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Offshore 690 MPa Heavy-Gauge Steel Plates Required in Modern Wind Turbine Installation Vessels

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INTRODUCTION

Offshore wind energy is recognized as a possible solution for delivering cleaner and renewable electricity while reducing CO2 emissions. Consequently, offshore wind energy is currently experiencing rapid expansion and the demand for modern wind turbine installation vessels (WTIVs) to install large offshore wind farms has recently increased due to the number of active large-scale offshore wind projects and the ever-increasing output power of wind turbines.

Since the first offshore wind farm built in Denmark in 1991, global installed offshore wind capacity has surged to approximately 65 GW by 2022, with projections indicating growth to exceed 200 GW by 2035 [1]. The need to reduce costs associated with offshore wind farms has driven the development of larger turbines, reaching heights of up to 260 meters and boasting outputs ranging from 10 to 20 MW per turbine.

Wind Turbine Installation Vessels (WTIVs) are specialized installation vessels capable of transporting various turbine components on their decks and equipped with cranes of high lifting capacities to facilitate installation in water depths of up to 80 meters. To establish a stable working platform and safely install turbine components, these vessels are equipped with jack-up legs featuring racks and pinions used to elevate their decks above the sea surface comparable to platforms used for oil and gas exploration, as illustrated in Figure 1. However, jack-up racks used for the legs of WTIVs require stronger teeth to withstand the enhanced wear and fatigue caused by the higher frequency of up and down operations compared to classical drilling platforms [2]. Consequently, modern WTIVs require rack plates made of offshore structural steel with a nominal yield strength of 690 MPa of thickness up to 254 mm compared to the standard 180 mm thickness used for oil and gas platforms.

From the perspective of steel manufacturers, maintaining consistent mechanical properties and low-temperature impact toughness across the whole thickness while ensuring good welding and flame cutting behavior during fabrication is anything but trivial [3-7]. The same or better mechanical properties shall be guaranteed for the whole thickness and the material characteristics in terms of processing and welding must be qualified. This study considers the experimental characterization of 210 and 250 mm thick base metal plates industrially produced by Industeel in France.

Figure 1: Pictures of jack up WTIV and the high strength steel racks used to elevate the platform. From ref. [8,9].

MATERIALS AND PRODUCTION ROUTE

Extra high strength steels with nominal yield strength of 690 MPa are widely used in jack-up legs for many years [10]. They offer the advantages of thinner sections, weight reduction, less welding costs and overall savings in material costs and construction schedule. The offshore certification companies like DNV, ABS and others, also grouped in the International Association of Classification Societies (IACS), include these steels in their recommendations and defined their specifications for the mechanical and chemical properties for both the base material and the weld properties. Table 1 summarizes the requirements for mechanical properties of NV EO690Z35 grade. It is worth pointing out that, whatever the plate thickness, consistent properties must be obtained through the whole thickness of the rack plate: the same or better mechanical properties must be fulfilled for both ¼ and ½ t positions across the plate thickness.

Tensile	**Direction**	**Min YS (MPa)**	**UTS (MPa)**	**Min A%**
	Transverse	690	770 - 940	14
	Through-thickness (Z)	Min 35% reduction area		
Impact	**Direction**	**Temperature (ºC)**	**Min energy (J)**	
	Longitudinal	-40	69	
	Transverse	-40	46	

Table 1: Requirements for mechanical properties of NV EO690Z35 grade applicable for both t/4 and t/2 positions across the plate thickness

To reach the necessary combination of yield strength and toughness up to 254 mm thickness, the steel is produced by quenching and tempering in our production facility in Rive-de Gier near Lyon, France. Large bottom-poured cast ingots are made from electric arc furnace with ladle refining and vacuum degassing to provide a clean and homogenous steel with adequate alloying additions. The large ingot is then hot-rolled into the final product dimensions in a four-high reversible mill. For such extra-heavy gauges, an initial hot forging step is also performed to ensure efficient deformation and grain refinement in the mid-thickness zone of the plate, which could not be achieved by hot rolling alone. An overview of the processing route is schematized in Figure 2. Industeel has obtained accreditations from offshore certification companies DNV and ABS up to 254 mm thick plates, and several commercial WTIV projects were recently delivered.

