INDUSTRY APPLICATIONS AND PRODUCTS OF THE NEW GENERATION TMCP *

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Abstract
To meet the requirements of high-performance steel plates, while reducing manufacturing costs and saving energy, the advanced cooling system for plate mill (ADCOS-PM) with functions of accelerated cooling (ACC), ultra-fast cooling (UFC), and direct quenching (DQ) was researched and developed by the State Key Laboratory of Rolling and Automation (RAL). Since 2003, several sets of ADCOS-PM device were developed and implemented in industrial practice. To fully utilize the ADCOS-PM technology, the combination of various strengthening mechanisms was promoted by NG-TMCP technology and low-cost, high performance plates were produced such as pipeline steels, and high-strength construction machinery steel.
Keywords: Ultra fast cooling; New generation TMCP; Steel plate; High performance

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1 INTRODUCTION

The TMCP technology has been widely used for steel production because of its significance in the development and production of high-performance steels [1-4]. Since the beginning of the 21st century, attention has been paid to ultra-fast cooling technology [5-7]. The State Key Laboratory of Rolling and Automation (RAL) of Northeastern University has made significant progress in terms of microstructure control, strengthening mechanisms, and industrial applications [8,9]. Several sets of ADCOS-PM equipment were developed and installed in industries. Making full use of the ADCOS-PM technology, the on-line heat treatment technology was greatly improved, the combination of various strengthening mechanisms in steels were promoted by NG-TMCP technology, and the low-cost, high performance plates were produced such as pipeline steels, and high-strength construction machinery steels.

2 TECHNICAL FEATURES OF ADCOS-PM

The first ADCOS-PM system was installed in Jingye (in Hebei province) for production of plates. Until now, seven sets of ADCOS-PM system have been installed domestically at Qinhuangdao Shouqin Metal Material Co., Ltd. (Figure 1), Anshan Iron and Steel Group Corporation, and Nanjing Iron and Steel Co. Ltd (NISCO) as shown in Figure 2.

Figure. 1 ADCOS-PM Equipment in Shouqin 4300 mm medium plate factory

Figure. 2 ADCOS-PM Equipment in NISCO 2800 mm medium plate factory

To systematically describe the technical features of the ADCOS-PM, the system of NISCO 2800 mm product line is described in detail. In 2012, combining with the pre-leveler equipment, a new set of ADCOS-PM equipment using jet impingement heat transfer technology with high cooling capacity, continuous adjustment of cooling intensity over a large range and uniform cooling performance was employed in NISCO 2800 mm medium plate factory. The technology process is shown in Figure 3. The major equipment consists of furnace, roughing mill, finishing mill, pre-leveler, ADCOS-PM and hot leveler etc. The distance between the finishing mill and the pre-leveler is 57 m, the distance between the pre-leveler and the ADCOS-PM is 4 m, and the distance between the ADCOS-PM and the hot leveler is 50 m. The length of the ADCOS-PM is 18 group headers including 2 group slit nozzles and 16 group high density cooling nozzles.

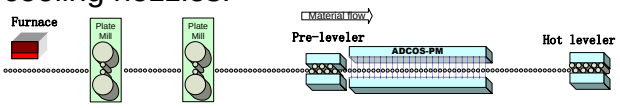

Figure 3. The technology process of some medium plate factory.

To enhance the heat exchange efficiency and improve uniformity during the cooling, the inclined jet impingement cooling technology was adapted instead of the traditional laminar cooling technology in the ADCOS-PM system. As illustrated in Fig. 4, the flow of the jet impingement heat transfer is divided into two distinct regions, a stagnation region and a wall jet region [10-12]. The thickness between flow boundary layer and heat boundary layer

becomes thin in the stagnation region, where the strong efficiency of heat transfer and mass transfer exists. In the wall jet region, the turbulence between wall jet and surrounding air is transferred to the boundary layer of heat transfer surface, as a result the heat transfer efficiency in the wall jet region is higher than the efficiency in the parallel flow region. This results in high cooling intensity and good cooling uniformity is obtained in the jet impingement cooling method [13-15].

