

HIGH-STRENGTH LOW-ALLOY (HSLA) STEELS

VISOKOTRDNNA MALOLEGIRANA (HSLA) KONSTRUKCIJSKA JEKLA

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Micro-alloyed, high-strength, low-alloy (HSLA) steels are important structural materials and contain small amounts of alloying elements, such as niobium, titanium, vanadium, and aluminium, which enhance the strength through the formation of stable carbides, nitrides or carbonitrides and have an effect on the hardenability. Such steels contain less than 0.1 % of the alloying additions, used individually or in combination. Yield strength increments of two or three times that of plain carbon-manganese steel can be attained. Nowadays, also micro-alloyed cast steels have found many applications in the manufacturing of industrial parts that used to be produced by more expensive manufacturing processes.

Keywords: high-strength low-alloy (HSLA) steels, micro-alloying elements, carbides, nitrides, carbonitrides, mechanical properties

Visokotrдна malolegirana konstrukcijska jekla (HSLA) spadajo med tehnično pomembne konstrukcijske materiale in vsebujejo majhne količine legirnih elementov, kot so niobij, titan, vanadij, aluminij, ki zaradi tvorbe stabilnih karbidov, nitridov ali karbonitridov zvišajo natezno trdnost materiala in vplivajo na trdnost. Ta jekla vsebujejo manj kot 0.1 % legirnih elementov, ki se lahko uporabljajo posamezno ali v kombinaciji, natezna trdnost pa je lahko dva do trikrat višja kot pri navadnem ogljikovo-manganovem jeklu. Danes so v uporabi tudi mikrolegirana lita jekla, ki se največ uporabljajo za izdelavo raznih industrijskih delov, za kar so bili prej potrebni dragi proizvodni procesi.

Ključne besede: visokotrдна malolegirana jekla (HSLA), mikrolegirni elementi, karbidi, nitridi, karbonitridi, mehanske lastnosti

1 INTRODUCTION

High-strength, low-alloy (HSLA) steels, or micro-alloyed steels, are aimed to provide better mechanical properties and/or greater resistance to atmospheric corrosion than conventional carbon steels. They are designed to meet specific mechanical properties, such as a yield strength greater than 275 MPa,^{1,2} rather than to obtain a specific chemical composition. The chemical composition of a specific HSLA steel may vary for different product thicknesses to meet mechanical property requirements.

The factors that led to the initial development of micro-alloyed steels, at least up to the late 1960s, were:³

- a) materials cost savings could be obtained directly by the application of micro-alloyed steels;
- b) in-service benefits could be obtained in the development of lighter goods;
- c) the need for a higher strength line-pipe that was easily weldable provided an expanding market for higher-yield-strength steels;
- d) the extensive use of welding as the principal fabrication method meant that conventional ways of increasing the strength would result in more expensive and much less practicable welding procedures, whilst the new micro-alloyed steels with their generally lower carbon and alloy levels could often be welded using existing procedures;

- e) the strength increase could be obtained relatively cheaply, as both niobium and vanadium, are not readily oxidised by steel melt processing.

The development of micro-alloyed steels was not restricted to plates; development work was already reported for hot-rolled strip and for bar material for reinforcement. Another significant development in the period between 1963 and 1967 concerned hot-rolling practices, when a process now known as "controlled rolling" was developed.^{3,4} This enabled fine-grained microstructures to be obtained in the "as-rolled" condition, with benefits for both strength and toughness. By allowing the hot-rolling process to occur at lower temperatures, a finer austenite grain microstructure was produced, which resulted in finer ferrite grain sizes after transformation during cooling.⁵

The above described developments in micro-alloyed steels are summarised in **Figure 1**, where the various developments are shown on a time base and compared with external influences (modern welding methods, oil crises, development of environmental pressures).³

Micro-alloyed steels are nowadays divided into six categories:^{2,4-5}

- a) Weathering steels, which contain small amounts of alloying elements such as copper and phosphorus for an improvement of the atmospheric corrosion resistance and solid-solution strengthening.