The chemical composition and heat treatment of SuperElso® 690 CR is carefully adjusted to achieve high impact values at low temperatures across the thickness while respecting the required tensile properties. The reduced carbon content allows the use of low preheating temperature prior to flame cutting and welding under classical conditions. Table 2 compares the composition max limits of the SuperElso® 690 CR with those specified by the DNV-OS-B101 standard (also adopted in the IACS UR W16 standard). It is seen that extra-thick plates up to 254 mm are produced without excessive alloying addition, as the chemical composition complies with the limits specified for thinner products under 150 mm thickness.

Industeel is the only steel company producing this steel via the electric arc furnace route, allowing a substantial reduction in CO_2 footprint compared to steels produced via the blast furnace route. Despite our already very positive results in the steel industry, Industeel is committed to reduce CO_2 emissions by 35% by 2030 by a combination of energy savings, waste heat recovery, optimized processes and alternative technologies to reduce natural gas consumption combined with the use of renewable electricity over natural gas.

Max wt%	C	Mn	Si	P	S	Ni	Mo	Cr	Al
SuperElso® 690 CR	0.15	1.2	0.45	0.01	0.002	4	0.7	0.7	0.06
NV EO690Z35	0.18	1.70	0.8	0.020	0.008	[*]	0.7	1.5	≥ 0.018

Table 2: Chemical composition max limits of the SuperElso® 690 CR (up to 254 mm) with those specified by the DNV-OS-B101 standard (up to 150 mm). *[*] Ni content higher than 2% permitted for thicknesses > 150 mm.*

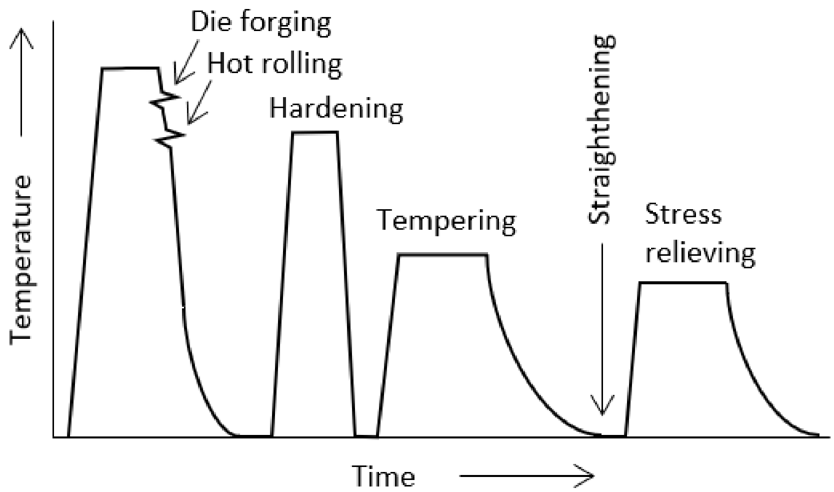


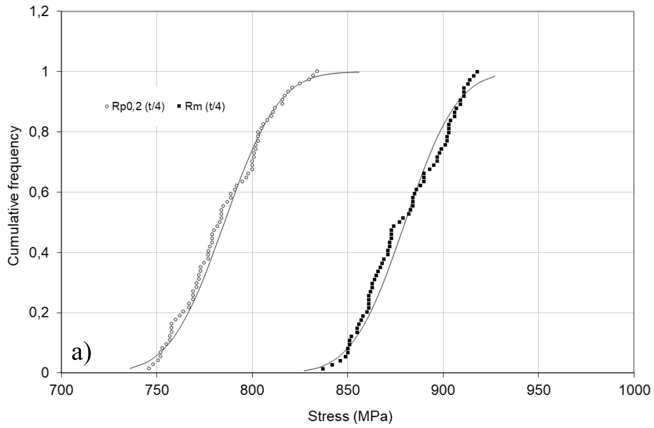
Figure 2: Overview of the ultra-heavy steel plate processing schedule.

