MANUFACTURING TECHNOLOGY OF HIGH STRENGTH, HIGH TOUGHNESS OFFSHORE WIND POWER STRUCTURAL STEEL PLATES

BY

WAN-LIN HSIEH*[1], JU-CHIN TANG*[2], PO-CHIH LIU*[1]

SYNOPSIS

Taiwan is proactively establishing renewable power sources, and the goal is to raise its offshore wind power capacity to 5.5 GW by 2025. To fulfill the national development strategy, China Steel Corp. (CSC) developed offshore structure steel plate to implement the localization of the wind power industry. The steel grade is mainly EN10025 S355ML, which is used for crucial heavy-duty components. The quality characteristics require high strength and extremely low temperature impact toughness at -40°C. Due to the demand of the plates is mostly over 60 mm in thickness, the insufficiency of core toughness caused by segregation should be overcome. Therefore, the composition is designed with low carbon, extremely low phosphorus and sulfur. Electromagnetic stirring is applied in continuous casting to reduce columnar crystal segregation, and holding thickness is increased to approach grain refinement. Additionally, by the research and development of EACC (Extended Accelerated Control Cooling) compound cooling control technology, the cooling rate is precisely controlled so that the steel plate could be cooled evenly, thus enhancing impact toughness, and stably supplying high-quality steel plates for the wind power industry.

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

*Engineer, [1]Metallurgical Department, China Steel Corporation, [2]Sing Da Marine Structure, Kaohsiung, Taiwan

1. Introduction

In response to the policy of energy transformation, Taiwan's government is proactively establishing a green supply chain. The Ministry of Economic Affairs plans to build an offshore wind power capacity target of 5.5GW in 2025. The underwater foundation is one of three key components of offshore wind turbines with height up to 80 meters and weight about 1200 metric tons. The steel grade is mainly EN-10025 S355ML, which is used for crucial heavy-duty components. China Steel Corp.(CSC) designed the S355ML steel plate with low carbon, low phosphorus and sulfur, and micro-alloy. After implementing TMCP process, the microstructure of granular bainite is obtained, and multiple performances including high strength, high toughness, and excellent weldability could be achieved. However, due to the limitation of steel slab thickness in production, as the plate thickness increases, the reduction ratio becomes relatively low. It may lead to instability in impact toughness and reduction of area in through-thickness direction(ZRA), and thus bring a major challenge for development.

2. Quality Criteria

2.1. Underwater Foundation Structure

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 about 74%, and its structure is shown as Figure 1. The weight is about 1200 metric tons each.

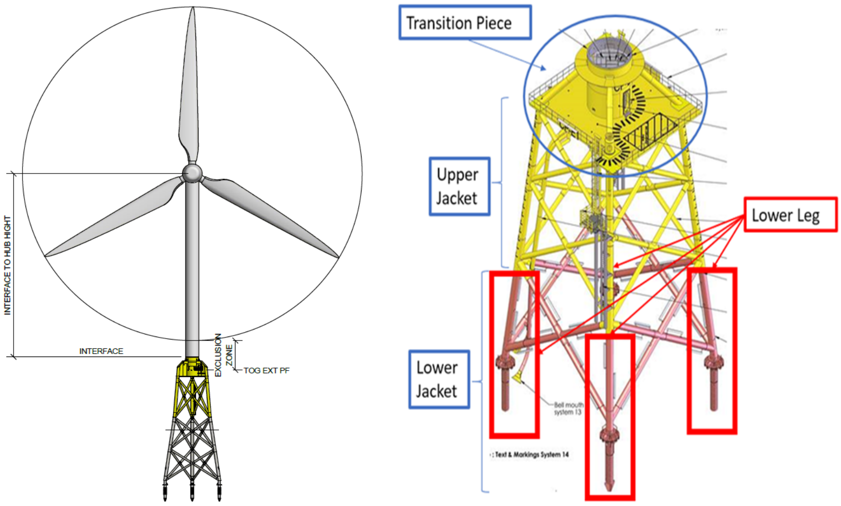


Figure 1. Design of jacket structures (a) whole view (b) jacket type (Ref: SDMS Corp.)

