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HIGH STRENGTH NB MICROALLOYED HOT ROLLED STEEL COILS (CUT TO LENGTH PLATES) FOR STRUCTURAL APPLICATIONS

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Abstract

Hot rolled strip products are generally used for direct processing for various applications in structural and engineering industries, wherein there is strong demand for steel with high strength levels, balanced formability and good impact toughness. This combination of steel properties enables the construction and engineering industries to meet the stringent demands of the heavy structures and hence has direct impact on the total life of the structures. To meet these requirements, at Essar Steel the development of hot rolled high strength steel grades is in principle focused on two different concepts: on one hand the high strength micro-alloyed and thermo-mechanically rolled steel grades and on other hand the transformation hardened (ferritic bainitic, multiphase) steel grades. The present paper focus on the newly developed very high strength Nb micro-alloyed steel grade with minimum yield strength of 600MPa and 650MPa coupled with good impact toughness at sub-zero temperatures. Some aspects of the alloy design and the industrial production process for these steel grades are also highlighted. The specific mechanical and mechanic-technological properties of these high strength steel grades are derived from the complex micro-structure consisting of ferrite, irregular ferrite, bainite, martensite and micro-alloying constituents.

Introduction

The demand for steel grades with increased strength coupled with adequate formability has strongly been increasing over the last few years for a wide range of applications including structural engineering. The prime objective is always on the weight reduction of the constructional elements without affecting the life of the structure. High strength low alloy steels are currently produced from hot strip mills for many years. They are generally available in a range of yield strength from 280 MPa to 550 MPa. In recent years, the need for as rolled high strength steel has increased considerably because they enable the replacement of heat treated plates. Presently, there is a strong interest in using as-hot-rolled steels in the mechanical sector in place of quenched and tempered (Q&T) steels due to cost and energy conservation. Additionally, quenched and tempered plate has inherent metallurgical disadvantages such as retained austenite, residual stresses, quench cracking and distortion. In order to meet the growing need of weight reduction for many applications, Essar had developed steel grades in very high strength category with yield strength of 600 MPa to 650 MPa in thickness range of 3.00-10.00mm. Figure 1 gives an overview of the normal, high strength and very high strength hot rolled steel grades directly produced through hot strip mill route. Figure 1 shows the journey from normal strength to very high strength and further beyond. These grades are tried and developed in the last few years to cater to the market segment of various applications including structural engineering.

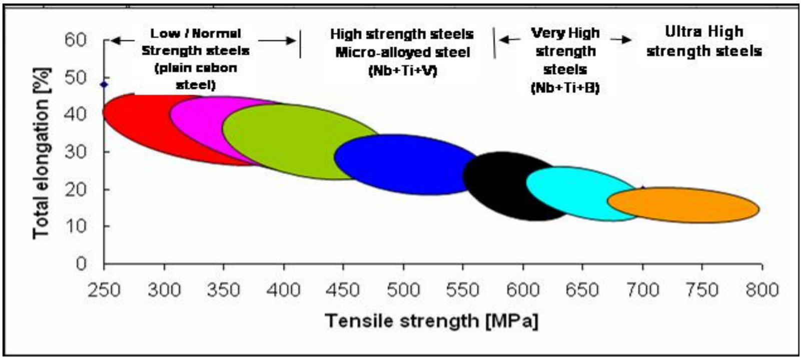


Figure 1. Overall view of hot rolled steel grade made at Essar in different strength level

To reach such high strength levels it is necessary to optimize the contribution of each strengthening mechanism which can be briefly described with the following keywords:

1. Solid solution strengthening by interstitial and substitutional elements (C, Mn & Si)
2. Precipitation strengthening and grain refinement (Ti, Nb &V)
3. Strengthening due to dislocation and transformation.