BASE METAL PROPERTIES

The mechanical properties from industrial production campaigns of 210 mm and 250 mm thick industrial plates are presented in the Figures 3 to 5. While some degree of variation from one plate to another is inevitable in industrial production, the statistical distribution shows that the produced plates consistently meet the technical requirements for the mechanical properties. The robustness of the industrial production is an important factor to ensure the reliability of the delivered product and meet customer expectations.

The statistical distribution of tensile properties in Figure 3 shows the low scatter of properties for the same delivery batch and no drop of properties with the increase in thickness from 210 to 250 mm. The evolution of tensile properties through the thickness of the 250 mm thick plates is illustrated in Figure 4 for the yield strength. We can observe an average drop of about 30 MPa only for the yield strength measured at the center of the plate compared to the ¼-thickness position.

Whereas the tensile properties are virtually unchanged, the CVN-impact energy absorbed at -40°C is more affected by the change in plate thickness, as displayed in Figure 5: lower average values are found on the thicker 250 mm plates. For both thicknesses, the CVN-impact energy is higher on longitudinal samples compared to transversal direction, as reflected by the different min values requirements of 69 and 46 J respectively in the product specification. For the same delivery batch, the scattering of the CVN results is significantly larger compared to YS and UTS, indicating that the impact properties are more sensitive to small variation in the microstructure.



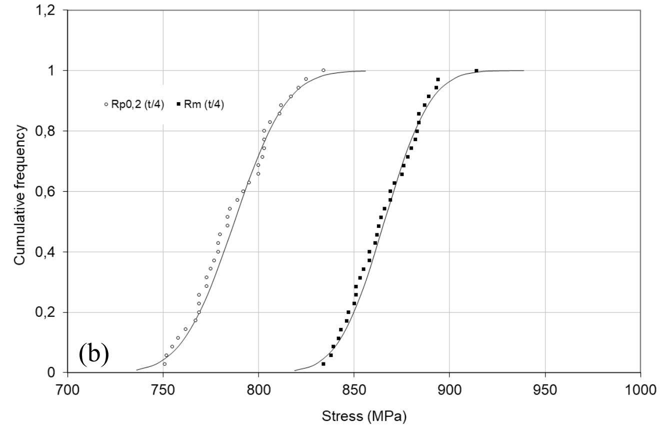


Figure 3: Statistical distribution of tensile properties (a) 210 mm; (b) 250 mm. Tests are performed on transversal samples taken at ¼-thickness position. Each point represents a different plate.

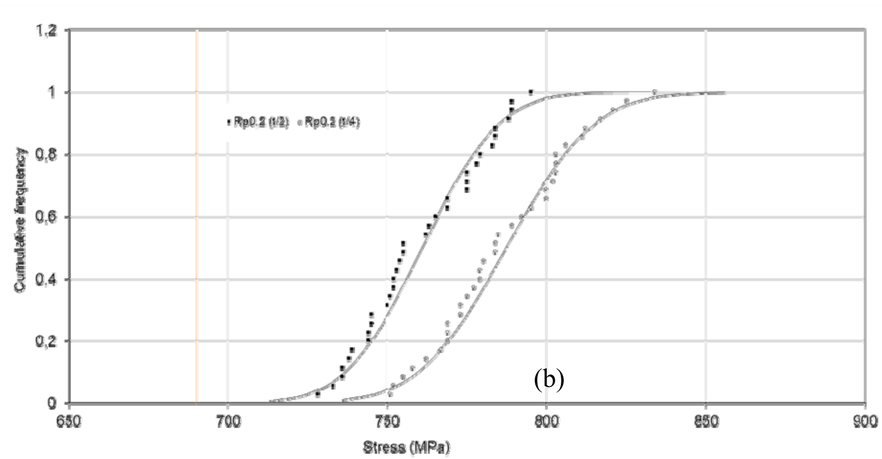
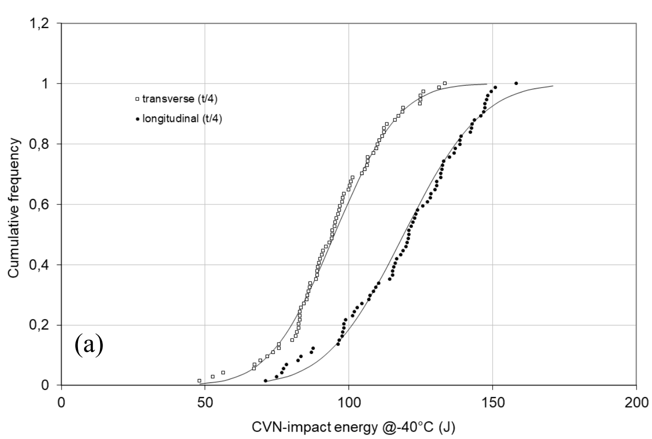