2.2. Quality Requirements

The expected lifetime of offshore wind turbines must exceed 25 years. However, due to the nature of the environment in Taiwan, which is usually struck by earthquakes, ocean currents and typhoons, the steel plates for underwater infrastructure must meet the quality characteristics of high strength and high impact toughness at temperature of -40°C. The quality of reduction of area in through-thickness direction is also required. In addition, as shown in Table 1, CSC sets the lower limit of impact resistance from 35J to 50J as the development goal which is stricter than EN 10025 standard, in order to assure the reliability performance of the components.

Table1. Mechanical Properties for EN10025-4 S355ML

Thickness (mm)	Carbon Equivalency	YS (MPa)	TS (MPa)	EI (%)	ZRA (%)	Temp -40℃ 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

2.3. Research on Composition and Rolling Process

(1) Chemical Composition

Besides high strength and excellent low temperature toughness, the steel plate shall also have extraordinary welding performance. The composition design adopts low carbon content to reduce carbon equivalency and enhance welding efficiency. The additions of microalloy containing niobium, vanadium and titanium lead to an improvement of both strength and toughness. Ultra-low level of phosphorus/sulfur is also under control to avoid deleterious inclusions.

(2) Rolling Process

Among the factors that improve the strength and toughness properties, grain refinement has a significant contribution [1]. To obtain finer structure, during the rolling process, the holding thickness is increased. In result the high reduction ratio at the finish milling stage leads to an increment in dislocation density and storage of the strain energy in the grains. Furthermore, the finish rolling temperature is also controlled to hinder the grain growth at elevated temperature. The accumulated dislocations and deformed grains induce more nucleation sites and subsequently introduce the refinement of bainite microstructure after phase transformation.

(3) Cooling Control

In order to obtain fine, uniform and granular bainite structure, the steel plates are rolled under thermomechanical control, and the compound cooling system, EACC (Extended Accelerated Cooling) is applied. EACC is an innovative technology combined DQ(Directed Quenched) and ACC(Accelerated Cooling) in the consecutive cooling process. By the use of EACC, it is found that precise cooling rate as well as the finish cooling temperature could be obtained. With EACC, apart from grain coarsening, the hard and brittle M/A (Martensite-Austenite) constituent is also avoided. Therefore, improvement of the strength and toughness could be achieved at the same time.

3. Results and Discussion

3.1. Influence of Holding Thickness on Impact Toughness

In order to improve the impact toughness of steel plates for wind power structure, according to the above research, the trial production was carried out in the factory. From the test results, it shows a substantial difference between Group A and B. As shown in Table 2., Group B with a higher holding thickness exhibits better impact toughness up to 250J in average. The relation between different holding thickness and impact value is shown in Figure 2. As the holding thickness increased, the finish reduction ratio increased. In consequence, the impact value increased significantly and steadily. This is because the finish rolling was not performed below the crystallization temperature. Not only does the relatively low temperature inhibit grain growth, but grain refinement also accomplished due to more nucleation sites. The sites were induced from higher density of sub-grain boundaries or slip zones caused by sufficient amount of strain energy during rolling process. Accordingly, the toughness in the center of the plate is also effectively improved. The metallographic observation is shown in Figure 3. As the holding thickness increased, the effect of grain refinement is evident. Therefore, the ultra-wide and thick steel plates are produced from wider and thicker slabs aiming to provide sufficient finish reduction.

Table 2. Mechanical difference of holding thickness of heavy plates

Group	Holding Thickness	Tensile Test			ZRA (%)	Temp -40℃ 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

