Line pipe steel – treading the tightrope

by Waldo Stumpf

→ *Prof Waldo Stumpf busy at the Gleeble test facility used for the study of the hot deformation behaviour of steels.*

Natural gas as an energy source

South African industry and even more so South African households have traditionally used very little natural gas as an energy source for heating because of low cost electricity being widely available. Two things have, however, changed over the past few years that may change this preference for electrical heating. First, Sasol has introduced a large capacity gas transmission line from the recently discovered Pande and Temane gas fields in Mozambique to Secunda, while some gas fields have also been discovered off the coast of Namibia, providing viable alternatives for heating, power generation and, for Sasol, for conversion to liquid fuels. Second, the widely publicised shortage of electricity generating capacity in recent months has made the average South African much more aware of alternative sources of power and heating. It is, therefore, quite likely that a larger scale secondary distribution network of heating gas, initially to industries and possibly later to households, will become the norm rather than the exception in the near to medium future. For such a widespread gas distribution system the manufacture of locally produced line pipe steel of thinner gauge than for the 11 mm wall thickness used for the line from Mozambique needs to be developed.

The transmission line from Mozambique to Secunda

High Strength Low Alloy (HSLA) steel pipe with a wall thickness of 11 mm was supplied locally from the ArcelorMittal plant at Vanderbijlpark for the major part of the approximately 865 km and $1.2 billion line from Mozambique to Secunda (see Figure 1). This line pipe steel had to satisfy the requirements of the API X65 standard, an American Petroleum Institute standard. The steel has low carbon content (0.06%), a relatively high manganese level (1.6%), and contains small additions of chromium (0.02%), vanadium (0.06%), niobium (0.04%) and titanium (0.02%). Low limits were set on sulphur and phosphorous impurities, and a mixed microstructure of polygonal ferrite (PF), acicular ferrite (AF) and little pearlite was prescribed.

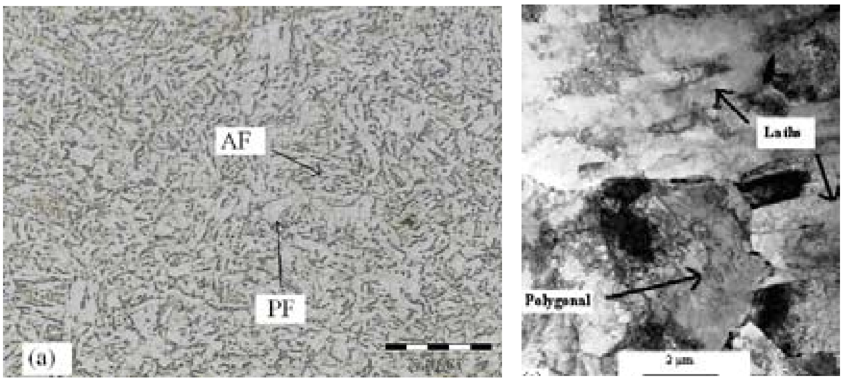
Apart from typical strength and ductility requirements for the design pressures expected in the line, gas lines also usually have to provide a yield strength/ultimate tensile strength (or YS/UTS) ratio below a specified maximum value. The YS/UTS ratio specified for X65 by the API is 0.93. Achieving this ratio is normally ensured through careful balance of the yield strength (not too high, although still above the design minimum) and a high ultimate tensile strength. This leads to a relatively high work hardening rate in the steel, resulting in localised strain redistribution in service should any small area on the line become thinned due to corrosion or due to prior weld dressing during fabrication and pipe laying, providing an additional safety margin in operation. Steel manufacturers for the line pipe industry, therefore, need to "tread this tightrope" very carefully in order to achieve YS/UTS values below 0.93 and, at the same time, minimum yield and tensile strengths of 448 MPa and 530 MPa, respectively, with a minimum elongation of 20.5% for API X65. This is achieved through optimisation of the chemistry, the hot rolling schedule and the cooling and coiling practice after hot rolling to achieve an optimum strength/microstructure combination in the steel. Should South African industry and its households adopt a higher preference for gas heating over electricity in future, the local flat steel manufacturing and subsequent line pipe fabrication industries will need to gear up for producing approximately 6 mm plate for thinner wall line pipe on a much larger scale.