Figure 4: Statistical distribution of yield stress values measured at ¼- and ½-thickness on several 250 mm thick plates. Tests are performed on transversal samples. Each point represents a different plate.



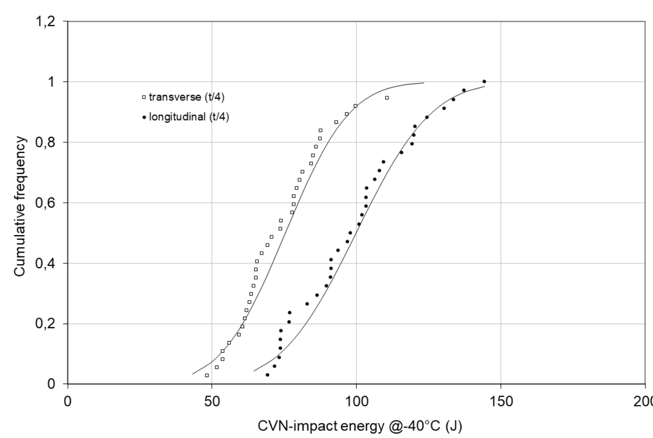


Figure 5: Statistical distribution of CVN-impact test results (a) 210 mm; (b) 250 mm. Tests are performed at -40°C on longitudinal and transversal samples taken at ¼-thickness position. Each point represents the average value of 3 single test specimens taken from a different plate.

MICROSTRUCTURE

Achieving an optimum microstructure during production of ultra-heavy plates is difficult because of the different heating and cooling rates across the thickness resulting in heterogeneous microstructure, internal stresses and even distortion or cracking, Figure 6 presents LOM and SEM micrographs observed at different positions across the section of a 210 mm thick heavy plate. Whereas different cooling rates are achieved across the thickness during the quenching process, it can be seen from the LOM images that the microstructural homogeneity is only marginally affected. Quarter and mid-thickness microstructure consist mainly in tempered martensite or lower bainite (LB), with fine carbides located within martensite/LB laths and between martensite/LB laths boundaries. Carbides also form at the prior austenite grain boundaries. At the t/2 position in the center of the plate, where the cooling rates are slower, some granular bainite is also observed.

Figure 6 also shows the morphology of the prior austenite grains (PAG). According to the LOM images, the prior austenite grains size exhibits a non-uniform distribution: some PAG are severely coarsened whereas clusters of finer PAG are also observed. Mid-thickness position tends to form mixed PAGs due the slower heating and cooling, variation in rolling reduction and persisting centerline segregation zones that affect the local chemical composition.

WELD PROPERTIES

The butt-welding assembly consisted of two samples of approx. 254 x 1530 x 550 mm each which were machined after oxy-cutting to an asymmetric K-type bevel preparation of 20° angle opening and a root face of 6 mm located at 100 mm under the top surface of the plate. The bevel preparation can be seen in Figure 7.