High strength steel grade development involves adequate and optimum design of chemical composition of the steel as the first step, considering the effect of each element on the final properties of steel. Secondly, to apply the appropriate rolling practices such as thermo-mechanical rolling, multi stage cooling and or accelerated cooling, so that the desired micro-structure of the steel can be obtained. Considering various strengthening mechanism as the basis, the hot rolled strip with high strength can be categorized in two different concepts, first the micro-alloyed and thermo-mechanically rolled steel grades and secondly, the transformation hardened grades (ferrite bainite, multiphase) steel grades. Thermo-mechanically rolled steel grades for example utilize grain refinement and precipitation hardening. Transformation hardening is based on the dislocation hardening, grain refinement and solid solution hardening. Nevertheless, especially when aiming for higher strength levels the above mentioned hardening mechanism must be used in combination to achieve the high and ultra high strength levels. It is a known fact that strength level about 500 MPa is achieved typically by ferrite and pearlite micro-structure, while higher strength steels need to have bainitic constituents and steel with about 700MPa yield strength is typically bainitic steel. With higher amounts of bainite in steel, one can achieve higher strength by further grain refinement and higher dislocation density without impairing toughness, wherein finer grain size will compensate the toughness deterioration by dislocation hardening [1,2]. The metallurgical concept chosen in order to give the optimum balance between strength, toughness, weldability and suitability for bending or forming is based on the low carbon and ferrite-bainite steel. This paper is aimed at describing the development effort involved in design and optimization of alloy and thermo-mechanical processing parameters to obtain the best combination of strength and toughness.

Preliminary Study

In general, low carbon micro-alloyed steels have %C <0.080 wt % and %Mn ~1.50% and utilize micro-alloying concepts to attain a fine grained micro-structure. The fundamental basis for the development of very high strength hot rolled steel is to obtain ferrite bainite micro-structure in the hot rolled product through controlled rolling and alloy design.

The basic principle adopted for the development was to fully exploit the exceptional effect on the mechanical properties achieved by the addition of Nb and B. The joint effect of Nb and B addition in steel results in a dramatic lowering of the nucleation rate of ferrite, about 100 times lower than in a plain C-Mn steel, providing a wide bainitic range in the case of a C=0.05% even for lower cooling rates. The effect of Boron is to segregate at austenite grain boundaries where it inhibits ferrite nucleation because of strong interaction between boron atoms and lattice defects such as dislocations and vacancies. Solute Boron thereby promotes formation of a fine bainitic micro-structure after controlled rolling and cooling. Even though carbon plays a significant role in achieving the final properties, it should be lower to prevent martensite formation during cooling. It is also deleterious to toughness, weldability and formability but on the other hand, it should not be excessively low which reduces toughness owing to insufficient grain refinement.

To ensure the hardenability effect of Boron, Nitrogen must be fixed by other strong nitride forming elements. The element Ti has greater affinity for Nitrogen and hence, it is to be maintained as per the stochiometric ratio. Moreover, formation of TiN prevents austenitic grain growth during the re-heating before hot rolling. With all the above considerations taken from the literatures, optimum alloy composition was designed with appropriate thermo-mechanical processing parameters to obtain the required combination of strength, toughness and good bend properties coupled with excellent weldability [1].

Experimental

Based on the preliminary study made on the effect of individual elements on the steel properties and taking into consideration the combined advantage of Nb+Ti+B in steel, initial trials were planned at Essar. The chemical composition of the heat was based on the tentative alloy design as described for grades with 600 (SR60) and 650MPa (SR65) yield strength respectively. The heats were processed at Essar Steel through process route HBI ➔ EAF ➔ LF ➔ CCM ➔ HSM. Figure 2 shows a schematic diagram of process flow chart at Essar steel. The chemical composition of heats made is given in Table 1.

Table 1. Chemical composition of micro-alloyed steel grade SR60 and SR65

Steel grade	Chemical composition in Wt%							
	C, max	Mn, max	Si, max	S, max	P, max	Al, min	Nb+Ti max	B, max
SR60	0.060	1.600	0.250	0.005	0.015	0.020	0.120	0.0020
SR65	0.050	1.700	0.200	0.005	0.015	0.020	0.150	0.0020

