reducing the coiling temperature to 500°C the same toughness values can be obtained by. No difference in the impact toughness can be seen in the range of 0.014% to 0.006% phosphorus (Figure 13). A decreased coiling temperature can be achieved without any further costs penalties.

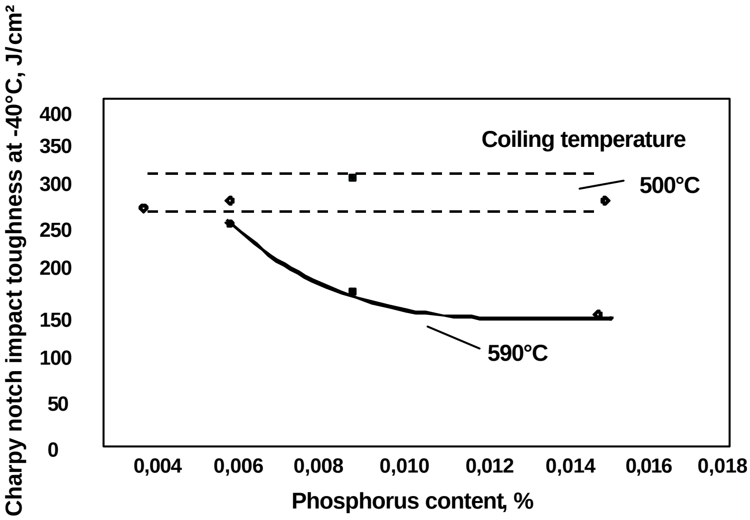

Figure 13: Effect of phosphorus content on temper embrittlement (31).

Summary

Thermomechanically treated line pipe steel grades combine good weldability (low carbon equivalent) and high impact toughness at low temperatures. Niobium as a microalloying element widens the temperature range for the thermomechanical rolling. Therefore, Niobium enables or facilitates the thermomechanical rolling of steel.

As well as the steels chemical composition, all the process parameter have to be optimised for this rolling process. Temperature and duration of the slabs in the furnace and the parameter in the rolling stands are crucial for the latter pipe properties. The cooling rate on the run-out-table is important for the microstructure of the material.

The production of the pipe itself has an impact on the properties obtained. Thermomechanically rolled hot strip is anisotropic. The measured properties differ with changing specimen location. Specimen location is usually perpendicular or parallel to the pipe axis. The location of these samples in the hot strip changes with different pipe forming processes.

The values for the Charpy impact toughness can be reduced by the formation of separations. Several types of separations are known, but the most common separation is the grain boundary type. This type is related to phosphorus segregation on the grain boundaries that causes reversible temper embrittlement. T he most economic way to solve this problem is coiling at low temperatures. This reduces the velocity of phosphorus diffusion and avoids embrittlement. Modern line pipe steel grades achieve excellent properties after a sophisticated thermo-mechanical treatment when all the process parameters optimised.

Practical Examples of Line Pipe Steel Grades

The company Salzgitter Flachstahl GmbH offers hot strip in line pipe steel grades up to grade X80 according to API 5L and L555MB according to DIN EN 10208. The maximum strip gauge is 24mm. The effect of rolling technique and chemical composition will be discussed on the basis of two different steel grades in the gauge range between 17mm and 24mm. In the first example an analysis with merely vanadium as a microalloying element examined (Table I). In the second, the addition of niobium and vanadium leads to a significant decrease in the carbon content by maintaining a higher strength characteristic. All values displayed are measured on the hot strip. For an estimation of the mechanical properties on the pipe the Bauschinger effect has to be considered.

Table I Chemical analysis of the compared line pipe steel grades

	C	Si	Mn	P	S	Ti	V	Nb
Example 1	0.14		1.45				0.070	
	0.16	<0.50	1.60	<0.015	<0.002	<0.010	0.090	<0.010
Example 2	0.10		1.70				0.090	0.038
	0.12	<0.45	1.80	<0.015	<0.005	<0.010	0.100	0.045

The chemical composition of example 1 was used to produce hot strip with a gauge of 17.5mm and 24mm respectively. No additional cooling in front of the roughing mill was required and the final rolling temperature was 870°C and the coiling temperature was 620°C.

The strength characteristics possess a homogenous distribution which is almost constant over a wide range of strip thicknesses at the given process parameter (Figures 14 and 15). The ratio of yield to ultimate tensile strength is rather low (in the range of 0.80). The influence of the strip gauge on the elongation is also rather low (Figures 16).

