A study was undertaken in India to increase understanding of the mechanisms associated with deformation and restoration of austenite during continuous multipass hot rolling of microalloyed steel sheet and plate.

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To keep pace with the rapidly changing needs and technological requirements of the steel construction industries, many efforts have been directed toward development of special grades of steels with higher strength levels and superior product attributes. New technologies such as continuous casting and thermomechanical controlled processing (TMCP) introduced at the Steel Authority of India Limited (SAIL), have resulted in the successful development and commercialization of several new grades of steel.

This article discusses some of the recent developments: SAILMA-450 HI plates for the fabrication of excavators, impellers, and bridges; ASTM-A537 Cl.1 pressure vessel steel for oil tankers and containers; and API X65 line pipes for oil and natural gas transmission.

Thermomechanical processing

The critical features of a conventional thermomechanically controlled processing steel are:
- Selection of alloy chemistry
- Choice of slab reheating temperature
- Degree and distribution of deformation in the γ-recrystallization zone
- Cumulative deformation in the γ-non-recrystallization zone
- Finish rolling temperature
- Accelerated cooling

The slab reheating temperature determines the initial grain size and distribution of microalloying elements in the form of solid solution and precipitates. The recrystallization-stop temperature \( T_{\text{RXN}} \) rises with microalloying additions, resulting in a wider temperature zone of deformation of austenite in the γ-non-recrystallization region. The finish-rolling temperature controls the final state of austenite conditioning and its transformation kinetics. Accelerated cooling after finish rolling refines the ferrite grain size, and also helps in attaining a wide array of microstructures and associated mechanical properties. In this program, researchers attempted to simulate actual plate and hot strip rolling conditions and to study the evolution of microstructures at different stages of the hot-deformation process.

To simulate TMCP, controlled hot deformation studies were conducted on an MTS-458 machine modified for deformation under constant true strain rate conditions. Figure 1 shows a temperature-time schematic diagram of deformation sequence. To study the microstructural changes during hot deformation of austenite, specimens were directly quenched (WQ1, WQ2, WQ3) at different stages of austenite conditioning. After single pass/multipass hot deformation, the steel specimens were cooled to room temperature to study the evolution of the final microstructure.

Plate development

The development of thicker plates (20 to 32 mm thick) of SAILMA-450 HI steel posed a challenging
task due to the lack of state-of-the-art TMCP facilities at the Bhilai Steel Plant. Two alloy chemistries were designed: A niobium-vanadium microalloyed steel for plates up to 20 mm thick, and a niobium-titanium combination for plates 20 to 32 mm thick. A schematic representation of the TMCP schedule followed is shown in Fig. 2. A cumulative reduction of 60 to 65% in the finishing stand facilitated elongation of austenite grains, thereby leading to a finer ferrite grain size. A finish rolling temperature of 810 to 850°C (1490 to 1560°F), followed by spray water cooling to a temperature of 700 to 720°C (1290 to 1330°F), led to a further refinement of ferrite grain size and ensured a superior strength-toughness combination in the final product.

The microstructure revealed a typical ferrite-pearlite banded structure. The minimum mechanical properties conformed to those specified for SAILMA-450 HI, which include yield strength of 450 MPa, tensile strength of 570 MPa, elongation of 19%, and Charpy impact energy of 29 J at 0°C and 19 J at −20°C.

Figure 3 shows the tensile properties of plates processed from ten different heats and rolled to various thicknesses. It should be noted that the properties vary within a narrow range, reflecting the close control of both the steel chemistry and the hot rolling parameters. The Charpy impact energy was also determined at different test temperatures, with values of 71 J at 0°C and 63 J at −20°C.

**Pressure vessel plates**

Pressure vessel grade steel conforming to the ASTM-A537 Cl.1 specification is extensively applied in containers, tankers, and spheres for the storage of oil and natural gas. The steel requires moderately high strength levels (yield strength of 345 MPa, tensile strength of 485 to 620 MPa), good low-temperature toughness (Charpy impact energy of 19 J at −20°C), and a guarantee against internal defects as per ASTM-A435/435.

One major problem associated with the developmental exercise was a high incidence of rejection because of defects found by nondestructive tests (NDT). A careful analysis of the distribution of elements across the thickness of the plate revealed a strong tendency for carbon and manganese segregation at the mid-thickness. This resulted from a higher volume fraction of pearlite, which constituted ~80% at the mid-thickness as opposed to ~24% in the matrix. Another cause of segregation was the localized formation of a hard phase consisting of bainite/martensite. Cracks initiated within these bainite pockets and propagated through the plates, leading to NDT rejection.

To minimize this problem, a major technological change was recommended. Namely, the 250 mm slab caster was converted to a 320 mm slab caster with modified casting parameters. Steel processed through the 320 mm slab caster includes a harder secondary cooling regime of 0.5 liter/kg. (This indicates that half a liter of water was consumed for cooling each kilogram of steel cast.) The caster also has a low degree of superheat at a ΔT of 20°C max, meaning that its casting temperature is only twenty degrees above the melting point. This cooling regime and the low superheat have resulted in significant reduction in NDT rejection. The plate acceptance level, especially for thicker plates of 32 and 36 mm, increased from 24% (before conversion) to 78% (after conversion). The product is now commercially available in both the domestic and export markets.