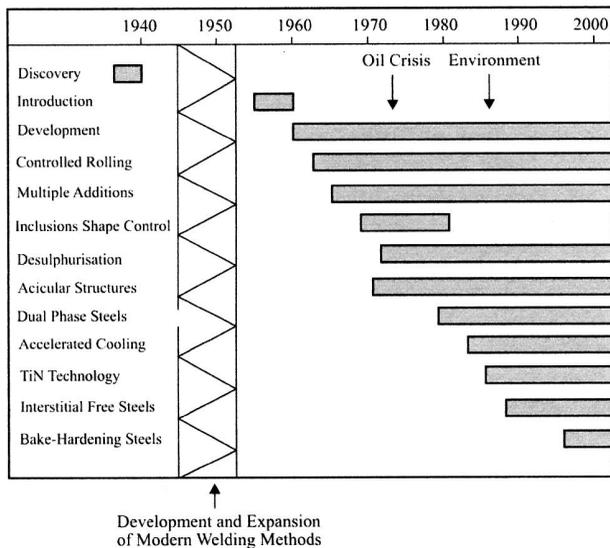


Figure 1: Development of HSLA steels from 1940 to 2000³

Slika 1: Razvoj HSLA-jekel od leta 1940 do 2000³

- b) Micro-alloyed ferrite-pearlite steels with very small (generally less than 0.1 %) additions of strong carbide- or carbonitride-forming elements, niobium, vanadium, and/or titanium, for precipitation strengthening, grain refinement, and possibly, transformation temperature control.
- c) As-rolled pearlitic steels, which may include carbon-manganese steels with small additions of other alloying elements to enhance strength, toughness, formability and weldability.
- d) Acicular ferrite (low-carbon bainite) steels are low-carbon (less than 0.05 % C) steels with an excellent combination of high yield strengths (as high as 690 MPa), weldability, formability and good toughness.
- e) Dual-phase steels with a microstructure of martensite inserts dispersed in ferritic matrix and with a good combination of ductility and high tensile strength.
- f) Inclusion-shape-controlled steels with improved ductility and through-thickness toughness due to small additions of calcium, zirconium, titanium or rare-earth elements that change the shape of sulphide inclusions from elongated stringers to small, dispersed, almost spherical globules.

The wide applications of HSLA steels include oil and gas pipelines, heavy-duty highway and off-road vehicles, construction and farm machinery, industrial equipment, storage tanks, bridges, offshore structures, power-transmission towers, light poles as well as building beams and panels.⁶⁻⁸

The choice of a specific high-strength steel depends on a number of application requirements, including thickness reduction, corrosion resistance, formability and weldability. For many applications, the most important factor in the selection is the favourable strength-to-weight ratio⁵ of HSLA steels compared with conven-

tional low-carbon steels. This characteristic of HSLA steels has led to their increased use in automobile components.

2 STRENGTHENING MECHANISMS

The micro-alloyed steels used nowadays are obtained by means of a suitable combination of chemical composition and thermo-mechanical treatment parameters, with the aim to achieve the proper balance between strength, toughness, ductility and formability. These properties depend upon microstructural features, while weldability is generally accepted as being composition dependent.

The yield strength of steel can be increased by one or more of several strengthening mechanisms. These include:^{2,3,5,9,10}

- a) Dislocation strengthening: the resistance to dislocation movement due to the obstacles presented to other dislocations. The limitations of this mechanism are due to the saturation of the structure with dislocations.
- b) Grain-boundary strengthening: grain-boundary hindering of dislocation movement. Grains can be refined to a very small size, and a very high strength may be achieved. Below a critical grain size the toughness may be lowered.
- c) Solid-solution strengthening: the resistance to dislocation movement due to the presence of interstitial or substitutional solute atoms in a crystal lattice. The limitation of this mechanism is imposed by the solubility limit in each alloying system.
- d) Precipitation strengthening: the resistance to dislocation movement due to the effect of second-phase particles. Second-phase particles may be dispersoids (stable particles mechanically added and sintered) or precipitates (particles formed from a supersaturated solid solution) which is more present in practice. The limitation of this mechanism is governed by the influence of the size and shape on toughness, not on the strengthening.
- e) Texture strengthening: the resistance to dislocation movement due to the presence of a texture-preferred orientation in the structure. This mechanism does not seem to be as potent as other strengthening mechanisms, while the development of texture is difficult in steels with a dispersed second phase.
- f) Phase-transformation strengthening: the resistance to dislocation movement due to the presence of newly formed phases introduced by a phase transformation that starts simultaneously with a deformation. This mechanism gives new opportunities and it may be considered as the main research challenge in the future.

