An overview of Steel Plates: Metallurgy & Applications
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Abstract
Steel plates find wide applications in various segments such as infrastructure; defence, ship building, capital goods and process machinery etc. These applications call for advanced design concepts and cost reduction methods for meeting the stringent and conflicting requirements of plate products worldwide. In this paper, an overview of plate rolling technologies such as Accelerated Direct Cooling (ADCO), thermomechanical controlled rolling, quenching and tempering, and normalizing are discussed. The process technology needed to achieve the critical properties like high strength, high toughness, fatigue, creep resistance, abrasion and wear resistance are discussed.

Introduction:
The demand for high-strength extra wide plates is growing due to changing market trends. The steel plates are required to have very good mechanical properties like high strength, high toughness, fatigue, creep resistance, corrosion resistance coupled with excellent weldability. Among many factors that have contributed to this demand is the increased use of sophisticated technology in various strategic sectors, coupled with the shift in manufacturing paradigms and locations across these sectors worldwide. Today, steel plates are available in strength levels ranging from 210 MPa to 1100 MPa offering excellent flexibility for applications. The combination of high strength coupled with wider width enables efficient use of steel plates, durability, reduced fabrication costs, weight savings, advanced designs, optimized nesting etc. This paper discusses Essar’s plate mill, metallurgy of plate rolling, plate applications and the processes involved in achieving the critical properties for different applications[1-2].

Metallurgy of plate rolling
The key concept in design of alloy for plate rolling is based essentially on grain refinement together with other strengthening mechanisms for achieving desired properties. Some of the other mechanisms involved in achieving the properties are,

- Solid solution strengthening
- Precipitation strengthening
- Dislocation strengthening/Work hardening
- Transformation strengthening

Grain refinement is influenced by the complex effects of alloy design and processing methods. For example, the various methods of grain refinement used in the three different stages of hot rolling (i.e. reheating, hot rolling, and cooling) include:

- The addition of Ti, Nb or Al to retard austenite grain growth when the steel is reheated for hot deformation.
- The controlled rolling of microalloyed steels to condition the austenite so that it transforms into fine-grain ferrite and use faster cooling rates to attain finer grain size.
In practice, grain refinement can be achieved during plate rolling by the interaction between micro alloying elements (niobium, vanadium, or titanium) and hot deformation. Grain refinement may be further enhanced by accelerating cooling after the completion of hot rolling. The under cooling of austenite enhances the rate of ferrite nucleation and slows down the rate of growth. A combination of these two factors contributes to the formation of smaller grains.

As shown in Figure 1, the success of microalloyed steels is due to complimentary strengthening mechanisms, specifically grain refinement and precipitation hardening. Precipitation hardening increases strength but may contribute to brittleness. Grain refinement increases strength but also improves toughness. As a result, grain refinement counteracts any embrittling caused by precipitation hardening. In high strength low alloy steels, micro alloying elements such as vanadium and nitrogen provide up to 70% of the strength by contributing to grain refinement and precipitation hardening [3].

Precipitation strengthening occurs from the formation of finely dispersed carbonitrides developed during heating and cooling. Because precipitation strengthening is generally associated with a reduction in toughness, grain refinement is often used in conjunction with precipitation strengthening to improve toughness. Precipitation strengthening is influenced by the type of carbonitride, its grain size, and, of course, the number of carbonitrides precipitated. The formation of MC is the most effective metal carbide in the precipitation strengthening of micro alloyed niobium, vanadium, and/or titanium steels. The number of fine MC particles formed during heating and cooling depends on the solubility of the carbides in austenite and on cooling rates. The most desirable are those micro alloys, which contribute to both grain refinement and precipitation hardening. The combined effect of these two strengthening mechanisms may provide as much as 70% of the yield strength, accounting for the remarkable cost-effectiveness of micro alloyed steels. Because these two dominant strengthening mechanisms operate in micro alloyed steels, their carbon content (or CE) is very low. A yield strength of 550 MPa can be obtained in a steel containing only 0.04 to 0.06% carbon. This low-carbon content contributes to excellent weldability. The effect of grain refinement and various strengthening mechanism is depicted in fig. 2 & fig.3.