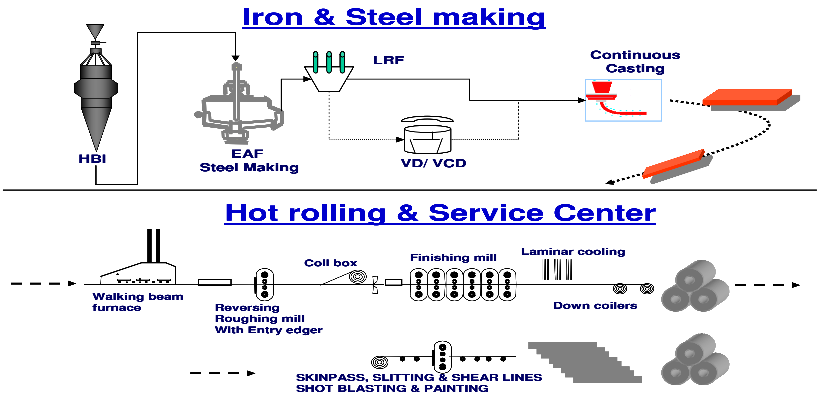


Figure 2. Process flow chart at Essar Steel

The chemistry was basically aimed at %C <0.060, %Mn <1.70 and %Si <0.25 as the primary elements. The secondary element includes Nb+Ti (0.15 max) and Boron (20ppm max). The steel was also calcium treatment for modification of the inclusion morphology. The production process of hot rolling starts with thermo-mechanical processing schedule. This involves re-heating of slabs (soaking) at a temperature of about 1220-1260°C. The re-heating temperature controls the required dissolution of Ti and Nb precipitates which have formed while cooling the slabs after casting process. The presences of TiN in the steel prevent the austenitic grain coarsening. The slabs were rough rolled in a reversible 4-Hi mill to intermediate bar with the defined exit temperature from roughing mill. The bar is hot coiled intermediately to attain uniformity in the temperature all along the bar. Subsequently, the bar is rolled in 4-Hi Six-stand tandem finishing mill with predefined entry temperature and %reduction at each stand. The strip is further cooled to the required temperature in two step cooling on run-out-table to have the desired micro-structure and hence the tensile properties. The strip after attaining the required temperature is coiled in down coiler. Figure 3 shows the coil after rolling from hot strip mill.

Figure 3. Steel coil after hot rolling at Hot Strip Mill, Essar

The trial heats were hot rolled in thickness from 3.00-10.00mm. The as rolled coils were tested for tensile and impact toughness evaluation for all along the length of the coil to check for the variation. Bend-ability which is the most important parameter for the structural application was also tested with different bend radius to have the critical bend radius of the material. Micro-structure of different thickness rolled was also analyzed both qualitatively as well as quantitatively. Finally the hot rolled coils were also processed at service center in cut to length and were subsequently profile cut to evaluate the plate behavior after profile cutting in the ready to use shapes.

Results and Discussions

Mechanical properties

The key properties of steel plates for structural applications are of course, yield strength (YS), tensile strength (UTS) and total elongation (%El) as well as low temperature toughness and balanced formability. These properties are required not only on the flat strip in as rolled condition, but also after processing. Criticality in high strength grades for structural applications demands for the suitability for bending operations and weldability. Table 2 shows the properties of SR60 and SR65 grades achieved in the as rolled condition. The tensile properties were also tested at different location all along the length of coil to evaluate the variation. Figure 4 a & b**,** shows the tensile properties along coil length. Figure 5 shows the comparison of typical mechanical properties of SR60 and SR65 grades.

Table 2. Mechanical Properties of SR60 and SR65 grade steel in as supplied condition.

Steel grade	Mechanical Properties at room temperature				
	YS, MPa	TS, MPa	%El (50mm)	Bend 180°	Impact Energy in J at -20°C
SR60	>600	670-710	26-28	1.0 x thickness	180
SR65	>650	740-760	16-20	1.0 x thickness	175

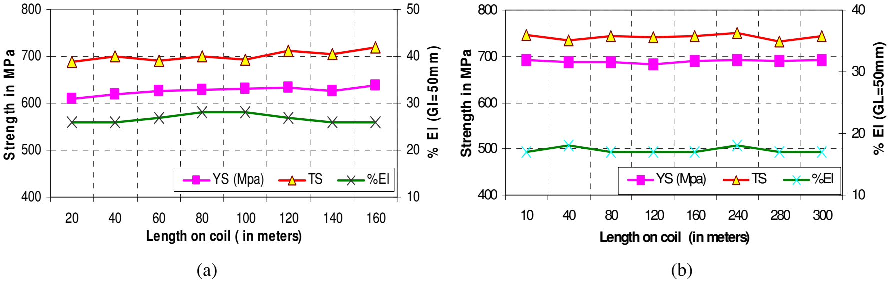


Figure 4. Tensile properties variation along the coil length a) grade SR60 and b) grade SR65.