From all six mechanisms, the dominant mechanism is grain-boundary strengthening, because the influence on the grain size can be accomplished by a modification of

the chemical composition, production parameters and/or routes.

2.1 Grain refinement

Grain refinement is an effect of micro-alloying on steels because it simultaneously produces increased strength and toughness, without affecting weldability and ductility¹ (Figure 2). The quantitative relationship between yield strength and grain size in metals is known as the Hall-Petch equation:^{11,12}

$$\sigma_0 = \sigma_t + k_0 \cdot d^{-1/2} \quad (1)$$

where:

σ_0 – yield strength

σ_t – yield strength of a single crystal

k – Hall-Petch factor (a constant, representing the blocking effect of grain boundaries on the movement of dislocations at the initial stage of the plastic deformation)

d – grain size

Grain refinement can be achieved by three types of precipitation:¹

- small particles that do not dissolve, and therefore pin down austenite grain boundaries, during reheating prior to hot working (usually TiN, sometimes Nb(C,N));
- particles that dissolve during reheating, but precipitate in austenite during hot rolling and prevent recrystallisation and/or grain growth (usually Nb(C,N), sometimes VN);
- particles that precipitate after rolling, during the transformation of austenite to ferrite (usually V(C,N), sometimes NbC or TiC).

2.2 Precipitation strengthening

The precipitation strengthening is produced by the particles' precipitation in ferrite. These particles hinder dislocation movement under loading and increase the

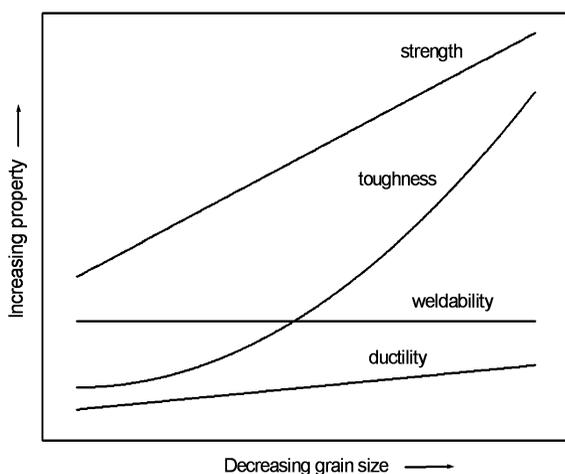


Figure 2: Effect of ferrite grain size on properties¹

Slika 2: Vpliv velikosti feritnih zrn na mehanske lastnosti¹

yield strength and tensile strength. The precipitates most often used to strengthen ferrite are V(C,N), although NbC and TiC particles can be used in low-carbon, low-nitrogen steels. TiN is a less soluble micro-alloying precipitate. TiN particles form at very high temperatures and, if finely distributed, prevent austenite grain growth at normal reheating temperatures. The content of the micro-alloying elements carbon and nitrogen as well as the thermomechanical processing determine whether TiC, NbC, VN or other complex carbonitrides precipitate in austenite or ferrite. The most soluble micro-alloying precipitate is VC, which normally precipitates only in ferrite.^{1,3,10}

The relationship between the grain size (R), the volume fraction (f) and size of precipitates (r) was first proposed by Zener in his well-known equation:¹⁰

$$R = \frac{4r}{3f} \quad (2)$$

where:

R = radius of the matrix grains

r = radius of the precipitates (pinning particles)

f = volume fraction of the precipitates (pinning particles).