Single wire submerged arc welding (SAW) was performed to a welding procedure specification developed at Industeel. The combination of Oerlikon Fluxocord 42 flux cored wire of 3.2 mm diameter with OP 121 TT W flux was selected to ensure low diffusible hydrogen and maintain high yield strength above 690 MPa for the weld properties.

The first 10 runs on the side A were made at an increasing low heat input from 1.0 to 1.9 kJ/mm. The first two passes on side B were made with a heat input of 2.8 kJ/mm. Then, the filling passes were made with a heat input of 2.0 kJ/mm. During welding, the assembly was turned over several times to balance distortion. Preheating was applied at 125°C and interpass temperature was between 110 and 170°C. After welding, post-heating during 5 hours at 250 °C was performed.

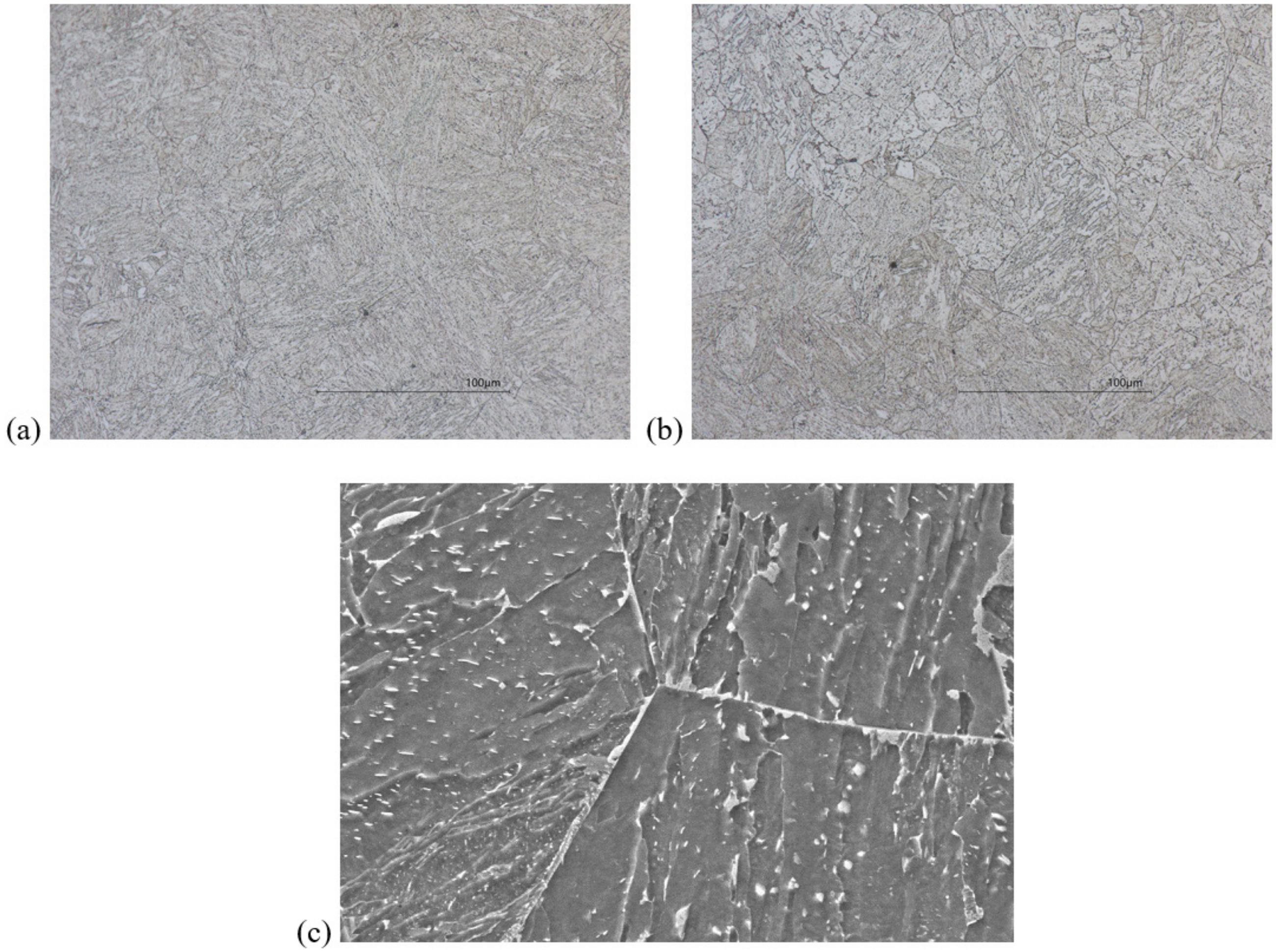


Figure 6: Microstructure observed on an industrial 210 mm thick plate: (a) and (b) Light Optical micrographs after 3% Nital etching at t/4 and t/2 thickness positions respectively; (c) SEM micrograph of t/4 specimen, showing a triple joint of prior austenite grains.

Hardness testing

Full cross-sections of the weld were polished and used for hardness testing. HV10 hardness profiles were made approx. 2 mm from either external surface and through the weld root. The hardness results are summarized in Table 3. From this table, it can be seen that there is a good match between weld metal and base material hardness. The highest hardness is found in the CGHAZ, but all weld locations meet the hardness requirement of max. 450 HV10.

Tensile testing

