Processing of high strength hot rolled strips through the Thin Slab Casting and Rolling facility of TATA Steel, Jamshedpur

Thin slab casting and rolling (TSCR) also known as Compact Strip Production (CSP), was developed by SMS Semag® for the production of hot rolled strip in a compact production line. Although soft unalloyed grades were the first TSCR products, the technology has been successfully used for the production of HSLA with over 500MPa tensile strength at TATA Steel, Jamshedpur.

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Thin slab casting and rolling (TSCR) has emerged as a modern technology for near net shape production of hot rolled strip. In this facility, thin slabs are cast at high speed (up to 6 m/min) and are directly hot rolled into strip of the required dimensions. There is no requirement for any intermediate cooling and reheating of slabs, unlike with the conventional hot rolling route. The higher casting speeds of thin slabs and their direct charging into soaking furnaces play an important role in enhancing productivity, reducing costs and overall energy consumption **[1,2]**. The economic advantages of TSCR plants make them considerably more attractive than large, capital intensive integrated conventional steelworks **[2]**.

Furthermore, the design of thin slab casters enables certain metallurgical advantages due to the rapid solidification rates in thin slabs. A finer solidification structure is produced which reduces the intensity of micro-segregation, thereby producing slabs with sound internal quality and better chemical homogeneity. Additionally, facilities such as liquid core reduction bring flexibility in slab thicknesses and enhance the refinement of dendritic cast structure.

TSCR technology was originally adopted for bulk production of soft unalloyed steel grades but, given the commercial benefits of this process, the production of high strength steels to meet increasing demands of automotive industries became an important area of interest. Grain refinement and precipitation hardening are commonly adopted strengthening mechanisms to develop high strength steels. However, the absence of intermediate reheating facility and the shorter soaking time of thin slabs induce various peculiarities in processing, which limits the effective usage of microalloying elements that are added in the steel for strengthening **[3]**.

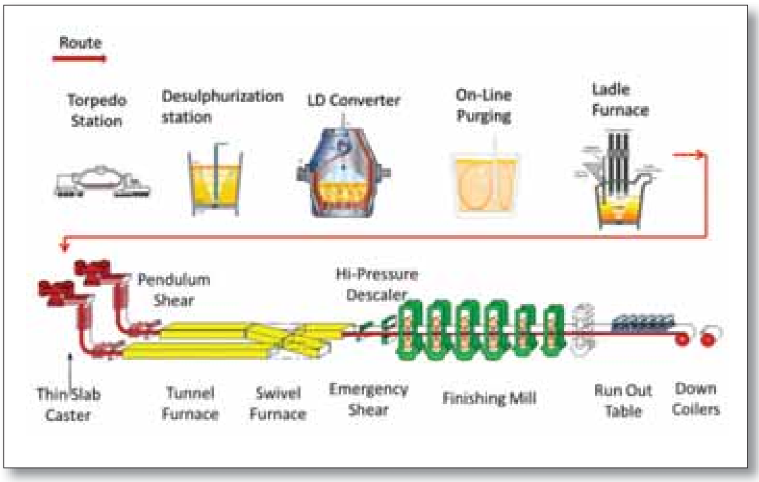


Fig 1 Process layout of LD3 & TSCR in TATA Steel Ltd, Jamshedpur

Successful development of high strength steels through TSCR requires the microstructure of the strips to be carefully engineered. The steel chemistry and slab rolling parameters need to be optimised with precision to impart the strip with the target microstructure. This paper illustrates the various types of steel grades developed through the thin slab caster route in TATA Steel, Jamshedpur having tensile strengths over 500MPa, and the strategies taken to design such grades.