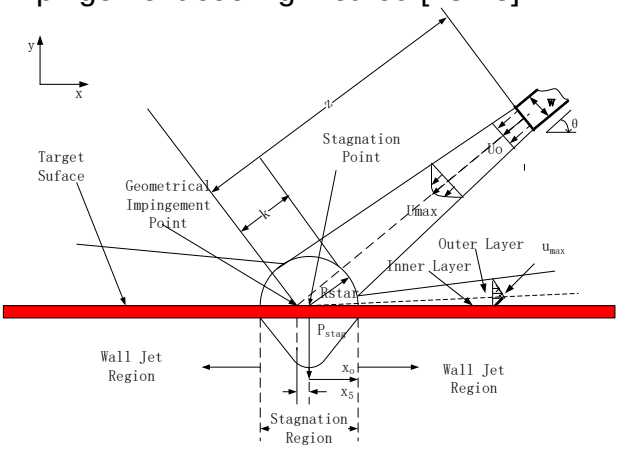

Figure 4. The sketch of jet impingement heat transfer process

Based on the inclined jet impingement heat transfer principle, the slit nozzle with high velocity flow evenly distributed along the width direction and small-caliber staggered arranged jets were designed for the ADCOS-PM system (Figures 5 and 6). The gap width of slit nozzle is in the range of 1.5-3.0 mm, and the inclined angle is 30-60°. The jet diameter of the high density cooling nozzle is 3-5 mm, the distance between adjacent jets is 40-50 mm, and the inclined angle of nozzle is 30-60°. The flux adjustment range of slit nozzle is 300-2300 $l/m^2 \cdot min^{-1}$ and is controlled by the water pressure (0.2MPa - 0.5MPa continuous adjustment) and the control valve opening (0-100% continuous adjustment), and the flux adjustment range of high density cooling nozzle is 100-2100 $l/m^2 \cdot min^{-1}$. Under these conditions, the flux is kept in a good shape to break the vapor film adhering to the hot steel surface. Furthermore, the impact heat transfer zone and nuclear boiling heat transfer zone extends along the fluid direction outflow from the inclined nozzle, and the unstable film boiling and transition boiling heat transfer zone are restricted. The heat transfer between the high temperature steel surface and cooling water becomes homogeneous, and the heat transfer efficiency approaches theoretical limit for the designed water cooling conditions.

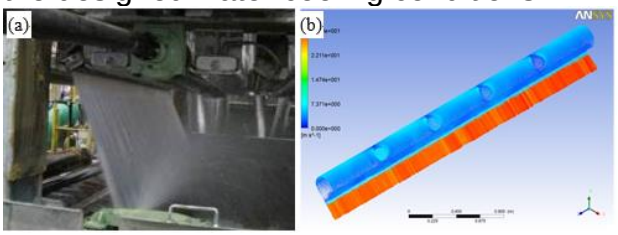

Figure 5. The spray and simulation picture of slit nozzle

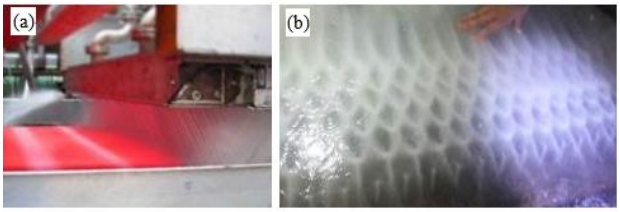

Figure 6. The spray picture of the high-density cooling nozzle

The instantaneous cooling adjustment ability covers almost all of water cooling ability from air cooling to ultra-fast cooling, including soft cooling such as mist cooling, accelerated cooling such as spray cooling, laminar cooling and ultra-fast cooling such as jet impingement cooling. As illustrated in Figure 7, the maximum and minimum cooling rate of 10 mm plate are 120℃/s and 10℃/s respectively, and the maximum and minimum cooling rate of 50 mm plate are 10℃/s and 2℃/s respectively, which meets the cooling ability of different products.