Transverse tensile testing of the welds was performed to ISO 6892-1 method B and using flat samples machined from successive positions across the full weld thickness. As can be seen from Table 4, all samples showed weld metal failure, except near the root line of the double-sided multipass weld.

CVN-impact testing

Charpy impact testing was performed using standard size (i.e. 55x10x10 mm) samples, taken 2 mm from the surface of the welded plate, as well as centered around the root line. From these locations, five sets of three samples each were tested at -40 °C, with the notch in the weld metal (WM), at the fusion line (FL) and at the FL+2 mm, FL+5 mm and FL+20 mm, respectively. The results are summarized in Table 5. In addition, the CVN-transition curves of the base metal are presented in Figure 8 together with the impact of the strain ageing parameters. All samples of the welded joint met the requirements of ≥32 J individually and ≥46 J average. At the FL + 20 mm location, the impact properties of the base metal are obtained near the surface, but a significant drop of impact energy is noticed near the root line where the effect of strain ageing is maximum due to the thermal history of the weld sequence.

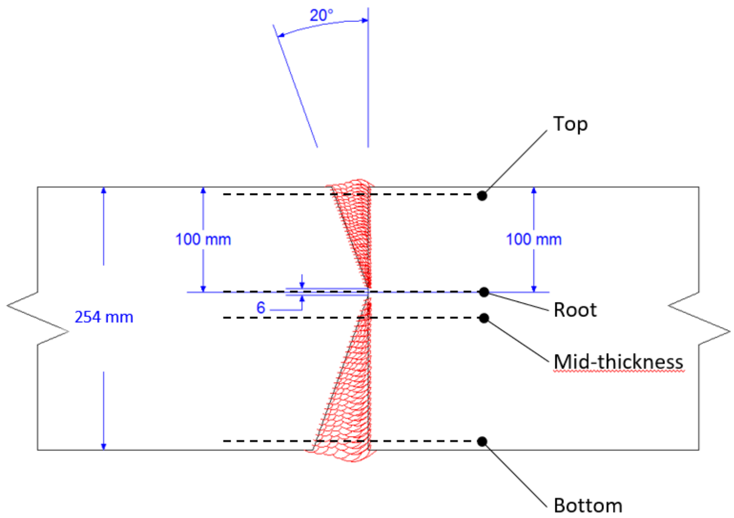


Figure 7: Bevel preparation geometry and location of testing positions

Number	1	2	3	4	5	6	7	8	9	10	11
HV10	BM			HAZ		CGHAZ			WM		
Top	276	258	275	373	346	354	364	375	283	271	258
Root	275	267	282	284	398	382	363	353	262	281	290
Bottom	271	264	269	377	389	360	349	367	257	280	264

Table 3: HV10 hardness profiles across the weld.

