

Development of High Strength, High Toughness Offshore Wind Turbine Steel Plates

WAN-LIN HSIEH*, JU-CHIN TANG** and PO-CHIH LIU*

*Metallurgical Department, China Steel Corporation

**Sing Da Marine Structure Corporation

Taiwan actively develops green renewable energy and plans to establish 5.5 GW offshore wind power generation capacity by 2025. China Steel Corporation is aligning with the national development strategy by researching and developing underwater steel foundations to localize the wind power industry. The steel plate specifications used for underwater foundations are mainly EN10025 S355ML, which are utilized for critical load-bearing structures. The quality of these steel plates requires high strength and impact toughness down to -40°C. The demand for steel plates is mostly for thicknesses above 60 mm. Consequently, it is necessary to overcome the problem of insufficient toughness in the central region caused by alloy segregation. Therefore, the composition is designed with low carbon, extremely low phosphorus, and sulfur content to reduce columnar crystal segregation during continuous casting using electromagnetic stirring. Furthermore, the rolling and holding thickness is increased to refine the grain size by enhancing the reduction rate. Additionally, the Extended Accelerated Control Cooling (EACC) composite cooling control technology has been successfully developed. This technology precisely controls the cooling rate to ensure uniform cooling of the steel plates, thereby improving low-temperature impact toughness and ensuring a stable supply of high-quality steel plates for the wind power industry.

Keywords: Offshore Steel, S355ML, ZRA, Impact Toughness, EACC

1. INTRODUCTION

In response to the energy transition policy, the Taiwanese government is actively working towards establishing a green supply chain. One of the significant initiatives in this endeavor is the "Thousand Wind Turbines Project", which received approval in 2012. This ambitious plan aims to construct more than 600 offshore wind turbines by 2030, capitalizing on Taiwan's favorable wind conditions in the Taiwan Strait.

To support these offshore wind turbines, robust underwater supporting structures are crucial, especially for water depths of up to 50 meters. Steel has emerged as a popular material choice for this purpose. The underwater foundations are typically designed to reach a height of 80 meters and weigh around 1200 metric tons. The predominant steel grade used for critical heavy-duty components is S355ML. However, the manufacturing of offshore steel to meet the stringent requirements poses several challenges.

2. QUALITY CRITERIA

2.1 Demands of Offshore Steel

Manufacturing offshore steel for wind turbines in

Taiwan presents several challenges. Firstly, turbines are continuously growing in size, and weight reduction is necessary to cut costs. This trend creates a demand for high-strength steel.

Secondly, wind farms in the region are exposed to not only wind and ocean currents but also the constant threat of powerful earthquakes. Being located in the Circum-Pacific seismic belt, Taiwan experiences over 40,000 earthquakes annually. Moreover, the expected operational lifetime of offshore wind turbines must exceed 25 years. Hence, there is a critical need for steel with exceptional impact toughness.

Thirdly, in line with the government's goal of achieving a wind power capacity of 5.5GW by 2025 to replace nuclear power with renewable energy, wind farm projects are rapidly increasing. This acceleration in construction leaves less time for building and less tolerance for repairs. Consequently, there is a growing demand for steel with superior weldability and anti-lamellar properties as well.

2.2. Quality Requirements

Offshore wind turbines are composed of fans, towers, and underwater foundations. The underwater foundations are generally divided into two categories:

jacket type and monopile type. The jacket type accounts for 74% of the total and its structure is shown in Figure 1. Its underwater foundation is designed with a lattice framework, featuring three sea bed anchoring points. Steel jacket support structures have gained popularity for water depths exceeding 20 meters. One of the key benefits of this structure is its ability to reduce the base shear force, thereby enhancing safety, which is particularly crucial for earthquake-prone areas like Taiwan. With a height of approximately 80 meters and weighing around 1200 metric tons per set, this structure constitutes 66% of the entire wind turbine assembly.

The steel grade primarily used for crucial heavy-duty components is S355ML, conforming to the EN 10025-4 standard as shown in Table 1. China Steel Corporation (CSC) has optimized the carbon equivalent content, lowering it to 0.35%, compared to the original standard's 0.40%. This adjustment improves the weldability during construction, ensuring a robust and reliable connection between components.