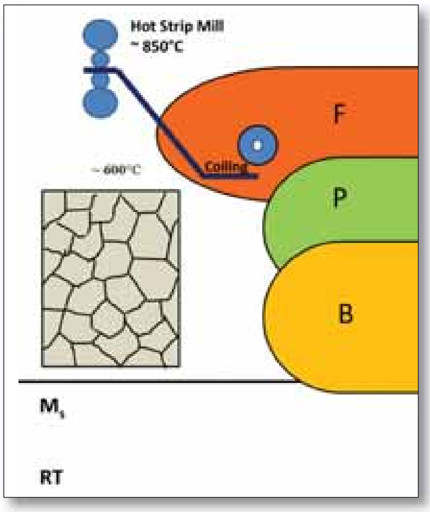
TSCR PLANT OF TATA STEEL, JAMSHEDPUR

The TSCR shop was commissioned in 2012. *Figure 1* provides the schematic representation of the TSCR in LD3. The primary steelmaking is carried out using 165t basic oxygen converters followed by secondary steelmaking using ladle furnaces. The steel is fully killed with aluminium. Calcium treatment is carried out to modify inclusions

Steel grade	C	Mn	Si	S	P	Al	Nb	V	Nppm	Cr
A	0.03-0.07	1.5 max	0.15 max	0.008 max	0.025 max	0.02 min	0.01-0.04	0.03-0.06	40-100	-
B	0.03-0.07	1.4 max	0.25 max	0.005 max	0.025 max	0.02 min	0.035 max	0.03-0.06	40-100	-
C	0.03-0.06	1.5 max	0.5 max	0.005 max	0.025 max	0.02 min	-	-	60 max	0.4-0.6

Table 1 Chemical composition of microalloyed steels, wt%
(A) Nb-V designed to provide tensile strength (500-550MPa) by precipitation hardening, (B) Designed to provide tensile strength (>550MPa) by precipitation and second phase hardening, (C) Designed to provide tensile strength (>550MPa) by dual phase

Fig 2 Cooling strategy for microalloyed steels with ferritic microstructure



before casting and ensure production of cleaner steels.

The liquid steel is fed via ladle and tundish into the funnel-shaped CSP mould of the thin slab caster. On leaving the mould, the thin slab runs through to the secondary cooling zone where it is water-cooled with the help of high speed spray nozzles. The caster is of vertical type with solid state bending. The hydraulic segments have the additional feature of liquid core reduction, which enables production of slabs in the range of 50-70mm thickness. The caster is equipped with the latest technologies, such as automatic width control, auto-SEN ramping, dynamic solidification control and dynamic soft reduction.

The thin slabs are cut into length by a pendulum shear and are directly charged into the tunnel furnace, which subsequently delivers them to the hot rolling mill. The mill is equipped with six 4-Hi rolling stands with modern CVC+ rolls for uniform rolling and better profile. The hot rolled strip undergoes lamellar cooling on the run-out-table from the finish rolling temperature to the desired coiling temperature.

STRATEGIES TO PRODUCE STEELS WITH TENSILE STRENGTH >500MPA

Since commissioning in 2012, several steel grades having tensile strengths up to 600MPa have been successfully developed and could be reliably used in manufacturing critical automotive components, satisfying the requirements for adequate formability.

Initially, steels were developed with a C-Mn-Si chemistry with no microalloy additions. The tensile strength of these steels was typically lower than 450MPa. When developing steels with higher tensile strength, increased use of solid-solution hardening elements was not supported in several applications due to their adverse impact on material formability and weldability. Achieving higher strength necessitated additions of microalloying elements for grain refinement and precipitation hardening **[4-8]**. In addition the microstructure of the strips was engineered and process parameters designed to achieve the target microstructure. The various categories of high strength steels exhibiting strength more than 500MPa are discussed below.

Precipitation hardened ferritic steels In this category, the strips were designed to possess a single phase ferritic microstructure. The ferrite was hardened by addition of solid-solution strengthening elements like manganese and silicon and additional strength was achieved through judicious choice of microalloying elements to promote strength through precipitation hardening.