**Line pipe steels**

The requirement of API grade line pipes has increased significantly in recent times. Table 1 shows the demand for electric resistance welded and spirally welded pipes during 1999 to 2000 for various pipeline projects in India. Out of an annual requirement of 200,000 tons of pipe, around 54,800 tons (27.4%) belong to the API X65 category. This preference conforms with the worldwide trend to operate pipelines at higher pressures and ensure greater ef-
A niobium-vanadium microalloyed steel has been designed with the following composition (max. wt.%): 0.1C, 1.35Mn, 0.01S, 0.015P, 0.30Si, 0.05Al, 0.05Nb, 0.08V. To ensure the required minimum properties (yield strength of 448 MPa, tensile strength of 530 MPa, elongation of 20.5%), the steel was TMCP processed into 6.4 mm hot strips. Process parameters included the finishing temperature at the roughing stage (R2) of 1000 to 1040°C; entry temperature in the finishing stage (F1) of 920 to 950°C; finish rolling temperature of 860 to 890°C; and coiling temperature of 650 to 680°C. The minimum reduction per pass at the roughing stage was 14%, and the cumulative reduction was ~70%.

Microstructural studies on 6.4 mm thick hot rolled strip revealed a typical ferrite-pearlite structure. The ferrite grain size was estimated to be ~5 µm. The mechanical properties were found to vary within a narrow range, with yield strength of 500 to 540 MPa, tensile strength of 600 to 640 MPa, and elongation of 28 to 34%. These properties reflect the close control of the alloy chemistry and hot rolling parameters. The Charpy impact toughness properties were found to be in excess of the specified minimum requirement of 35 J at 0°C, and were typically 40 to 50 J.

The hot strips were further processed into spirally welded pipes. The strength of the pipe body and pipe weld were evaluated by means of flat tensile specimens. Some typical results of tests conducted on hot strips, pipe body, and pipe weld are shown in Table 2. The pipe properties, both in the body and the weld joint, conform to the requirements of the API X65 specification. The corresponding strength of the input material (hot strip) for the tested pipes are shown to establish the drop in strength due to Bauschinger effect, in which plastic deformation causes strength to rise in the flow direction and to drop in other directions. The decline in strength varies between 20 and 50 MPa, and has a greater effect on yield strength than on ultimate tensile strength.

Hot-deformation studies

The present study also looked into the influence of deformation (strain) in the γ-recrystallization region (~1000°C, 1830°F) and of deformation in the γ-non-recrystallization region (~800°C, 1470°F). Strain rates of 5/sec simulated plate rolling, and strain rates of 20/sec simulated hot strip rolling, to study the effects of both on the austenite grain structure of a steel microalloyed with titanium and boron.

An optical micrograph of the steel austenitized at 1200°C (2200°F) and ice-water quenched, revealed packets of lath martensite within prior austenite grains. The average starting austenite grain size was estimated to be 125 µm. Simulated plate rolling involved deformation at 1000°C (1830°F), and produced elongation of 33% and a strain rate of 5/sec. This was followed by ice water quenching (Fig. 4a), and resulted in a finer austenite grain size of ~60 µm. A change in the cooling rate from ice-water quenching to air cooling resulted in the formation of a typical acicular ferrite structure (Fig. 4b).

The microstructural changes during simulated hot strip rolling in the γ-recrystallization zone was found to be similar to that observed for plate rolling. In this steel, elongation was 33% and the strain rate was 20/sec. The austenite grain size after deformation at 1000°C (1830°F) followed by ice-water quenching was estimated to be 53 µm. A change in cooling rate from water quenching to air cooling also led to an acicular ferrite structure.

It is of interest to note the nature of the flow stress curves of austenite under simulated plate rolling

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<th>Cast No.</th>
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<th>Tensile strength, MPa</th>
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<th>Yield strength, MPa</th>
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Specified property of pipes

448 min. 530 min. 20.5 min.
at a strain rate of 5/sec, and hot strip rolling at a strain rate of 20/sec. Fig. 5 represents the true stress-true strain curve of austenite from double-hit experiments. The graph shows that in curve (a), a specimen austenitized at 1200°C exhibits first-stage deformation of 33% (at 1000°C) when the strain rate is 5/sec. This is followed by second stage deformation of 50% (at 800°C) at a 20/sec strain rate to simulate hot strip rolling.

Simulated hot strip rolling led to higher flow stress values of austenite as compared to that for simulated plate rolling. This is expected to result in higher strength levels for hot strip products than for plate products deformed under identical conditions. Moreover, the flow stress curves exhibit continuous work-hardening of the austenite with increasing strain. It may be inferred that the dominant restoration process associated with hot deformation of austenite under the above conditions is dynamic recovery.

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How useful did you find the information presented in this article?

Very useful, Circle 451
Of general interest, Circle 452
Not useful, Circle 453