Furthermore, CSC has raised the lower limit of impact resistance from 20J to 50J, setting a stricter specification than the original standard. This measure is implemented to guarantee the exceptional reliability and performance of the components, reinforcing the overall

structural integrity of the underwater foundation.

3. DEVELOPMENT OF OFFSHORE STEEL

3.1 Chemical Composition

To meet the requirements of high strength, excellent low-temperature toughness, and superior welding performance, the steel plate's composition is carefully designed. This involves reducing the carbon content to lower carbon equivalency and enhance welding efficiency. Microalloys containing niobium (Nb), vanadium (V), and titanium (Ti) are added to improve both strength and toughness. Moreover, stringent control over phosphorus (P) and sulfur (S) levels ensures the avoidance of detrimental inclusions.

3.2 Rolling Process

Grain refinement plays a crucial role in enhancing strength and toughness properties. To achieve a finer structure, the holding thickness is increased during the rolling process. Consequently, a high reduction ratio is applied during the finish milling stage, leading to an increase in dislocation density and storing strain energy in the grains. Additionally, precise control of the finish rolling temperature inhibits grain growth at elevated temperatures. This accumulation of dislocations and

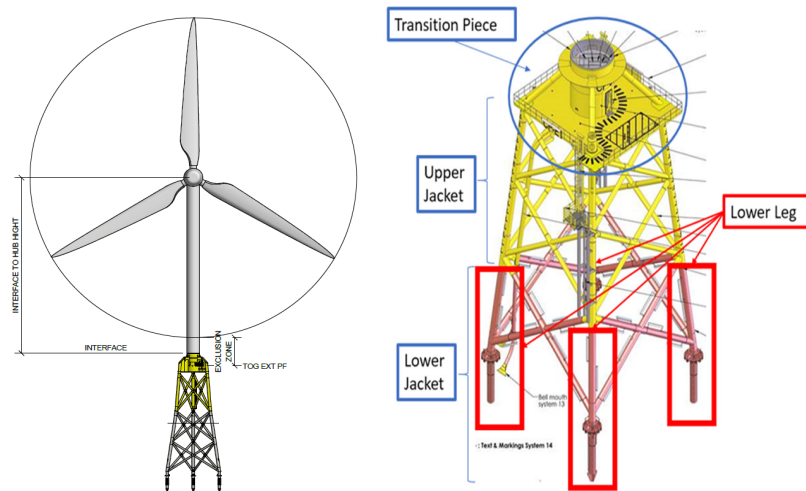


Fig.1. Design of jacket structures (a) whole view (b) jacket type (Ref: SDMS Corp.).

Table 1 Mechanical Properties for EN10025-4 S355ML.

Thickness (mm)	Carbon Equivalency	YS (MPa)	TS (MPa)	EL (%)	RA in through-thickness direction (%)	Temp -40°C Charpy V-notch Impact energy (J)
EN10025-4 Standard	≤ 0.40	335	450 ~ 600	22	Individual ≥ 25 Average ≥ 35	Longitudinal ≥ 31 Transverse ≥ 20
Customer Specifications	≤ 0.35	335	450 ~ 600	22	Individual ≥ 25 Average ≥ 35	Longitudinal ≥ 50 Transverse ≥ 50

deformed grains creates more nucleation sites, ultimately resulting in the refinement of the bainite microstructure after phase transformation.

3.3 Cooling Control

To achieve a fine, uniform, and granular bainite structure, the steel plates undergo thermomechanical control during rolling. An innovative compound cooling system called EACC (Extended Accelerated Cooling) is employed, which combines Directed Quenched (DQ) and Accelerated Cooling (ACC) in consecutive cooling processes. EACC ensures precise cooling rates and finish cooling temperatures. By adopting EACC, not only does grain coarsening get minimized, but the formation of the hard and brittle Martensite-Austenite (M/A) constituent is also prevented, resulting in significant improvements in both strength and toughness.