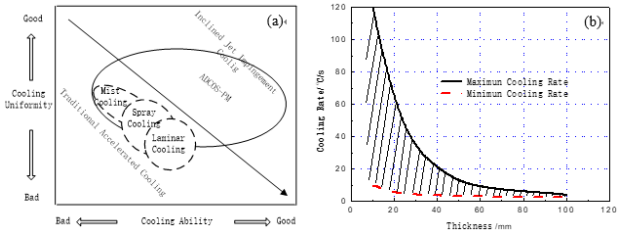

Figure 7. The adjustment range of cooling rate under ADCOS-PM

In wide steel plate cooling process, the temperature distribution along width direction especially near plate edges is

very important for properties and flatness of products. Therefore, the temperature distribution in the thickness and width direction should be considered by the online control model. High accuracy and quick response of control are the keys of industrial application [16]. ADCOS-PM can quantitatively control the temperature distribution through plate width by edge mask and water crown control, as shown in Figure 8. A pair of edge masks are driven by one motor to move along the plate width to prevent water cooling edges of plate. The water crown of one cooling header includes center flow and edge flow control respectively.

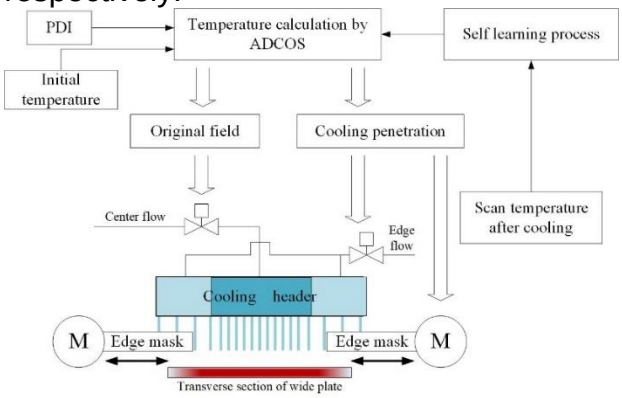

Figure 8. The method of wide-direction temperature control

The plate flatness in ultra-fast cooling is a critical problem for TMCP technology. To realize the homogeneous cooling process, the pre-leveler is arranged in front of the ADCOS-PM equipment to improve the original plate shape. Combined with the water retaining roller arrangement in the cooling zone, a series of control strategy was adopted to improve uniformity in cooling under the inclined jet impingement cooling condition. As a result, the cooling uniformity of integral and partial plate is vastly improved, and good flatness and surface quality of the controlled cooling plate are obtained (Figure 9).

Figure 9. Surface quality and flatness of the controlled cooling plate under ADCOS-PM technology

With characteristics of cooling rate large-range adjustment, accurate temperature control and cooling profile control, a variety of cooling practices including accelerated cooling (ACC), ultra-fast cooling (UFC), dual stage cooling (DC), direct quenching (DQ, UFC+M), direct quenching & partitioning (DQP), and interrupted direct quenching (IDQ) can be accomplished by ADCOS-PM system. A variety of products with the microstructure of ferrite/pearlite, bainite, bainite/martensite, and martensite can be obtained through phase transformation process controlled by ADCOS-PM system. The flexibility in on-line heat treatment technology is illustrated in Figure 10. Using new generation TMCP technology with UFC being the main feature, the strengthening mechanisms including precipitation strengthening, fine-grain strengthening, phase transformation strengthening are well developed.

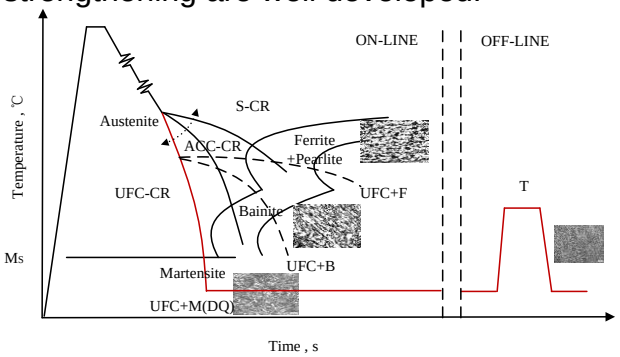

Figure 10. The flexibility on-line heat treatment technology by ADCOS-PM

3 NEW PRODUCTS MANUFACTURED BY ADCOS-PM

Based on the new generation TMCP technology, high strength low alloy steels with benefits of alloy reduction, value-added pipeline steel, and high-performance steel under the DQ (+T) technology were developed and successfully marketed by using ADCOS-PM system.