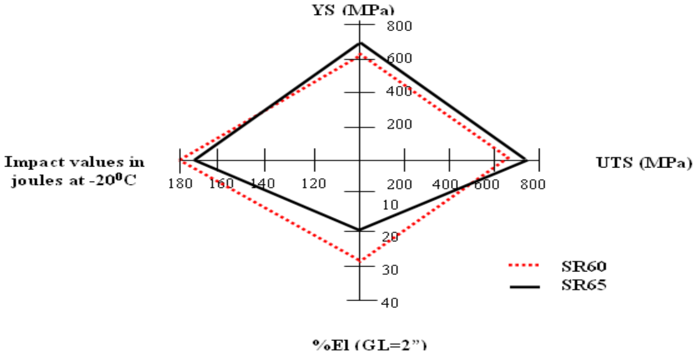


Figure 5. Comparison of typical mechanical properties of SR60 and SR65 grade steel.

Bend properties:

With respect to bend properties, inner radii of one times the thickness are reached for both materials at a bending angle of 180° if cut edges of the bend specimens are ground. The material had performed satisfactorily for close bend also without cracking. Figure 6, shows the bend tested specimen.

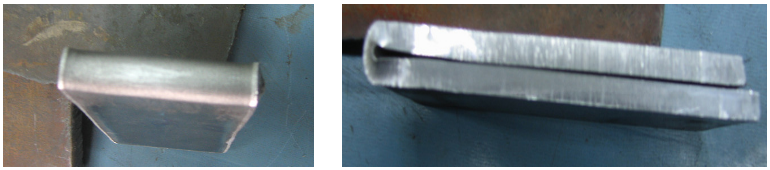
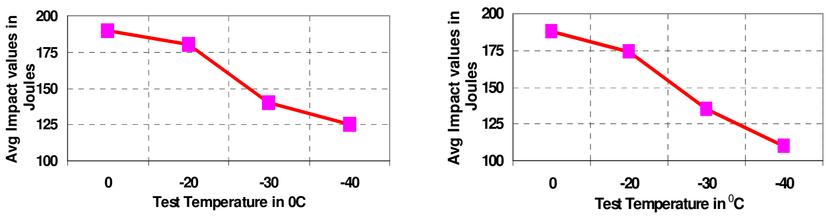


Figure 6. Close bend specimen in grade SR65.

Charpy impact toughness:

Transverse Charpy v-notch impact toughness of both the grades was tested at different temperatures from 0°C to -40°C. Figure 7 shows the transition curve for both the grades. Temperature around -20 to -30°C is particularly important from the view point of practical applications. The values obtained were consistently more than 50 Joules in both the grades. The contribution of the toughness is from the fine grain size and modification of the inclusion morphology. The bainitic phase also helps in improvement of toughness by obstructing crack propagation.



(a) (b)

Figure 7. Impact energy transition curve for a) SR60 and b) SR65.

Grain size and general micro-structure:

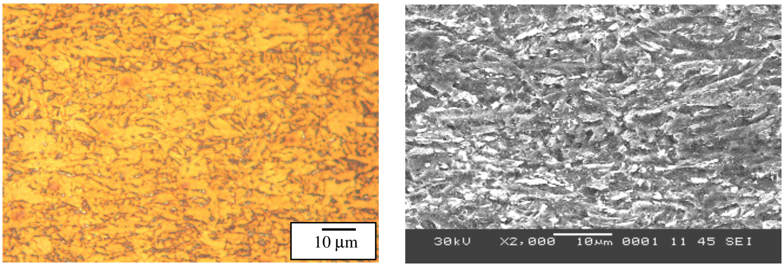
The longitudinal and transverse sections were prepared by standard metallographic procedure. The samples were analyzed for inclusion rating, grain size and micro-structure. Table 3 shows the summary of the micro-structural observations made on SR60 and SR65 grade material.

The samples were chemically etched with 2% nital and also with Le-Pera reagent to reveal the different phases present in the steel. Figure 8 a & b and Figure 9 a & b shows the optical and

SEM micro-photographs for hot rolled SR60 and SR65 grade material. The primary micro-structural constituent is ferrite with secondary phase as bainite. The bainitic region is characterized by a structure with distinct patches of plate-like carbides. Figure 9a shows the ferrite grains are fine grained and shows some elongation in the rolling direction. The elongation of the ferrite grains as observed in the micro-structure has been referred due to deformation of austenite during controlled rolling. Micro-alloying elements Nb and Ti have great influence on the kinetics of transformation processes namely recovery, recrystallisation and grain growth. This micro-alloying content also influences the microstructure of the deformed austenite, and the resulting grain size. Carbide forming elements, Nb and Ti, plays as important role in retarding the re-crystallisation during finish rolling and consequently, a pan-cake micro-structure is formed that promotes grain refinement during austenite to ferrite transformation. It is also inferred from the microstructure that during transformation the austenite grains retained their elongated shape and this grain morphology and possibly partial recovery influenced ferrite nucleation resulting in finer polygonal ferrite. Also in addition, increase in recrystallization temperature and retardation of recrystallisation of austenite is generally expected to favor finer grain size [3, 4].