**Fig.1 strengthening mechanism in hot rolled steel [3]**
While the basic metallurgy of strengthening mechanism is discussed in the preceding paragraphs, a brief summary of the various processes that are employed in plate rolling will be in order.

Thermo-mechanical controlled rolling (TMCR)

Thermo-mechanical controlled rolling is a technique designed to improve the mechanical properties of steels by combining controlled hot deformation process and accelerated cooling. The TMCR makes it possible to reduce the total amount of alloying additions and to improve weldability. The aim of TMCR is to get the fine and uniform acicular ferrite microstructure instead of ferrite/pearlite banded structure of conventional steels. Due to this fine and uniform acicular ferrite, TMCR steels have higher strength and better toughness. Microstructure control during TMCR process begins with slab reheating stage. The slabs are heated in the walking beam furnace within the temperature range of 1050°C to 1200°C which result in austenitization, including homogenization and the dissolution of micro-alloying elements. Depending on the temperature regime selected, a certain strengthening and grain refinement of the structure occurs during the rolling process. By the controlled rolling in the non-recrystallization region, fine and worked austenite grains are formed. These fine austenite grains are transformed into fine acicular ferrite or upper bainite in the following accelerated cooling after hot rolling [4-5].

![Fig.4. Thermo-mechanical controlled rolling [4]](image-url)
Normalizing

Normalizing is a process of heating steel plates above its upper critical temperature, holding at this temperature for desired period of time and finally cooling in air which results in reducing the average grain sizes and make more uniform and desirable grain size distributions. In the normalized condition, steels achieve optimum combination of strength and toughness. Parts subjected to impact and those that require maximum toughness with resistance to external stress are usually normalized [4].

Quenching and tempering

For producing steel plates with ultra-high strength and toughness, quenching and tempering processing technique is used. Using proper alloying & process selection the steel plates are austenitized by heating in a furnace and are water quenched. Quenching increases the hardness and the strength of the plates but makes it brittle. Thus to remove the brittleness the steels plates are tempered. The tempering is done at different stages below the lower critical temperature of steel [4].

ESSAR’s Plate mill

ESSAR Plate mill with a capacity of 1.5 MTPA is equipped with state of art technology and advanced controls. Partnering with best in class technology providers, the mill has advanced facilities and uses sophisticated processing techniques like TMCR coupled with ADCO, Direct quenching(DQ), indirect radiant heating for normalizing, roller water quenching and tempering, in-line ultrasonic testing for producing steel plates for extremely critical applications. The mill is India’s largest and widest with a capacity of producing plates in strength levels of 1500MPa and width up to 5000mm. The processing techniques are selected based on the application and properties required.

Basically, the unique features of plate rolling at ESSAR is the high powered mill for rolling heavy gauges, advanced temperature controlled heat treatment facilities and superior dimensional accuracy. The mill possesses some of the latest technologies like, plan view rolling

The high roll separating force of 10,000 MT as against conventional 4000 MT , helps in high shape factor rolling i.e., (higher reduction per pass) which results in good internal quality, improved mechanical properties like strength and toughness. Another specialty of this mill is ADCO facility, essentially this is a process wherein the plates can be directly quenched immediately after rolling. By proper choice of cooling rate and process conditions, the process gives an advantage to produce wide variety of products at different strengths levels as an alternative to expensive separate Quench and tempering process. Hot leveling, Ultra sonic tests, Heat treatment facilities, finishing facilities are some of the other salient features and first of its kind in India.
Some of the unique features of the plate mill are mentioned in the table 1.