The Zener equation includes the major features of grain-growth inhibition by second-phase particles. A finer grain size can be stabilised by an increased volume fraction of particles for a given particle size and finer particles are capable of stabilising a finer grain size for a given volume fraction of particles.^{3, 10}

One further important phenomenon that can affect the particle size is known as Ostwald ripening.^{2,3,10} It relates to the increase in particle size that occurs at a constant volume fraction of precipitate, and can result in a significant loss of the particles' performance. A definition of Ostwald ripening can be given as the selective growth of some second-phase particles, usually the larger particles, at the expense of other particles of the same phase, usually the smaller particles, the latter decreasing in size until they disappear completely. The equation, presented by Lifshitz, Slyozov and Wagner, describes the kinetics of particle coarsening with respect to both temperature and time:¹⁰

$$r_t^3 - r_0^3 = \frac{8\sigma D[M]V}{9RT} \cdot t \quad (3)$$

where:

r_t = particle radius at time t

r_0 = particle radius at time 0

σ = surface energy of the particle-matrix interface

D = diffusivity of relevant atom species

$[M]$ = concentration (solubility) of relevant atom species in the matrix

V = particle molar volume

R = gas constant

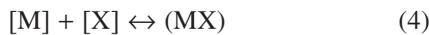
T = temperature

A most important feature of this equation is the concentration of relevant atom species dissolved in the matrix [M]. The growth of the pinning particles will be minimised by a small [M] dissolved in the matrix. Because of its thermodynamic stability and low solubility at high temperature, TiN resists particle growth and is thus a most effective grain-boundary-pinning particle.

The concept of Ostwald ripening was originally developed for the coarsening of solid particles in a liquid matrix, but the mathematical solutions have been applied successfully to second-phase particles in a solid matrix.

3 SOLUBILITY OF CARBIDES AND NITRIDES

With the aim to understand the influence of micro-alloying elements on the mechanical properties and the hot-working process it is necessary to know the processes and reactions in steel involving these elements and their compounds with nitrogen and carbon which form precipitates. The reaction of a micro-alloying element [M] with an interstitial [X], both dissolved in the austenite, gives a compound [MX] at a temperature T :³



$$k_s = [M][X] \quad (5)$$

The definition of the solubility product is:

$$\lg k_s = A - B/T \quad (6)$$

where A and B are constants for a given system and T is the temperature in K.

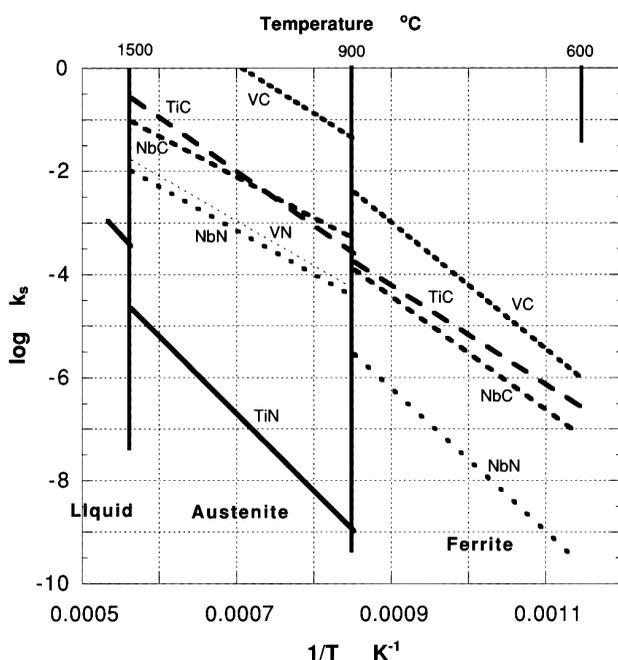


Figure 3: Comparison of the solubility products of carbides and nitrides.³

Slika 3: Primerjava topnostnih produktov za karbide in nitride.³

The solubility products of the micro-alloy carbides and nitrides are compared in Figure 3. The general conclusions drawn from this data are:³

- In austenite, nitrides are more stable than carbides. Large differences are between vanadium carbide and vanadium nitride and between titanium carbide and titanium nitride, whilst the difference between niobium carbide and niobium nitride is much less.
- Many of the micro-alloy carbides and nitrides have similar levels of solubility in austenite, with two notable exceptions. Titanium nitride is markedly more stable than other carbides and nitrides. On the other hand, vanadium carbide is far more soluble than other carbides and nitrides.
- The solubilities of niobium carbide and niobium nitride in ferrite suggest that the solubilities of these compounds are about an order of magnitude less in ferrite than the corresponding solubilities in austenite at the same temperature.