In the second example, the addition of niobium and the increase in the manganese content stabilize the austenitic phase at lower rolling temperatures. A cooling in front of the roughing mill was performed in order to receive a fine grained microstructure with sufficient fracture toughness. Rolling in the non-recrystallised austenite in both, the roughing and the finishing stands was performed in order to enhance the thermomechanical treatment. The final rolling temperature was 780°C and coiling temperature was 480°C. Hot strip with 18mm and 21mm gauge (for the 21mm samples specimen geometry according to API) was produced. The mechanical properties of the TM – rolled niobium containing steel are different for the two strip gauges (Figure 14 – 16). The higher of yield and tensile strength values of the thicker strip can be explained by a change in the cooling parameter.

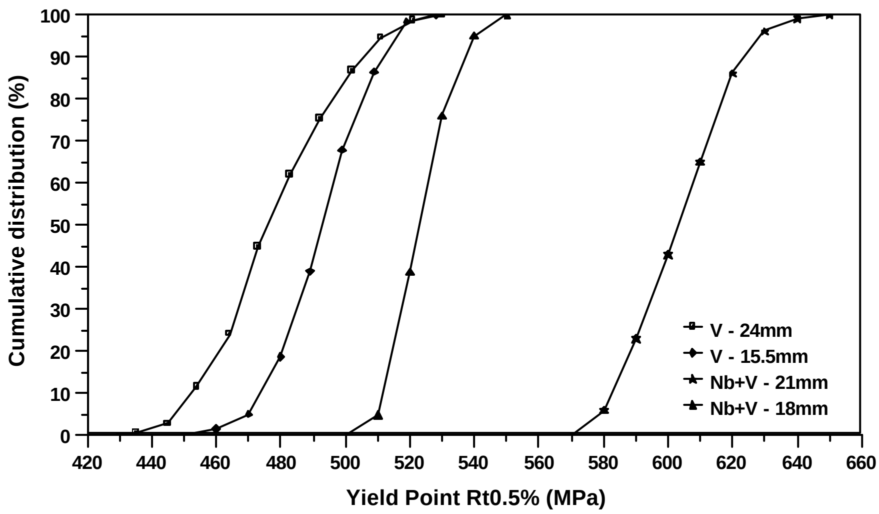

Figure 14: Distribution of the yield point for the vanadium alloyed steel at 24 and 17.5mm (Example 1); and for the niobium/vanadium alloyed steel at 21 and 18mm (Example 2).

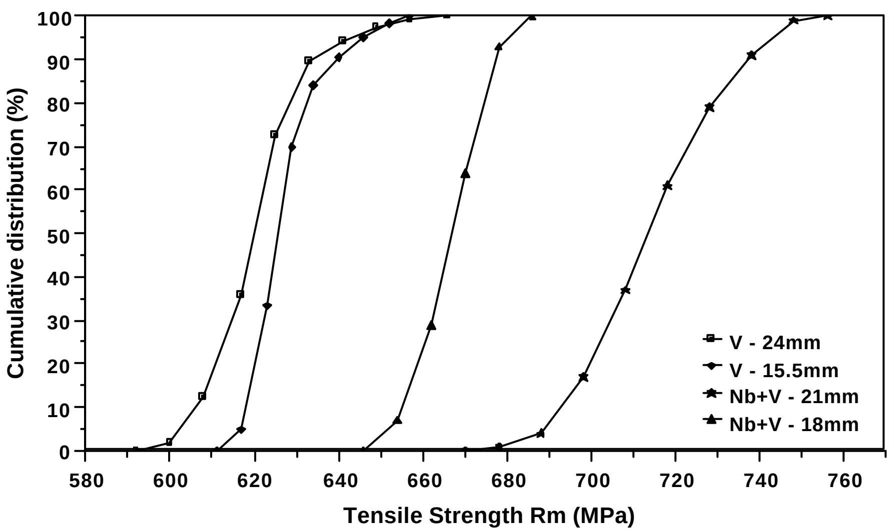

Figure 15: Distribution of the ultimate tensile strength for the vanadium alloyed steel at 24 and 17.5mm (Example 1); and for the niobium/vanadium alloyed steel at 21 and 18mm (Example 2).