<table>
<thead>
<tr>
<th>Features</th>
<th>Capacity</th>
<th>Technology partner</th>
<th>Advantages</th>
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<tbody>
<tr>
<td>High-power Reversible rolling Mill</td>
<td>RSF-10,000 T</td>
<td>SIEMENS-VAI</td>
<td>*High shape factor rolling for better properties and lower internal discontinuities for ultra high strength-high toughness plates.</td>
</tr>
<tr>
<td>ADCO( Accelerated Direct cooling ) with Direct quenching facility</td>
<td>11,000 m³/hr</td>
<td>SIEMENS-VAI</td>
<td>* Controlled cooling with edge masking facility * Direct quenching facility for producing ultra high-strength/high toughness/abrasion resistance steel plates.</td>
</tr>
<tr>
<td>Hot leveler</td>
<td>4000 T</td>
<td>SIEMENS-VAI</td>
<td>*High plastification ratio *Low residual stresses * Excellent flatness</td>
</tr>
<tr>
<td>Ultra-sonic testing</td>
<td></td>
<td>NDT</td>
<td>* Online ultra sonic testing up to 50mm thick plates.</td>
</tr>
<tr>
<td>Heat treatment facilities</td>
<td>Normalizing furnace Quenching and tempering furnace</td>
<td>LOI Germany</td>
<td>* Excellent mechanical properties * Wide range of heat treatment facilities * Inert atmosphere in furnace ensures less scale formation * Ultra-high strength/toughness/abrasion and wear resistant plates.</td>
</tr>
<tr>
<td>Cold leveling</td>
<td>3000 T</td>
<td>SIEMENS-VAI</td>
<td>*Excellent flatness</td>
</tr>
<tr>
<td>Finishing facilities</td>
<td>Shearing up to 50mm</td>
<td>SIEMENS-VAI</td>
<td>* Edge trimming with excellent dimensional tolerances *Squared edges</td>
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Table 1: Features of ESSAR plate mill.

Applications of Plates:

Construction

Generally the plates used in this application are pre-fabricated structures; some of the applications are in bridges, ports, buildings, dams etc. Steel plates used for construction require high strength, toughness and good weldability [6-7]. The plate products are manufactured predominantly through TMCR, for certain critical applications normalized and QT plates are used.

Line pipes

Steel plates are generally used in sour & non sour application. The pipes are subjected to high hoop/circumferential stress due to the transport elements. As the pipes are built across different geographies that demands very critical properties like high strength, high toughness, good weldability, high corrosion resistance, resistance to hydrogen induced cracking, sulphide stress corrosion cracking
The Plates used in this application are processed through TMCR route for achieving high strength coupled with high toughness.

Boilers and pressure vessels

The steel plates are generally hot/cold formed to desired shapes for major boilers or pressure vessels. The boilers and pressure vessels are characterized by the conditions like high temperature, high pressure, operating fluids etc. Under such extreme conditions the steel plates must possess high strength, high toughness, creep resistance, resistance to cracking etc [7]. The plates are in general normalized for high temperature and high pressure applications. For certain applications that demand for high toughness and better properties QT plates are used.

Ship-building

Steel plates for ship-building applications are exposed to adverse load conditions like large cyclical loads, wave slaps, slamming thermal excursions in tropical and arctic conditions, cargo buoyancy. High strength coupled with high toughness, corrosion resistance, excellent through thickness properties, resistance to lamellar tearing, good weldability, good fatigue properties are some of the vital properties required [7]. The plates are supplied in normalized, TMCR conditions. For special applications like ship-hulls that require high strength in combination with high toughness, QT process is used.

Defence

The plates are fabricated to be assembled in battle tanks, mine protective vehicles, wall structures, protection suits etc. The steel plates are required to have high strength, high toughness, impact resistance, high hardness and anti ballistic properties to withstand sever conditions in battle fields, land mines and high momentum bullets [9]

Yellow goods

The yellow goods applications are characterized by wear and abrasive conditions, hard mines, rocks, etc. The steel plates subjected to such applications require high strength, high toughness, and excellent abrasion and wear resistance. The use of ultra high strength steels plates help in providing good structural integrity, weight saving and reduced fabrication costs [8-9].