The effects of a steel's chemical composition and thermomechanical processing on the solubility and precipitation reactions of these precipitates are essential for obtaining the properties that are the basis for the successful application of micro-alloyed steels. Otherwise, the benefit of micro-alloying could be lost, as shown in following examples.

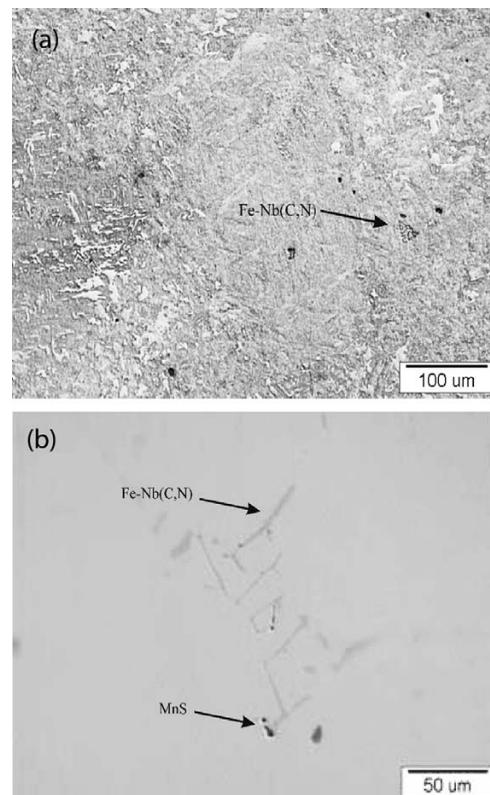


Figure 4: Form of eutectic niobium carbonitride particle in cast slab; a) etched with nital; b) non-etched surface

Slika 4: Oblika eutektičnega niobijevega karbonitrida v litem slabu; a) jedkano z nitalom; b) nejedkana površina

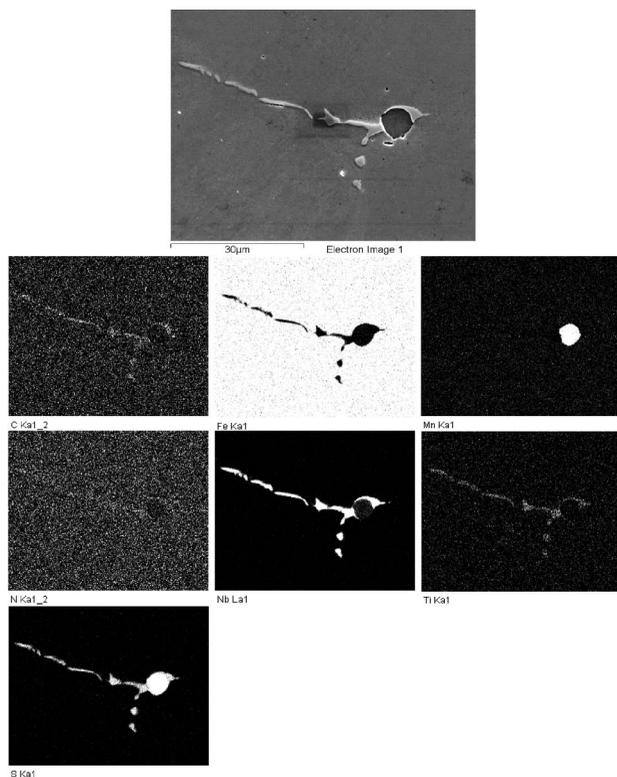


Figure 5: SE image and X-ray maps of niobium carbonitride precipitates bound to MnS

Slika 5: SEM-posnetek niza karbonitridnih vključkov, vezanega na MnS, in prikaz površinske porazdelitve elementov