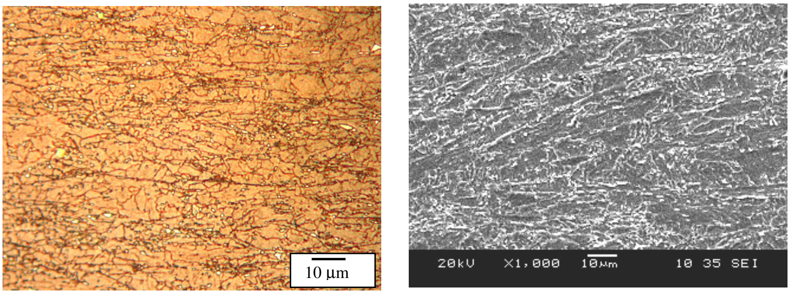
Table 3. Summary of micro-structure of SR60 and SR65.

Steel grade	**Inclusion rating as per ASTM E-45**	**Grain Diameter in microns**	**Micro-structure**
SR60	< Thin 1.0 D	< 6.00	Ferrite + Bainite
SR65	< Thin 1.0 D	< 5.00	Ferrite + Bainite



(a) (b)

Figure 8. Photo-micrographs of SR60 a) Optical micro-photograph (Etchant: Le Pera) and b) Scanning Electron Micro-scope (Etchant: 2% Nital).



(a) (b)

Figure 9. Photo-micrographs of SR65 a) Optical micro-photograph (Etchant: Le Pera) and b) Scanning Electron Micro-scope (Etchant: 2% Nital).

Strengthening mechanism:

The relationship between yield strength and the micro-structure is not direct in the case of micro-alloyed steel. As referred earlier, micro-alloyed steel derived their strength from the different strengthening mechanism. As an approximate estimate of the base metal yield strength in terms of chemical composition and grain size can be made using the relationship (Eq. 1) developed for plain carbon steel [5, 6].

$$\sigma_{base} = \sigma_o + \left(15.4 - 30C + \frac{6.09}{0.8 + Mn} \right) d^{-1/2} \qquad \text{.................. Eq. 1}$$

and

$$\sigma_o = 63 + 23Mn + 53Si + 700P \qquad \text{.................... Eq. 2}$$

The base strength is in MPa, the concentration of the elements is in wt%, and ferrite grain size (d) is in millimeters. In the case of present steel grade SR65 which is Nb-Ti micro-alloyed having average grain size of 5µm. The estimated base strength of the material as per the Eq. (1) is ~ 355 MPa. The estimation of contribution from the dislocation and precipitation hardening on the strength is not simple. However, the relation ship between the micro-structure and the yield strength of Nb-Ti steels can be expressed by Eq. (3) [5, 6]

$$\sigma_y = \sigma_{base} + \sigma_{dislocation} + \sigma_{précipitation} + \sigma_{transformation} \qquad \text{............... .. Eq. 3}$$

The above equation includes contribution due to solid solution strengthening by C and Mn and grain size effect. The average yield strength of SR65 grade was ~680 Mpa, considering the base strength as 355MPa from the Eq. (1), the contribution from the dislocation, precipitation and transformation hardening amount to 325 MPa for Nb-Ti steels.

Conclusions

1. Very high strength with yield strength of 600MPa and 650MPa minimum were developed at Essar Steel for various application fields including structural engineering. The contribution in the strength is considerable from the precipitation and transformation hardening apart from the base strength from solid solution hardening and fine grain size.

2. The specific mechanical properties of very high strength steel were derived from the complex micro-structures consisting of ferrite, bainite and micro-alloying constituents. Fine bainitic micro-structures show the excellent combination of the strength and toughness. Such micro-structure can be achieved by optimum alloy design and through thermo-mechanical rolling followed by the controlled laminar cooling.

3. The impact toughness achieved in both the grades were >50 Joules at -40°C, which may be due to very fine grain size and fine bainitic micro-structure. The material was found to have the good bend properties with bend radii of 1.0 x thickness with good weldability.

4. The material performance during the profile cutting at customer end was also found to be satisfactory with no event of warpage or any type of material deficiency for the intended structural application.

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