Achieving the Properties of high performance plates:

The clean steel technology (low sulphur, inclusion shape control, low tramp elements etc.) are the primary building block in the development of high performance steel plates. The effects of clean steel practices influence critical properties like toughness, fatigue, hydrogen induced cracking, sulphide stress corrosion cracking, ductility, etc.

The process of iron making involve reduction of iron ores through gas based Midrex process which doesn't involve coal or coke, thus producing low levels of sulphur, phosphorus and tramp elements. In the steel making stage, the products of Iron making DRI or briquettes are melted in the electric arc furnace and are processed through ladle refining and Vacuum de-gassing units for proper alloying, inclusion shape controls and reduced levels of gaseous contents. The steel is cast in vertical casters equipped with soft reduction technology for producing slabs with lowest level of segregation and excellent internal soundness.
The slabs are processed through high powered mill for producing plates in the required dimensions. The rolling procedure, heat treatment processes are based on the applications. Ultra high strength steels with excellent abrasion, wear resistance for yellow goods, impact strength/anti-ballistic for defence are processed through Quench and tempering facility, by using proper alloying technique, clean steel technology, etc. The High strength steels for construction, Line pipes are processed using the Thermo-mechanical controlled rolling processes through optimum alloy design. The steels for high temperature applications in boilers, pressure vessels are processed using the normalizing furnace. Table 2 shows the process by which critical properties are achieved and fig.2.a shows the mechanism of lamellar tearing, it is defined as the separation parent or base metal primarily in planes parallel to rolling direction due to high through thickness strains. The inclusions present in steel are primary reason for lamellar tearing. The Inclusions can be reduced and controlled using the inclusion shape control and calcium treatment in steel making. Fig.5.b shows the mechanism of hydrogen induced cracking (HIC) where the molecular hydrogen segregate on the metal defect like inclusions because of their higher diffusivity. The segregation of

<table>
<thead>
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<th>Properties</th>
<th>How it is achieved</th>
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<tr>
<td>Ultra high strength</td>
<td>Steel plates are subjected to state of art quenching and tempering facility for attaining ultra-high strength</td>
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<tr>
<td>High Toughness</td>
<td>Optimal alloy design, finer grain sizes along with low levels of inclusions</td>
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<tr>
<td>Internal Soundness</td>
<td>Soft reduction combined with high shape factor rolling</td>
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<tr>
<td>Excellent through thickness properties</td>
<td>Uniform grain size through high shape factor rolling and subsequent normalizing treatment</td>
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<tr>
<td>Fatigue resistance</td>
<td>Low inclusions, low sulphur levels and uniformity in grain size</td>
</tr>
<tr>
<td>Resistance to lamellar tearing</td>
<td>Low levels of sulphur and inclusions are ensured.</td>
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<tr>
<td>Good weldability</td>
<td>Lower Ceq through optimum alloy design</td>
</tr>
<tr>
<td>Creep resistance</td>
<td>Optimal alloy design and processing through Normalizing for attaining uniform properties</td>
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</table>

Table 2: Process route for achieving critical properties in plate rolling

Fig. 5- a. Lamellar tearing. b-Hydrogen induced cracking
hydrogen over a period of time causes crack. HIC resistant steel plates are produced through low levels of sulphur, inclusion shape control and minimum segregation by optimizing parameters in casting.

ESSAR has successfully manufactured and commercialized plate products for different applications by using advanced technologies like TMCR, Normalizing, and QT etc.

**Conclusion**

An insight on the plate mill metallurgy, applications and latest technologies used by ESSAR for producing its Extra-Wide Plates of superior mechanical properties is presented. Basic metallurgical concepts for alloy design for various applications are given. ESSAR with its unique state of the art facility has the capability to produce advanced plate products for critical applications and has positioned itself as one of the pioneer steel makers in India for advanced steel products.

**References**