The examinations of the plates of micro-alloying steel (Micral S690QL) showed lower ductility than was prescribed. To investigate the reason for such low ductility, samples for optical and scanning electron microscopy were taken from a cast slab. **Figure 4** shows optical micrographs with niobium carbonitrides. **Figure 5** shows a SE image and mapping micrographs of niobium-containing particles (Nb,Ti)(C,N)^{13–17} bound on a small manganese sulphide inclusion. The analysis of the chemical composition of the carbonitride particles has turned out to be very complicated. The problem arises from the proper determination of the concentration of nitrogen and titanium, also reported by other authors.^{18–20} The nitrogen concentration is, according to literature sources,^{21–23} responsible for the thermodynamic stability of carbonitride. A precise measurement of the nitrogen concentration would enable a determination of the limit nitrogen concentration in carbonitride, which considerably decreases the ductility of the steel.

The solubility product for niobium carbonitride is given by the equation:³

$$\lg k_s = -6770/T + 2.26 \quad (7)$$

There are variations in the stoichiometry, some authors consider niobium carbonitride given by the formula NbC_{0.8}, others as NbC or Nb(C,N).³

The next example of an inadequate precipitation of micro-alloying elements is shown in **Figure 6**. In this

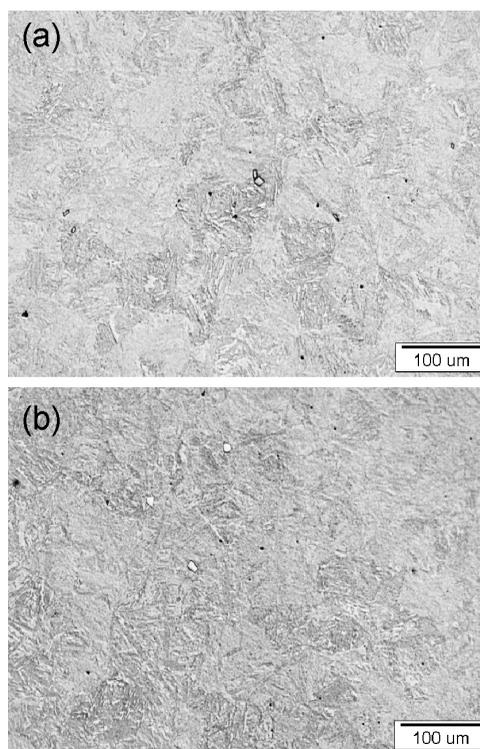


Figure 6: Steel, micro-alloyed with a) titanium and b) zirconium with large precipitates of these elements¹³

Slika 6: Jeklo, mikrolegirano s a) titanom in b) cirkonijem z velikimi precipitati teh elementov¹³

case the micro-alloying elements titanium and zirconium have been precipitated as large particles (up to 10 μm), which are typically coloured after etching. The improved mechanical properties can be obtained only by finely distributed Nb, Ti or Zr precipitates on a nanometre scale size; and therefore it is not surprising that in this case an improvement of mechanical properties was not obtained.

4 STEEL PROCESSING

The desirable properties of HSLA steels are achieved basically through ferrite grain refinement and by the precipitation of micro-alloy carbonitride particles. For economic production it is necessary to maximize these effects with various types of thermomechanically controlled processing (TMCP). The prevailing share of steel products is manufactured by rolling. For micro-alloyed steels two main types of rolling processes are used:^{3, 4, 24}

a) Thermo-mechanical rolling or recrystallisation controlled rolling (RCR) is used for steels with martensitic and bainitic structures. This rolling consists of rolling in the MX phases' precipitation temperature range, with pauses between the consecutive rolling passes, enabling a complete austenite recrystallisation as well as the isothermal holding of a properly selected temperature of the end of the hot working by time $t_{0.5}$ – needed for the development of 50 % fraction of recrystallised austenite and direct cooling with