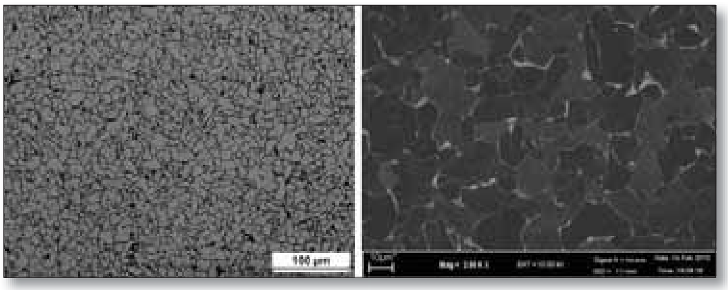
In the TSCR process, the equalisation temperature in the tunnel furnace is around 1,150°C, which puts a restriction on niobium additions over 0.05wt-% as excess additions for strengthening would be ineffective due to un-dissolved carbo-nitride precipitates that would be retained in the slab prior to hot rolling. Additionally, precipitates formed in the slab during casting do not have enough time for complete dissolution in the tunnel furnace, leaving niobium out of solution. This limits its thermo-mechanical processing effect. Such issues are not encountered with vanadium microalloying since precipitates mostly remain in solution prior to hot rolling **[7-8]**. However, to achieve strength levels over 500MPa with vanadium addition alone, large amounts of vanadium microalloying would be required, making the process commercially unattractive. Also at high vanadium levels, a large concentration of vanadium nitride precipitates adversely affects the ductility and toughness of the steel, thus it was required to employ complex microalloying with Nb and V to achieve the desired strength.

A typical microalloyed grade (A) shown in *Table 1* was developed, exhibiting tensile strengths of 500-550MPa. The effectiveness of microalloying additions was maximised by ensuring that the slab temperature does not drop below 1,050-1,100°C prior to entry to the tunnel furnace **[9]**.

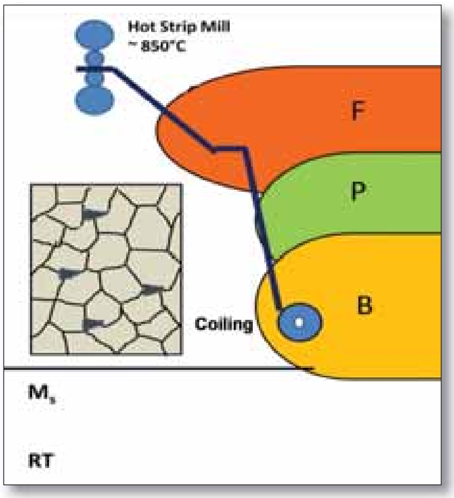
Figure 2 gives a schematic representation of the cooling profile and desired phase transformation with the help of a Continuous Cooling Transformation (CCT) diagram **[3]**. The strip is coiled above the bainite-start (BS) temperature to form a fully ferritic structure. The optical and SEM microstructure of the hot rolled strip (transverse section) is shown in *Figure 3*. The microstructure contains fine ferrite grains with small amounts of pearlite at the triple point locations. The ferrite grain sizes are of the order of ASTM 9-10.

Precipitation and second phase hardened ferrite-bainite steel Due to the limitation in the use of microalloying elements, achieving strengths over 550MPa requires an additional strengthening mechanism to be employed in addition to precipitation hardening. This was done by designing steel with a microstructure containing a mixture of fine ferrite grains along with a small amount of harder phases like bainite. Here the strength is achieved by a combination of precipitation and second phase hardening. A microstructure containing ferrite and bainite is also known to have good stretch flangeability **[10]**. The second phase can be introduced in the microstructure by suitable modification of strip cooling strategy on the run-out table.

This grade (B), illustrated in *Table 1*, was developed for automobile wheel application with a minimum tensile strength requirement of 550MPa. The desired microstructure was achieved by rapid cooling from the finish rolling temperature to a predetermined intermediate temperature followed by air cooling to the coiling temperature **[10]**. The coiling temperature in this case was kept below the bainite start temperature. The initial rapid cooling rate ensures that the formation of pearlite is avoided completely. This is important for applications that require the steel to have superior stretch formability. The schematic representation of the cooling profile and phase transformation is shown with the help of the CCT diagram in *Figure 4* **[3]**. *Figure 5* shows the optical and SEM microstructure of the transverse section of the hot rolled strip. The ferrite grain sizes are of the order of ASTM 10-12.



