Advanced cooling technologies for high-strength plate production

To produce the extremely high cooling rates necessary for the evolution of mechanical properties of high-strength plate steels, a combined laminar jet and spray nozzle design cooling facility is the most advanced tool available. Design, engineering, process control and operational aspects of modern cooling facilities are explained, together with the main metallurgical aspects of accelerated cooling and direct quenching. Typical plate applications are described.

Authors: Gerhard Horn, Roman Dehmel and Dirk Schmidt
SMS Siemag AG

The production of high-strength steel grades is a major trend in the heavy plate market. In particular, plate for shipbuilding and pipe grades are high-volume products in this sector, and a strong demand for these grades is expected in years to come. These applications are major drivers for the further development of plate technology, since high-strength plates have to combine increasing tensile strength with excellent toughness, good weldability and excellent flatness.

The production of high-strength line pipe and ship plate has implications for all aspects of a plate mill as the complete equipment, from the mill stands to the finishing line, has to be adapted to the special requirements of these grades. The cooling section, however, remains the main metallurgical tool in this process.

THERMO-MECHANICAL ROLLING OF PLATES
Hot rolling of heavy plate can be divided into two basic processes: conventional hot rolling and controlled rolling. In conventional hot rolling, the objective is to produce specified product dimensions with a minimum of rolling passes. Controlled rolling is an independent rolling procedure in which both the shaping and the temperatures during rolling are precisely controlled to achieve the desired high material strength and toughness properties.

The final pass in thermo-mechanical controlled rolling (TMCR or TM) is carried out within the non-recrystallising temperature range. The mechanical properties and the fine-grained microstructure are set with the subsequent water cooling of the shaped austenite structure.

In water cooling, two substantial cooling modes are distinguished: Accelerated Cooling (ACC) and Direct Quenching (DQ) (see Figure 1). When applying ACC, the cooling process starts at ~800°C and is stopped between 500 and 600°C. ACC improves the mechanical properties by refining the microstructure which consists mainly of fine-grained ferrite/pearlite (F/P), ferrite/bainite (F/B), or of a fully bainitic structure.

For DQ, the plates are cooled as rapidly as possible. The starting temperature for cooling is ~900°C and the cooling stop temperature is below 250°C. DQ plates usually show a bainite and/or martensite (M) microstructure depending on the chemical composition and the cooling stop temperature. They have high hardness and are commonly used for structural components exposed to high mechanical stress and/or heavy abrasion.

In addition to the stop temperature, the cooling rate is the main influencing factor in plate cooling. Cooling rates are determined as the relation between temperature (entry – exit) and the cooling time. The cooling time is the dwell time in the active cooling section.
Laminar cooling and spray cooling systems

SMS Demag has developed two types of cooling system which can be used both for ACC and DQ. In laminar cooling systems, water is applied by a large number of U-tubes arranged in four or six rows per header (see Figure 5). As well as being capable of operating in both cooling modes, its chief advantages are its simple design, low energy consumption and low maintenance costs. The laminar cooling system is the most frequently used cooling equipment in heavy plate mills worldwide.

In recent years, SMS Demag developed a spray cooling system that is able to cool ultra-thick and ultra-thin plates at high cooling rates, while at the same time achieving increasing cooling rates achieved by ACC refine the microstructure of the plate and improve its strength. Figure 2 shows examples from an X65 line pipe steel (0.04% C, 1.4% Mn, 0.04% Nb).

The strengthening by ACC is due to three factors: enhanced ferrite grain refinement, precipitation hardening and strengthening by bainite formation. However, the mechanisms are different for yield strength and tensile strength. The increase in yield strength is due to ferrite refinement and precipitation hardening, whereas that of tensile strength is mainly the result of bainite strengthening.

Figure 3 shows the typical microstructure development for increasing cooling rates in DQ mode of an abrasion-resistant 400 HV10 steel grade (0.15% C, 1.4% Mn, 0.04% Nb). Air cooling of these steel grades leads to an F/P microstructure with some martensite islands and a hardness of 220 HV10 (corresponding to a tensile strength of ~740 N/mm²). Medium cooling rates yield a bainite microstructure showing a hardness of about 290 HV10 (~940 N/mm² tensile strength). A fully martensite structure with a hardness of about 1300 HV10 (~1300 N/mm² tensile strength).

The maximum cooling rate is, however, defined and limited by the thermal conductivity in the plate. Particularly in the case of thicker plates, the maximum cooling rate in the plate core is distinctly lower than at its surface (see Figure 4). Different cooling rates through the thickness of the plate lead to various layers of material properties. Plates with high ductility in the plate core and a wear-resistant surface are utilised, for instance, in bent components, such as the extension arm of a mobile crane.

Increasing cooling rates achieved by ACC refine the microstructure of the plate and improve its strength. Figure 2 shows examples from an X65 line pipe steel (0.04% C, 1.4% Mn, 0.04% Nb).

The strengthening by ACC is due to three factors: enhanced ferrite grain refinement, precipitation hardening and strengthening by bainite formation. However, the mechanisms are different for yield strength and tensile strength. The increase in yield strength is due to ferrite refinement and precipitation hardening, whereas that of tensile strength is mainly the result of bainite strengthening.

Figure 3 shows the typical microstructure development for increasing cooling rates in DQ mode of an abrasion-resistant 400 HV10 steel grade (0.15% C, 1.4% Mn, 0.04% Nb). Air cooling of these steel grades leads to an F/P microstructure with some martensite islands and a hardness of 220 HV10 (corresponding to a tensile strength of ~740 N/mm²). Medium cooling rates yield a bainite microstructure showing a hardness of about 290 HV10 (~940 N/mm² tensile strength). A fully martensite structure with a hardness of about 1300 HV10 (~1300 N/mm² tensile strength).