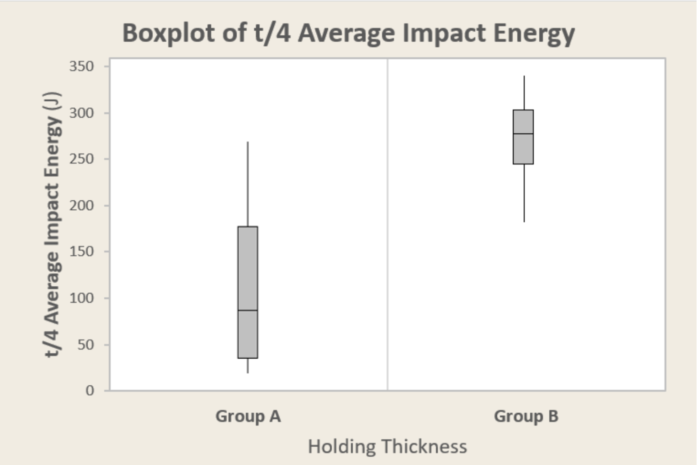
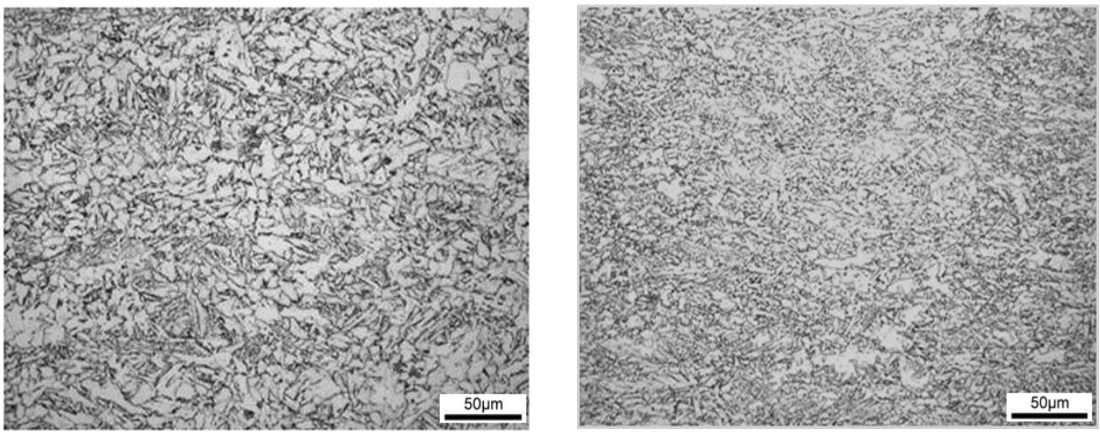


Figure 2. The relation between holding thickness and impact toughness (a) Group A with lower holding thickness; (b) Group B with higher holding thickness.



(a) (b)

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

3.2. Influence of Carbon Content on Mechanical Properties

As the holding thickness was increased, there were still some discrete low impact values. Through analysis it was found that the M/A constituents in the structure reduced the impact toughness at low temperature. After decrease in carbon content, the formation of hard and brittle structure was eliminated. The mechanical results are shown in the table 3. The tensile and ZRA properties can maintain the same as the original level and fulfill the requirements of the specification. The impact toughness was increased approximately by 30J in average.

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

Content	Tensile Test			ZRA (%)	Temp -40℃ 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

3.3. Effect of EACC Technology on Mechanical Properties

The EACC compound system is a combination of DQ and ACC cooling equipments. When plates are produced by ACC, the edges of the plate receive too much water and easily over-cooled. This is basically due to the entrained water caused by the laminar flow cooling over the edges on the top side of the plate. After introducing the water crown repartition of DQ equipment, water flow is allocated larger in the center part of the plate but smaller in the edge part. In result, the consecutive cooling of DQ and ACC makes a balance of the water flow in the lateral direction and attributes to a better temperature profile. When using ACC, in the length direction, the head and the tail of the plate undergo excessive cooling owing to the mismatch control of the opening and closing of the water. If the sprayers are open too early, the water from the bottom sprayer often splashes to the top side of the plate. Therefore, utilizing the end masking technology from DQ compensates the loss of temperature at the ends, and brings lengthwise homogeneity of the temperature. Figure 4 exhibits the temperature profile of ACC and EACC. It is noticed that EACC features uniform temperature distribution. On the basis of approaching better temperature uniformity and the ability to control cooling rate in a wider range by using EACC technology, the critical cooling rate and the desired finish cooling temperature could be reached accurately. Therefore, the formation of M/A phase caused by partially over-cooling is avoided, and it prevents the weakening in both strength and fracture at low temperature. EACC is also beneficial to less difference in cooling temperature between the ends and the body of the steel plates, which enables a stable mechanical quality and flatness.