(1) High strength low alloy steels

For the case of high strength low alloy steel plates, the ADCOS-PM technology allows as to improve mechanical properties, save alloying element cost. For instance, Mn is reduced by about 20~30%, which means that the cost of Q345 reduces about ￥ 40~60 per ton. Comparing the microstructure of products made using different technology, product of grain size 11.5 produced by UFC technology is fine compared with the grain size 10 produced by ACC technology. Furthermore, a series of high-quality plates were developed using UFC technology such as Q370q, Q460q bridge steel, Q420GJ architectural construction steel, AH36 shipbuilding steel, and Q345R pressure vessel steel.

(2) Pipelines steels

Pipeline steel is a typical product to take the technical advantage of new generation TMCP technology, with properties of high strength, excellent low temperature toughness, good weldability, low yield ratio, or antacid H_2S. A series of steel products with good mechanical properties in the pipeline family such as X52MS, X65, X70 and X80 etc. were produced using new generation TMCP technology. The UFC technology combined with finish rolling at high temperature promoted the effect of fine grain strengthening mechanisms. Taking X70 for example, the microstructure is illustrated in Figure 11a, which consists of acicular ferrite (AF) of grain size about 12.5 to 13. In 18.4 mm, X80, fine acicular ferrite and less M/A were obtained (Figure 11b) with superior mechanical properties. As a result, elements, Mo, Cu, Cr are reduced or eliminated to reduce the product cost and improve product weldability.

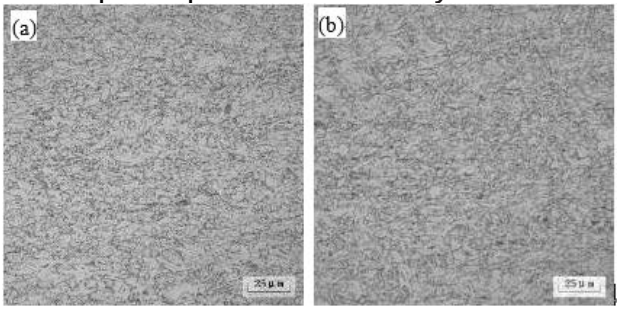

Figure 11. the microstructures of pipeline (a)X70, (b)X80

(3) High-strength Construction Machinery Steel

High-strength construction machinery steel represented by 25 mm thickness Q690D were developed through the new generation TMCP technology of direct quenching combined with tempering, and the chemical composition is listed in Table 1. During the controlled cooling process, the plate was cooled from 780℃ to 300℃ at a high cooling rate of 30℃/s to realize the direct quench technology. As illustrated in Table 2, the mechanical properties of the product met the standard requirements, which has excellent toughness at -20℃ together with high hardness and high ductility.

Table 1 Chemical elements content of the product

Chemical Content	C	Si	Mn	P	S	Ni+Cr+Nb+Mo
Mass Fraction /%	0.049	0.253	1.68	0.013	0.001	＜0.3

Table 2 Mechanical properties (hot rolled state) of the product

Grade	Thickness /mm	Properties	$Rt_{0.5}$ /MPa	Rm /MPa	A /%	A_{KV} /J (-20℃)
Q550	25	standerd	⩾530	670-830	⩾16	⩾47
Q690	25	standerd	⩾670	750-920	⩾14	⩾47
hot rolling	25	actural	782	915	19	226
Tempering	25	actural	763	796	20	223

The microstructure of the product consists of about 10% acicular ferrite, 30% granular bainite, and 60% lath bainite as shown in Figure 12a. The major tempered microstructure is sorbite as shown in Figure 12b. The grain boundary becomes indistinct, and there are many small precipitates in the vicinity. The typical hot-rolled upper bainite and precipitates in the vicinity of dislocations are shown in Figure 13. The existence of small precipitates hinders the movement of the dislocation and enables high strength to be obtained.