Line pipe steels

The demand for high-performance line pipe steels has resulted in extensive research being conducted over the past few decades towards increasing, first, performance of HSLA steels and second, to improve large diameter forming processes to increase the carrying capacity of pipelines used at higher operating pressures. Current trends are towards the use of thinner wall thicknesses and UOE pipe-forming, (plate-U-forming-O-bending and shrinking-E-expanding). These demands include the introduction of higher strength and higher toughness steels with lower ductile-to-brittle transition temperatures, higher impact fracture energies together with a suitably low YS/UTS ratio by advancing from the grade API X65 through to X70, X80, X100, and even beyond.

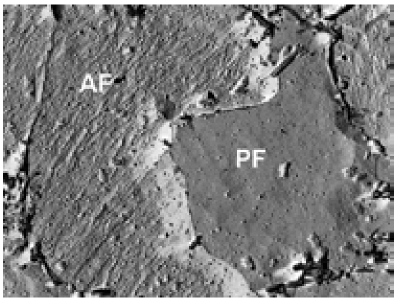
The main strengthening mechanisms used in line pipe steels are strengthening by solid solution hardening (the addition of carefully selected alloying elements), by dislocation substructure (introducing defects in the crystal structure), by phase transformation strengthening, by precipitation hardening and by grain refinement. Solid solution strengthening results from alloying elements such as manganese and molybdenum, and the phase transformation strengthening from non-equilibrium lower transformation temperature phases such as acicular ferrite (see Figure 2) and bainitic ferrite or martensite which lead to finer microstructures with a higher dislocation density. On account of the micro-alloying element additions, carbonitrides of vanadium, niobium and titanium contribute to precipitation strengthening. Besides dispersion hardening, niobium has an added benefit on the refinement of the ferrite grains. Higher hot rolling pass strains below the non-recrystallisation temperature during the controlled rolling process, also contribute to good ferrite grain refinement. Grain refinement through controlled rolling is a particular feature of these niobium containing steels in which the hot rolled deformation in the austenite is retained as unrecrystallised "pancake grains" at temperatures below the nil-recrystallisation temperature or T_{nr} which, for the 11 mm HSLA Nb-Ti steel used in the Mozambique Secunda line from ArcelorMittal, was measured to vary from 956°C to 916°C, depending on rolling parameters such as the strain per pass, strain rate per pass and the interpass times. Higher pass strains and longer interpass times tend to depress the T_{nr} while the pass strain rate (at least in the range of 0.1 to 2.2 per second used in this study) had a smaller effect on the T_{nr}. The "operating window" between the T_{nr} and the hot rolling


→ 1. Gas pipe laying from Mozambique to Secunda

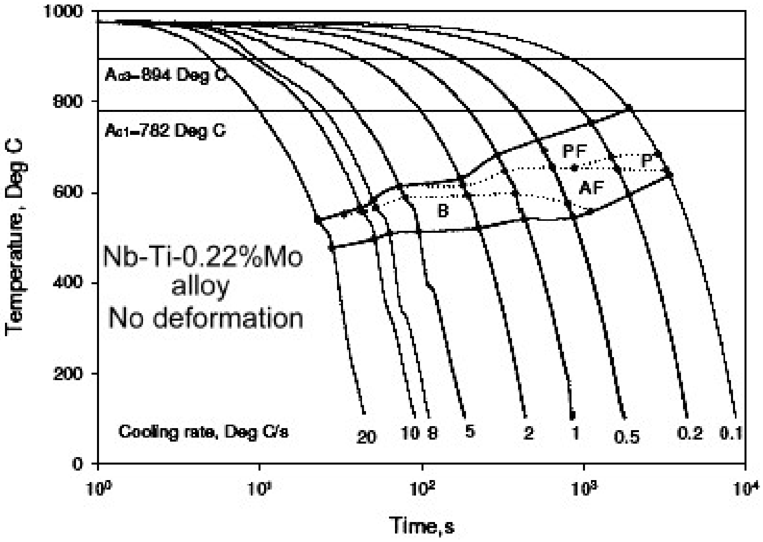


(a) (b)

→ 2. (a) Optical microstructure and (b) Transmission Electron Micrograph of the Mozambique to Secunda line's 11 mm thick Nb-Ti steel (AF = Acicular Ferrite, PF = Polygonal Ferrite). Note the absence of the delineation of any of the prior austenite grain boundaries in the optical micrograph and the "chaotic" nature of the AF laths in the TEM micrograph, which are typical features of AF.