4. RESULTS AND DISCUSSION

4.1 Impact Toughness Improvement with Varying Holding Thickness

In pursuit of enhancing the impact toughness of steel plates for wind power structures, trial production was conducted, yielding distinct outcomes for Groups A and B. As shown in Table 2, Group B, featuring a higher holding thickness, exhibited superior impact toughness, averaging 250J, while Group A, with a lower holding thickness, only achieved 110J on average. The relation between different holding thicknesses and impact values is shown in Figure 2.

The increased holding thickness results in a higher finish reduction ratio, which significantly and consistently enhances the impact toughness of the steel plates. This improvement occurs because the finish rolling takes place below the recrystallization temperature, preventing the growth of austenite grains. Instead, it promotes grain refinement through an increase in nucleation sites induced by higher sub-grain boundary density or slip zones generated from sufficient strain energy during rolling. As a consequence, the toughness at the center of the plate experiences a notable enhancement. Furthermore, with a further increase in holding thickness, the effect of grain refinement becomes more pronounced.

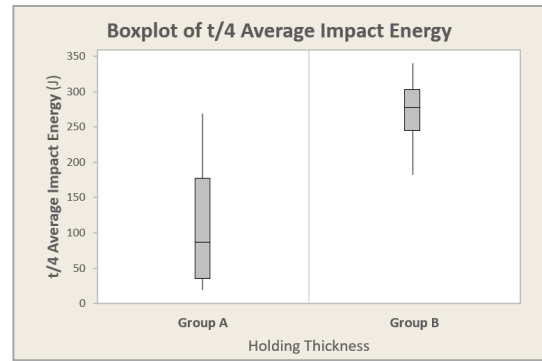


Fig.2. The relation between holding thickness and impact toughness (a) Group A with lower holding thickness; (b) Group B with higher holding thickness.

Metallographic observation, as depicted in Figure 3, confirms the evident effect of grain refinement with an increase in holding thickness. This substantiates the positive impact of grain refinement on the steel's properties. Consequently, ultra-wide and thick steel plates are produced from wider and thicker slabs, ensuring sufficient finish reduction to optimize the impact toughness of the final product.

4.2. Influence of Carbon Content on Mechanical Properties

After increasing the holding thickness, some discrete low-impact values were still observed. Further analysis revealed that the presence of M/A constituents in the structure was responsible for reducing the impact toughness, particularly at low temperatures. To address this issue, the carbon content was reduced, successfully eliminating the formation of the hard and brittle structure, as shown in Figure 4. The mechanical test results, displayed in Table 3, demonstrate that the tensile and reduction of area in through-thickness direction properties remain consistent with the original level and meet the specification requirements. Additionally, the impact toughness has shown an average increase of approximately 30J, signifying a significant improvement in the material's performance.

Table 2 Mechanical difference in holding thickness of heavy plates.

Group	Holding Thickness	Tensile Test			RA in through-thickness direction (%)	Temp -40°C Charpy Impact Energy (J)	
		TS (MPa)	YS (MPa)	EL (%)		Longitudinal	Transverse
Group A (Control)	Low	514	380	26	67	136	85
Group B (Test)	High	499	394	28	66	264	252