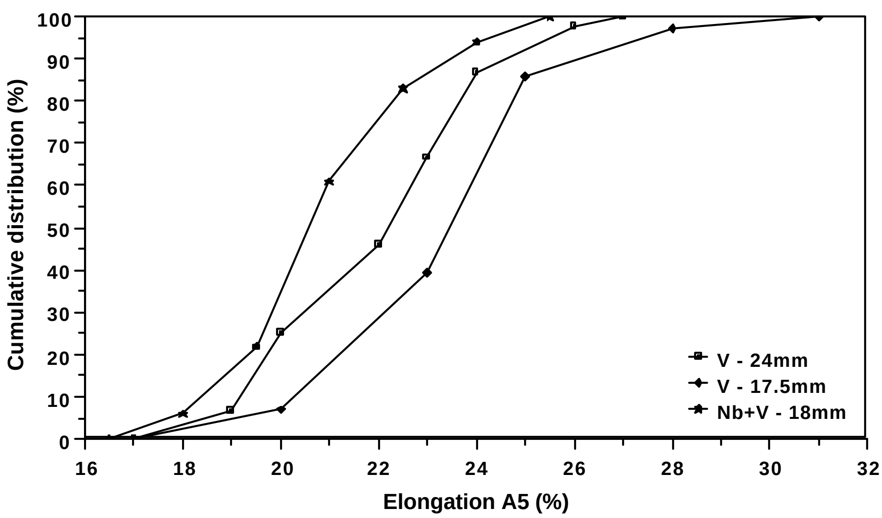

Fig. 16: Distribution of the elongation (A_5) for the vanadium alloyed steel at 24 and 17.5mm (Example 1); and for the niobium/vanadium alloyed steel at 18mm (Example 2).

The two steel grades (Example 1 + 2) are to be distinguished by their different chemical compositions. The hot strip in example 1 displays mechanical properties which are sufficient for grade X60 according to API 5L or L415MB according to DIN EN 10208 (at least for the 17.5mm).

The addition of niobium and the increase of the manganese content in example 2 permits rolling to take place at lower temperatures. Therefore, extensive TM–rolling is possible. A significant increase in strength characteristics at lower carbon contents has been observed. This could be enhanced by different cooling parameters. The 18mm material can be used as an X70 grade (L485MB). The 21mm material is even stronger and can be utilized as a non-standard X75 or even X80 grade. Of course, the TM–rolled niobium alloyed material has improved weldability and higher fracture toughness properties.

References

(1) M.K. Gräf, H.-G. Hillenbrand, "High Quality Linepipe-A Prerequisite for Project Cost Reduction," 3R International, 3 (39) (March 2000), 182 – 188.

(2) A.M.Sage, "An Overview of the Physical Metallurgy of High Strength Low Alloy Line Pipe and Pipe Fittings"(Paper presented at the Conf. on "Steel for Line Pipe and Pipeline Fittings," London, England, 21 – 23. October 1981).

(3) F.J. Humphreys, "A new analysis of recovery, recrystallisation and grain growth", Materials Science and Technology, 15 (January 1999), 37 – 44.

(4) J. Hertel, "Ein Modell der dynamischen Erholung bei Warmumformung", Z. Metallkunde, 71 (H10) (1980), 673 – 680.

(5) G. Aigmüller, F. Wallner, "TM-Behandlung mikrolegierter Baustähle", Berg- und Hüttenmännische Monatshefte, Vol. 1 133.Jg (1988), 42 – 50.

(6) L.J. Cuddy, J.J. Bauwin, J.C. Raley, "Recrystallization of austenite", Met. Trans A, 11A (1980), 387-402.

(7) J.J. Irani et al., "Strong Tough Structural Steels", The Iron and Steel Institute, (Special Report No. 104 London 1967), 110.

(8) L. Meyer, Optimierung der Werkstoffeigenschaften bei der Herstellung von Warmband und Kaltband aus Stahl (Düsseldorf, Germany: Verlag Stahl und Eisen, 1988), 8 – 26.

(9) J. Pertulla, P. Kantanen and P. Karjalainen,, "Effect of precipitation on flow stress and recrystallization in Nb - and Ti - bearing austenite", Scandinavian Journal of Metallurgy, 27 (1998), 128 – 132.