▲ Fig 3 (*left*) Optical microstructures (200X) and (*right*) SEM micrograph of 0.025Nb-0.035V microalloyed hot rolled strip



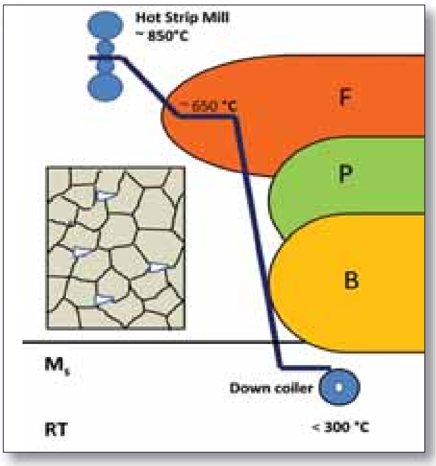
◄ Fig 4 Cooling strategy for microalloyed steels with ferrite-bainite microstructure

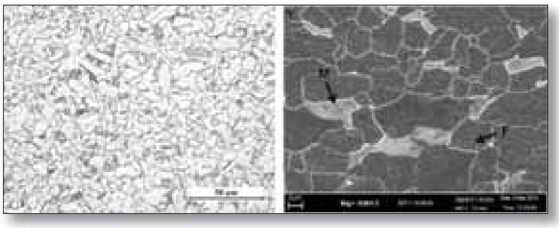
▲ Fig 5 (*left*) Optical (1,000X) and (*right*) SEM micrographs of microalloyed strip with Ferrite plus Bainite microstructure

Second phase hardened ferrite-martensite steels The microstructure of this category of steels was designed to contain 10-15% of fine martensite laths in a ferritic matrix. Conventionally known as Dual Phase (DP) steels, this variety of steel is known to exhibit superior formability in addition to tensile strength of over 550MPa. The strength is achieved by the combined effect of solid solution hardened ferrite and hard second phase. The steel displays excellent ductility and a continuous yielding behaviour owing to the presence of a large amount of mobile dislocations, which are introduced during martensitic transformation. Such steels are of immense interest for crash resistance applications **[11]**.

The designed chemistry of the steel (C) is shown in *Table 1*. Nb and V are omitted, but Cr is used to provide the necessary hardenability. The desired microstructure was achieved by a two-step cooling process on the run-out-table. In the first step, the strip is rapidly cooled from the finish rolling temperature to a predetermined intermediate temperature where it is held for a period of 5-7 seconds to ▷

▶ **Fig 6 Cooling strategy for dual phase steels with Ferrite (85%) + Martensite (15%) microstructure**





▲ **Fig 7 (*left*) Optical (1,000X) and (*right*) SEM micrographs of dual phase strip with Ferrite (F) - Martensite (M) microstructure**

allow the formation of soft phase, ie, ferrite. Following this, the strip is rapidly cooled to a temperature lower than the Ms temperature to allow the transformation of remaining austenite to martensite. The schematic representation of the cooling profile and phase transformation is shown with the help of the CCT diagram in *Figure 6* **[3]**. The optical and SEM micrographs of the transverse section of the hot rolled strip are shown in *Figure 7*. The ferrite grain sizes are of the order of ASTM 10-12. MS

CONCLUSIONS

1) The TSCR plant at TATA Steel, Jamshedpur is successfully producing HSLA steels with tensile strengths of more than 500MPa.

2) To achieve strength (500-550MPa) through precipitation hardening only, it was required to employ a combination of multiple microalloying elements such as niobium and vanadium.

3) For strength levels greater than 550MPa, a combination of precipitation hardening and second phase hardening mechanisms were employed. For this a Nb-V microalloyed steel with ferrite + bainite microstructure was developed through an optimised cooling strategy. The premature precipitation of microalloying elements was suppressed by ensuring a high slab temperature above 1,050-1,100°C at the entry to tunnel furnace.

4) By replacing Nb and V with Cr, a strength of more than 550MPa could be achieved by generating a microstructure consisting of ferrite (85% volume fraction) along with dispersed islands of martensite (15% volume fraction).

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