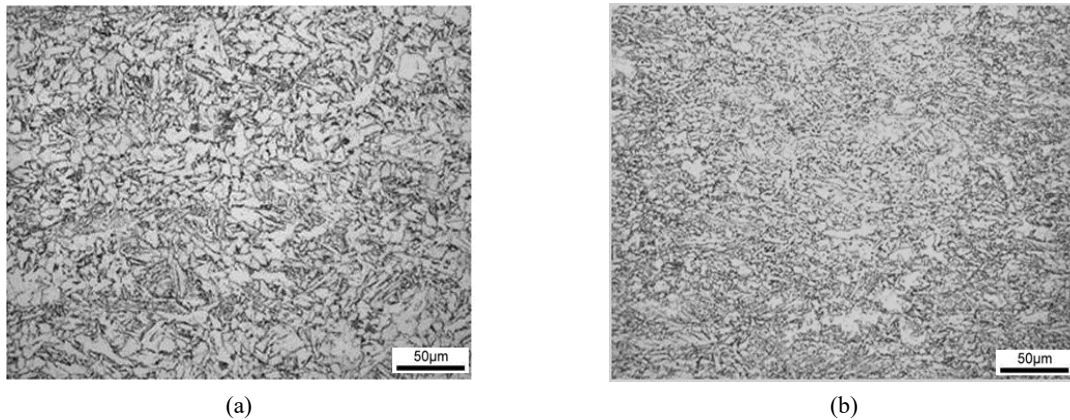


Fig.3. Grain size of holding thickness in (a) Group A (b) Group B.

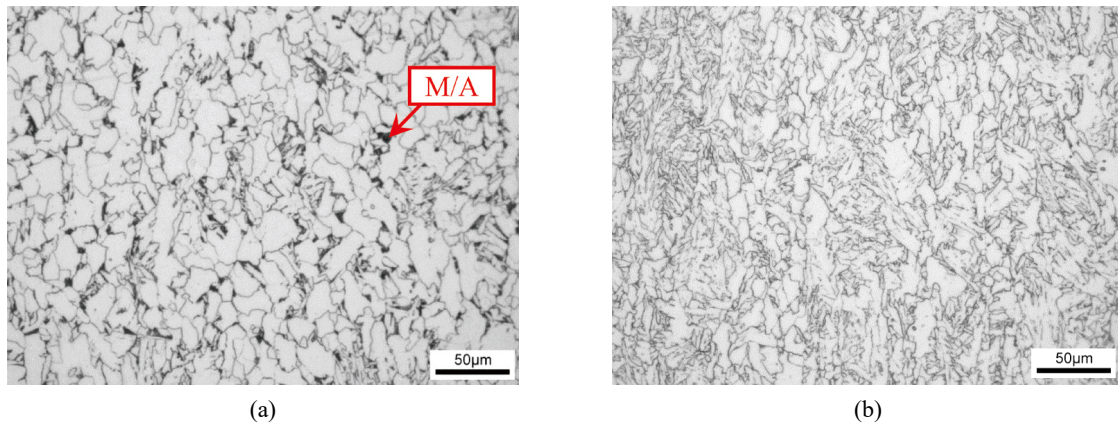


Fig.4. Grain Structure of (a) Original (b) Low Carbon Content.

Table 3 Mechanical properties of a heavy plate in different carbon content.

Content	Tensile Test			RA in through-thickness direction (%)	Temp -40°C Charpy Impact Energy (J)	
	TS (MPa)	YS (MPa)	EL (%)		Longitudinal	Transverse
Original	499	394	28	66	264	252
Low Carbon	495	387	31	71	299	285

4.3 Influence of EACC Technology on Mechanical Properties

The EACC compound system integrates DQ and ACC cooling equipment. When plates are produced using ACC, the plate edges receive excessive water, leading to over-cooling due to entrained water caused by laminar flow cooling over the edges on the top side of the plate. In contrast, DQ equipment employs a water crown repartition, directing a larger water flow towards the center part of the plate and a smaller flow towards the edges. Therefore, it achieves a better water flow balance in the lateral direction and contributes to a more

favorable temperature profile, as shown in Figure 5.

In ACC, the head and tail of the plate experience uneven cooling in the lengthwise direction due to mismatches in the control of water opening and closing. This can result in water splashing from the bottom sprayer to the top side of the plate if the sprayers are opened too early. To address this, the end masking technology from DQ is employed to compensate for the temperature loss at the ends, ensuring lengthwise homogeneity of temperature.