(10) S.S. Hansen, J.B. Vander Sande and M. Cohen, "Niobium Carbonitride Precipitation and Austenite Recrystallization in Hot-Rolled Microalloyed Steels", Met. Trans. A, 11A (1980), 387 – 402.

(11) Niobium Information No. 7/94 "Fundamentals of the Controlled Rolling Processes".

(12) H. Asahi, A. Yagi and M. Ueno, "Effect of Ferrite Formation on Abnormal Austenite Grain Coarsening in Low-Alloy Steels during the Hot Rolling Process", Metalurgical and Materials Transactions A, 29A (1998), 1375 – 1381.

(13) L. Meyer, "Grundlagen der Werkstoffentwicklung durch Verknüpfung thermischer und mechanischer Vorgänge beim Warmumformen", Stahl und Eisen, 101 (7) (1981), 483 – 491.

(14) L.J. Cuddy, Proc. Riso Int. Symposium on Metallurgy and Material Science, (Roskilde, Denmark, 1980).

(15) L. Meyer, "Über die Auflösung, Ausscheidung und aushärtende Wirkung von Niob in unlegiertem Stahl", Z. Metallkunde, 58 (H6) (1967), 396-401.

(16) T. Gladman, "Precipitation hardening in metals", Materials Science and Technology, 15 (1999), 30 – 36.

(17) L.J. Cuddy, "Microstructures Developed During Thermomechanical Treatment of HSLA Steels" Met. Trans. A, 12 A (1981), 1313 – 1320.

(18) H. Gondoh et al., "Development of Acicular - Ferrite Steel for Arctic - Grade Line Pipe", Nippon Steel Technical Report, 14 (1979), 55 – 65.

(19) Baldur Sommer, ed., Stahlrohr - Handbuch 12. Edition, Chapter 4.2.4 Spiralrohrherstellung, (Essen, Germany: Vulkan – Verlag 1995).

(20) H. Groß, "High – frequency HFI – welded steel pipe", 3R International, 25.Jg., Heft 4 (1986), 193 – 198.

(21) H. Blume, W. Heß, 3R International, 20. Jg, 8 (1981), 443.

(22) H.-J. Leßmann, Fortschrittsberichte VDI, Reihe 2: Fertigungstechnik Nr. 325 "Elektromagnetische Vorgänge beim induktiven Längsnahtrohrschweißen" (Düsseldorf, Germany: VDI Verlag, 1994).

(23) Herstellung und Prüfung von Stahlrohren (Düsseldorf, Germany: Mannesmannröhren - Werke AG, 1975).

(24) H. Spliethoff, F.O. Koch, "Manufacture and quality control of inductively seam – annealed, HF – welded line pipes to DIN 17172", 3R International, 22.Jg., Heft 5 (1983), 242 – 247.

(25) W. Haumann, F. Koch and W. Recknagel, "Anwendung von pfannenmetallurgischen Verfahren bei der Herstellung von Vormaterial für geschweißte Hochdruckgasleitungsrohre", Stahl und Eisen, 104, 25-26 (1984), 1357 – 1360.

(26) Niobium Information No. 14/97 "Thermomechanical Rolling of Hot Strip for Line Pipe Application".

(27) K. Freier, "Über eine Bruchanomalie an Kerbschlagbiegeproben aus mikrolegiertem TM-gewalzten Warmbreitband" (Ph.D. thesis, Techn. Universität Clausthal, Germany1983).

(28) W.B. Morrison, "Relationship Between ThermoMechanical Treatment and Properties of HSLA Steels", Scandinavian Journal of Metallurgy, 9 (1980), 83 – 90

(29) K. Seifert, K. Freier and W. Zimnik, "Zusammenhang zwischen bruchmechanischen Kennwerten und Bruchaussehen bei TM-Stählen aus Warmbreitband", Stahl und Eisen, 108 (7) (1988), 333 – 338.

(30) W. Zimnik, K. Freier and K. Seifert, "Optimierung der thermomechanischen Behandlung von Grobblech und Warmbreitband aus mikrolegierten Baustählen", Stahl und Eisen, 11 (5) (1991), 59 – 64.

(31) K. Freier et al., "Einfluß geringer P – Gehalte auf die Gebrauchseigenschaften von Feinkornbaustählen und Stählen für Fernleitungsrohre", Stahl und Eisen, 111, (1) (1991), 83 – 90.