The maximum cooling rate is, however, defined and limited by the thermal conductivity in the plate. Particularly in the case of thicker plates, the maximum cooling rate in the plate core is distinctly lower than at its surface (see Figure 4). Different cooling rates through the thickness of the plate lead to various layers of material properties. Plates with high ductility in the plate core and a wear-resistant surface are utilised, for instance, in bent components, such as the extension arm of a mobile crane.
good flatness (see Figure 5). The spray cooling system is based on the combination of high water pressure (up to 5 bar) and pinch rolls between the spray cooling headers. The pinch rolls control the water flow on the plate, thereby improving the temperature distribution and the cooling efficiency. Plate guidance between the pinch rolls also contributes to uniform heat distribution over the plate surface and hence to better flatness. To prevent any out-of-flatness of the material from impairing the cooling effect, a pre-leveler may be installed in the entry section.

Combined spray and laminar cooling system In practical applications the two systems are combined, with the spray cooling system installed in front of the laminar section. Plate mill owners who strive for a product mix with a high proportion of thermo-mechanically rolled plate are increasingly investing in this type of equipment as both cooling sections can be used, in combination or separately, and thus offer a wide range of applications. The combined mode is used mostly for ACC and DQ of very thin, thick and wide plates. Such a combined system was first installed in 2005 at Baosteel's new 5m heavy plate mill (see Figure 6).

Since then it has been applied in several greenfield plants. When the laminar cooling equipment is installed the foundations and the space for future extension with a spray cooling system are already provided. The spray cooling system can also be added to an existing laminar cooling system in the course of a revamp. Such a revamp was implemented at our Finish customer, Rautaruukki who, thanks to this measure, could expand its program of high-strength and abrasion-resistant plates.

Cooling Control Equipment Water flow, quantity and distribution for each cooling header or each spray nozzle header is controlled individually and adjusted individually for each plate. The control loop consists of a control valve and a flow meter.

In order to attain the required cooling parameters, the availability of a good material tracking system is of utmost importance. To achieve precise control of the plate position, different sensors and controls are required, so for the tracking system, hot metal detectors, light barriers, pyrometers and pulse generators are installed before, within and after the cooling section. Several synchro points assure precise tracking directly inside the cooling system. This total package ensures very good tracking accuracy, which is the basis for plate head and tail-end masking and excellent cooling results.

Cooling model The cooling process itself is controlled by our cooling model and has to fulfill two major functions. First, it changes the microstructure of the material in a temperature range in which the steel passes through very different phases. This requires exact knowledge of transition kinetics. Second, the cooling rate has to be adjusted during cooling and the temperature difference existing between plate head-end and tail-end has to be compensated for.

The basic challenge in plate cooling is knowing the exact temperature distribution within the plate. The SMS Demag mathematical-physical cooling model – which is based on extensive experience in the design and manufacture of equipment, research investigations and feedback from many
FORMING PROCESSES

lower carbon steels, reduces the need for post-weld heat treatment and hence reduces cost. Another favourable aspect is that for a given wall thickness the pressure of the medium conveyed can be higher, which increases the capacity of the pipe line.

For pipe line applications, X100 and X120 grades with wall thicknesses of about 25.4mm have already been developed. For offshore projects, thicker, high-strength structural steel grades will be required, eg, S500 with wall thicknesses up to 80mm. All SMS Siemag cooling systems cover the complete range of cooling strategies for the production of line pipe, ship plate and other high-strength grades, thus customers will be able to meet these requirements. Current users of the technology include Baosteel, Tangshan, Anshan, MMK, OMK, Rautaruukki and ThyssenKrupp.

Gerhard Horn is General Manager, Technical Sales, Hot Rolling Mills, Roman Dehmel is Senior Specialist, Order Execution Hot/Cold Rolling Mills and Dirk Schmidt is Manager Technical Sales, Hot Rolling Mills, all at SMS Siemag AG, Düsseldorf, Germany.

CONTACT: Thilo.Sagermann@SMS-Group.com

RESULTS

Flatness The precise masking of head and tail ends is of particular importance for the metallurgical and geometrical quality of the processed plates. To illustrate the influence of exact head and tail-end masking which is implemented in our cooling model, a simulation of the cooling of an X70, 12.7mm thick plate was conducted. The start disturbance in the simulation was an uneven temperature distribution at the head-end of the plate where the temperature dropped by as much as 100°C within a length of 1m. For all other parts of the plate, uniform temperature distribution over the width and the length was simulated. The plate was cooled from 800°C to 500°C at a rate of 80K/s. The results in the simulation were flatness deviations of up to 160mm (see Figure 7).

Development of new pipe grades In 2002, SMS Demag built a new laminar cooling system including a cooling model for Voestalpine Grobblech GmbH in Linz, Austria. The main details are shown in Table 1.

With the new cooling system, Voestalpine Grobblech has succeeded in extending its range of high-strength low alloy grades and also to produce hardened steel plates. In tests for product development, pipe grades of X100 and X140 were produced successfully.

Microstructures of these grades are shown in Figure 8.

CONCLUSIONS

The ongoing development of the material properties of high-strength plate is of major importance to plate customers. For pipe grades, the major benefit of increasing yield strength is the possibility to reduce the wall thickness, which reduces the weight of a structure. The improved weldability, which arises from the ability to use...