EACC's key advantages lie in its uniform temperature distribution and its ability to control the cooling rate over a wider range, which enables precise attainment of

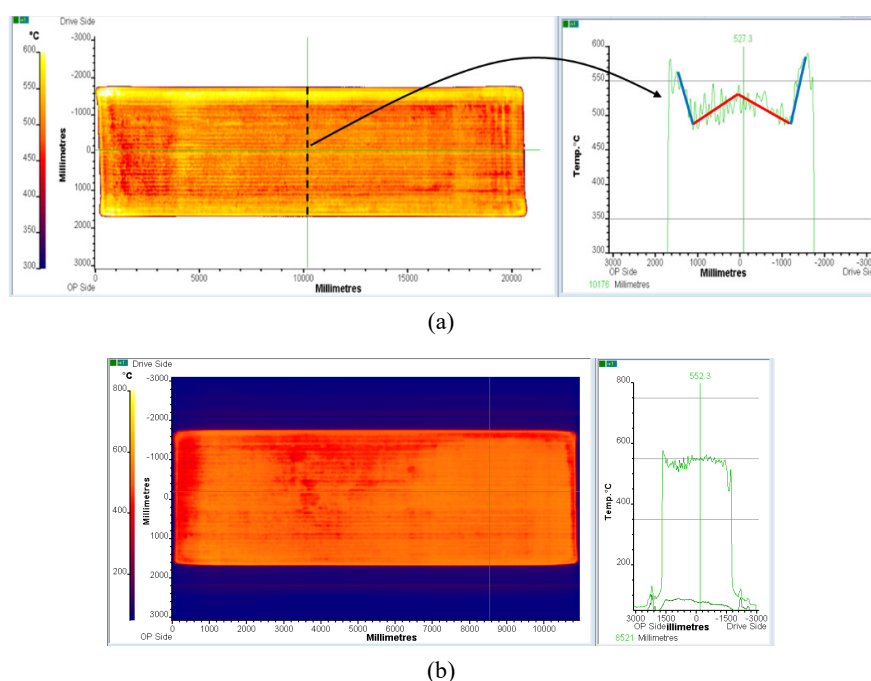


Fig.5. Temperature profile in following cooling process (a) ACC (b) EACC.

the critical cooling rate and desired finish cooling temperature. This prevents the formation of the M/A phase caused by partial over-cooling, subsequently preserving both strength and fracture toughness at low temperatures. Additionally, EACC leads to minimal temperature differences between the plate ends and the body, ensuring stable mechanical quality and flatness.

4.4. Quality Improvement

It is observed that the rejection rate increased with the rise in plate thickness. However, through the implementation of various methods, such as increasing the holding thickness, reducing the carbon content, and adopting the EACC cooling system during production, significant progress was achieved in quality enhancement.

As a result of these measures, the defect rate of heavy plates was reduced dramatically, declining from 83% to 0%. Moreover, the longitudinal impact value saw a substantial improvement, increasing from 85J to 298J. This marked a notable advancement in the overall impact toughness performance of the plates.

5. CONCLUSIONS

CSC has achieved successful development of the S355ML steel grade through a series of strategic implementations. Firstly, the composition design was optimized by reducing the carbon content and carefully controlling the levels of phosphorus and sulfur to minimize segregation in the middle of the slab. This approach ensures a more homogeneous composition

throughout the material.

Secondly, significant improvements were made in the rolling process by increasing the holding thickness, which resulted in a higher finish reduction ratio. This grain refinement technique led to a notable enhancement in impact toughness, contributing to the overall performance of the steel.

Moreover, CSC adopted the innovative EACC compound cooling process to precisely control the cooling rate during production. By effectively managing the cooling process, the formation of undesirable M/A constituents was prevented, thereby safeguarding the strength and toughness at low temperatures. The uniform cooling provided by EACC also played a vital role in enhancing the mechanical consistency and flatness of the entire plate.

These advancements have had a substantial positive impact on quality enhancement and increased production capacity in the manufacturing of offshore steel, positioning CSC at the forefront of steelmaking technology and further solidifying its position in the industry.

REFERENCES

1. M. C. Wu; Lo, W. Lo, K. F. Chien et al.: Improvement of TMCP Steel Plate Production and Accelerated Cooling Process in CSC Plate Mill, Technology and Training, 2022, vol. 47, pp. 30-38 (In Chinese)
2. J. C. Tang: Improving the qualification rate of wind power steel plates, Six Sigma Technical Report, 2021 (In Chinese).