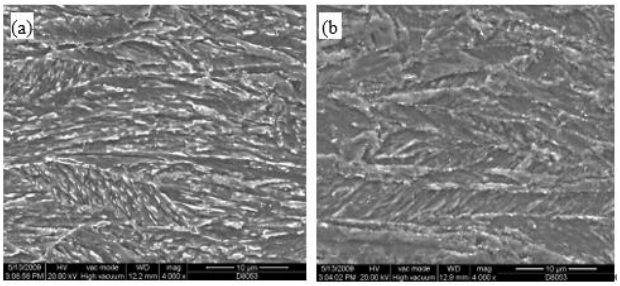

Figure 12. SEM of the product (a) hot rolling; (b) tempering

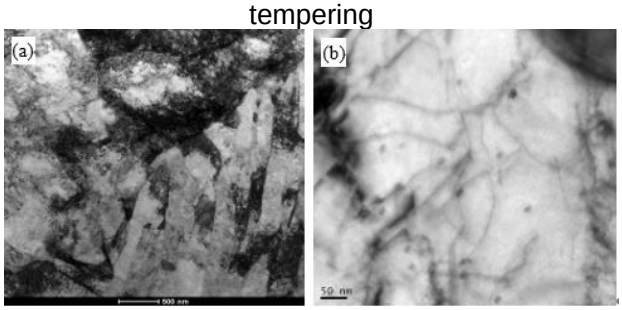

Figure 13. The microstructure of the product by TEM

(4) Oil Storage Tanks Steel

The traditional TMCP technology, offline quenching and tempering was usually adapted to produce oil storage tanks steel 610D with much expensive alloying element Mo, Ni. However, using ADCOS-PM system, the offline quenching was replaced by the direct quenching technology to reduce the cost of the production and improve the comprehensive mechanical properties. Figure 14 and Figure 15 show the microstructure of the 48mm 610D steel plate. The microstructure through the whole thickness is mainly composed of martensite and bainite after direct quenching and the tempering microstructure is in good uniformity. As shown in Table 3, the mechanical properties satisfy the standard well because that the direct quenching combined with controlled rolling contributes to improve mechanical properties of 610D. The high-density dislocations is formed during austenite recrystallization rolling process, and then the austenite concentrated rolling energy transforms phase into martensite and bainite with a large number of crystal defects during the direct quenching process which improved the mechanical properties of product. As a result, the expensive alloying elements Ni and Mo are reduced from 0.21% and 0.27% to 0.09% and 0.12% respectively.

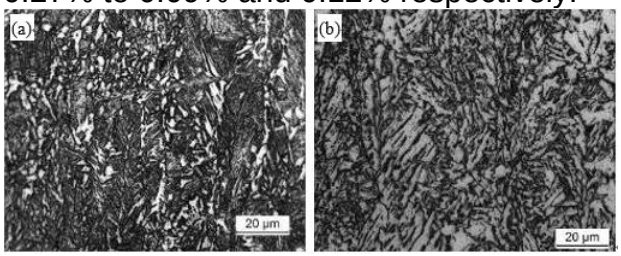

Figure 14. Microstructure of 610D after direct quenching (a) Surface, (b) Center

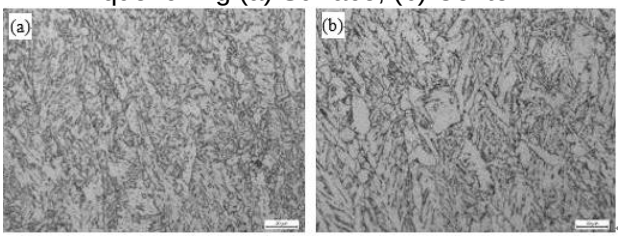

Figure 15. Microstructure of 610D after tempering (a) Surface, (b) Center

Table 3 Mechanical properties under DQ and T technology

Process	Steel Number	Thickness (mm)	YS (MPa)	TS (MPa)	A (%)	Cold-bending 180, d=3a	Impact Energy (-20℃) (J)		
DQ	610D	48	586	664	24	Qualified	330	340	350
Tempering	610D	48	559	656	25	Qualified	333	241	318

4 CONCLUSION

We have introduced the development and application of ADCOS-PM with characteristics of cooling rate adjustment, accurate high temperature control, and homogeneous cooling. The ADCOS-PM technology meets strict and more diverse requirements for new steel plates and broadens the product range. The products requiring high performance including high strength low alloy steels, pipeline steels, high-strength construction machinery steel were successfully produced.

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