→ 3. One of the TEM Au-Pd shadowed carbon replicas for the technique that was developed to measure the volume fraction of Acicular Ferrite through areal analysis. The above figure is from the base Nb-Ti steel with no molybdenum additions and was measured to have 45% AF after laboratory hot rolling and cooling at 39°C/s.



→ 4. CCT diagrams of the Nb-Ti steel with a 0.22% Mo addition (a) with no prior deformation and (b) with a prior strain of 0.6 below the T_{nr} before transformation to ferrite. Note the enlargement of the AF phase area with prior deformation.

finishing temperature at the last pass, therefore, give the steel manufacturer a powerful tool to optimise the steels' microstructure and mechanical properties.

In addition to the above optimisation measures, it has often been proposed that a higher percentage of acicular ferrite should be beneficial in lowering the YS/UTS ratio and that the addition of molybdenum to the steel should promote such a higher percentage AF. In research done in the Department of Materials Science and Metallurgical Engineering at the University of Pretoria on HSLA line pipe steels over the past few years, this hypothesis was critically examined and was found to have very limited benefit. The processing variable of hot deformation before transformation was actually far more effective in achieving greater percentages of AF, but that this did not necessarily have a measurable benefit towards a lower YS/UTS ratio.

Optimising the microstructure and alloy composition

In a series of 5 kg laboratory-vacuum melted and hot rolled steels, the percentage molybdenum was systematically varied in the current base Nb-Ti steel from 0.001% (the current steel) to 0.22% molybdenum. A technique was then developed enabling, for the first time, quantitative measurement of the volume fraction of AF after deformation and heat treatment while continuous cooling transformation (CCT) diagrams were determined for the above steels (see Figure 3). Initial experiments were conducted with no prior deformation, for steels without molybdenum and with molybdenum additions. In a second set of experiments, for the same steels, prior deformation was applied below the T_{nr} before transformation from the austenite to the different ferritic phases at cooling rates varying from 0.1 to 47°C/s.

It was found through both the areal analysis technique and later CCT transformation curves (Figure 4) that molybdenum additions up to 0.22% only very slightly enhanced acicular ferrite formation in the strain-free austenite. Prior deformation of 45% below the T_{nr} had a much greater effect, and strongly promoted acicular ferrite formation in both the molybdenum-free base alloy and the molybdenum-containing Nb-Ti alloys. The very often suggested addition of molybdenum to Nb-Ti base line pipe steels to achieve greater volume fractions of AF, therefore, appears to be questionable and is not supported by this study.

The YS/UTS ratio for both the molybdenum-containing and the molybdenum-free alloys ranged from 0.83 to 0.86, with microstructures of polygonal ferrite and acicular ferrite after hot rolling and rapid cooling. However, a microstructure with greater volumes of AF or bainite was not found to be beneficial in lowering the YS/UTS ratio. This ratio was only sensitive to the microstructure or the cooling rate in the case with *no prior deformation* below the T_{nr} and without any *simulated coiling process*, i.e. two requirements that are not possible in the hot rolling and cooling of a steel strip. The yield strength, ultimate tensile strength and the YS/UTS ratio were not sensitive to the cooling rate after a simulated coiling process. Varying the temperature of the coiling process between 575°C and 600°C also did not affect the YS/UTS ratio while the simulated coiling process itself diminished the effect of cooling rate and decreased the ratio in the case with no prior deformation of the austenite below the T_{nr}.

A prior deformation of 33% below the T_{nr} in the austenite, on the other hand, strongly *increased* the YS/UTS ratio at all cooling rates from 1 to 34°C/s and overshadowed the effect of micro-structure or cooling rate on this ratio. Molybdenum additions to Nb-Ti micro alloyed steels did not markedly affect the YS/UTS ratio after a simulated coiling process.

In conclusion, therefore, this study has disproved the widely held belief in literature that both molybdenum additions to Nb-Ti line pipe steels and greater volume fractions of acicular ferrite are beneficial in lowering the YS/UTS ratio. The results of this investigation suggest that line pipe steel manufacturers need to optimise their hot rolling, transformation cooling and coiling processes even more carefully to achieve the required mechanical properties. The "tightrope" they have to tread, is most likely even more "tight" than was previously believed.

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