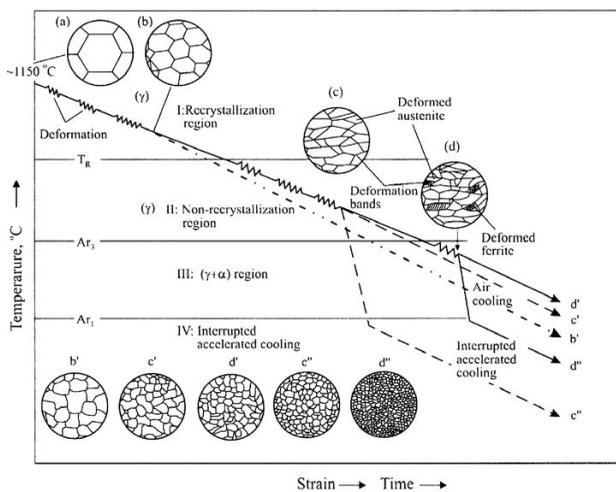


Figure 7: Schematic diagram of the influence of accelerated cooling on the microstructure of low-carbon micro-alloyed steel products during controlled rolling⁴

Slika 7: Shematski prikaz vpliva pospešenega ohlajanja na mikrostrukturo maloogljicnih malolegiranih jekel med kontroliranim valjanjem⁴

the appropriate cooling rate. Isothermal holding of products at the temperature of the end of rolling for the time $t_{0.5}$ is necessary, as the high dislocation density in the plastically deformed austenite increases the critical cooling rate. Products manufactured with this method are subjected only to the appropriate temperature tempering or ageing.

- b) Conventional controlled rolling (CCR) is normally used for steels with a ferrite and ferrite-pearlite microstructure. This rolling consists of roughing the feedstock in the upper part of the plastic working temperature range and of finish rolling in the lower part of the temperature range for this process, corresponding to the precipitation of the MX phases, limiting the grain growth of recrystallised austenite in pauses between the consecutive passes. Finish rolling usually ends at a temperature slightly lower than the austenite recrystallisation temperature T_R and a little bit higher than A_{F3} or A_{F1} for the steel with subsequent air cooling of the products (**Figure 7**). The presence of slip bands and deformation bands in non-recrystallised austenite causes an increase of the population of locations convenient for nucleation in the $\gamma \rightarrow \alpha$ transformation and leads to the development of a more fine-grained structure of the steel products.
- c) Two-phase rolling technology is a modification of the CCR technology. The main difference is that finish rolling is performed partially in the two-phase region. After cooling, austenite grains will transform into small ferrite grains, while deformed ferrite grains will recrystallise and become finer. This technology is normally used for the rolling of thin strips, due to their high resistance to deformation.

d) Dynamic recrystallisation controlled rolling (DRCR) is a modification of the CCR technology. The overall strain in finish rolling is higher than in CCR and the accumulation of deformation from pass to pass should lead to exceeding the critical strain for dynamic recrystallisation. In this case the effect of grain refinement is the strongest. This technology is not yet commercialized, due to the lack of reliable data.

- e) Conventional controlled rolling + accelerated cooling (CCR+AC) with accelerated cooling after the CCR or two-phase region rolling up to A_{F1} temperature that provides a certain amount of ferrite transformation, enriching the rest of the matrix with carbon and lowers the austenite transformation temperature. With further cooling the austenite transforms to bainite and/or martensite. This technology provides a two-phase microstructure consisting of very fine ferrite grains and bainite and/or martensite.

5 MECHANICAL PROPERTIES

There are three major property requirements for HSLA steels: a high yield strength, a low impact transition temperature and good weldability.² The high yield strength and low impact transition temperature are achieved through ferrite grain refinement, where nitrogen is partially useful. However, nitrogen dissolved in ferrite also influences the strength and toughness. This solid solution strengthening is very small, especially as the solid solubility of nitrogen in ferrite is very limited, but the embrittlement propensity may be increased, also. Thus nitrogen dissolved in ferrite must be minimised, which is done in micro-alloyed steels with additions of Al, V, Nb or Ti, all of which form stable nitrides. These nitrides have the ability to refine austenite grains and thereby ferrite grains, also.²

6 CONCLUSIONS

The paper gives a short review on the development and basic characteristics of micro-alloyed steels. The general conclusions are that in modern, control-rolled, micro-alloyed steels at least three strengthening mechanisms contribute to the final achieved strength. The relative contribution of each is determined by the steel's composition as well as by the steel's thermomechanical treatment. The effect of the finishing temperature for the rolling is important in determining the grain size and, therefore, the strength level reached for a particular steel.

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