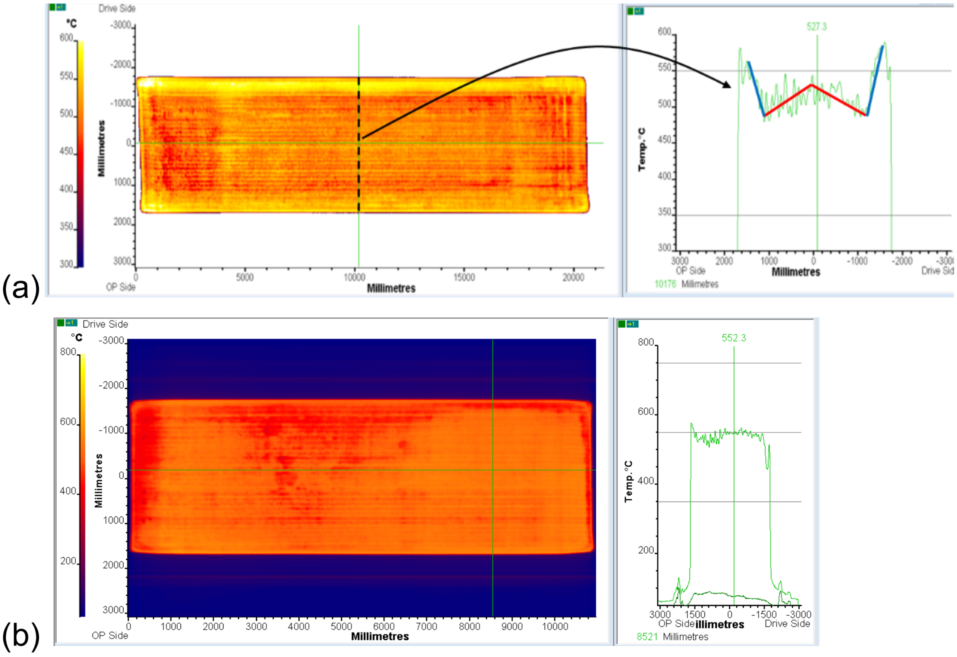


Figure 4. Temperature profile in following cooling process (a) ACC (b)EACC

3.4. Quality Improvement

Figure 5 shows the results of the statistics of impact toughness quality. The rejection rate raised with the increase of the plate thickness. After the implementation of the methods including increase of holding thickness, reduction of carbon content, and production by EACC cooling system, the defect rate of heavy plate dropped from 83% to 0%. The longitudinal impact value was raised from 85J to 298J which marked a notable improvement.

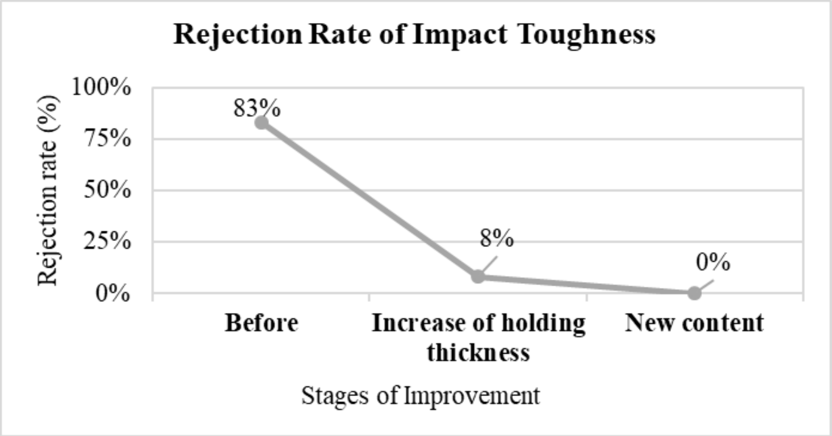


Figure 5. Rejection rate of impact toughness in different thickness

4. Conclusions

4.1 The design of composition was optimized by low carbon content, ultra-low phosphorus and ultra-low sulfur which lessened the segregation in the middle part of the slab. Furthermore, by enhancement of holding thickness during rolling process, the finish reduction ratio increased. Subsequently, it gave rise to the grain refinement, and hence improved the quality of impact toughness.

4.2 With the innovative EACC compound cooling process, the cooling rate was precisely controlled, and it prevented the formation of M/A constituents which is detrimental to the strength and toughness at low temperature. Because of its high cooling uniformity, it was found that the mechanical uniformity and flatness of the whole plate were improved. Therefore, it brought massive benefits to quality enhancement and higher production capacity.