Thickness position	Sample number	UTS (MPa)	Fracture location
Top	1	795	WM
	2	791	WM
	3	802	WM
	4	837	WM
Root	5	843	BM
	6	834	BM
Mid-thickness	7	831	BM
	8	831	BM
Bottom	9	822	WM
	10	803	WM
	11	808	WM
	12	794	WM
	13	768	WM
	14	762	WM

Table 4: Tensile test results of the welded joint.

Thickness position	Notch location				
	WM	FL	FL + 2 mm	FL + 5 mm	FL + 20 mm
Top	61	83	207	203	177
Root	67	91	72	144	60

Table 5: CVN-impact test results of the welded joint. Reported values are the average absorbed energy at -40°C from 3 specimens taken at different locations across the weld and along 2 positions in the thickness (top and root).

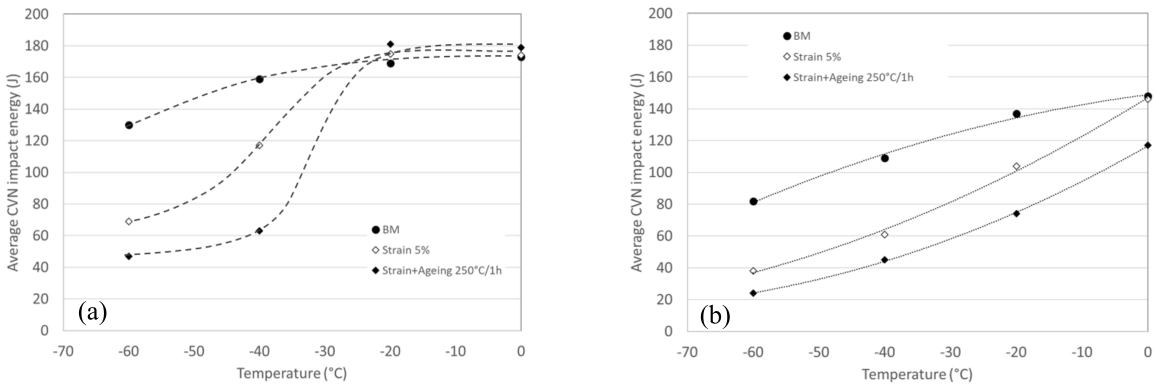


Figure 8: Impact of the strain ageing parameters on the CVN-transition curves of the base metal from 2 different specimen locations: (a) ¼-thickness and (b) ½-thickness.

CONCLUSIONS

Industeel has traditionally been a leading company in the market of heavy plates for oil drilling jack-up rig legs. Although the jack-up rig market has slowed down sharply over the past few years, this technology is now seeing a revival due to the Global Energy Transition, as there is a growing need of using the same jack-up concept for the special installation vessels used to set up offshore wind farms.

Today the last generation of WTIV requires extra high strength steel racks up to 254 mm according to ABS and DNV standards. Industeel remains one of the very few manufacturers worldwide that can supply such heavy plates, thus contributing to Europe's leadership in the modern offshore wind industry.

The number of active large-scale offshore wind projects combined with the short timelines and current price volatility will likely challenge the supply chain in the next years. Industeel has additional capacity to deliver processed parts and components and help fabricators to improve their production efficiency or to handle peak loads in their own facilities.

Industeel is the only steel company producing this steel grade via the electric arc furnace route, allowing a substantial reduction in CO_2 footprint compared to steels produced via the blast furnace route, helping companies developing offshore wind projects to control their Scope 3 emissions.

REFERENCES

1. Global Offshore Wind Report 2022, Global Wind Energy Council GEWC
2. Zhiyu Jiang, *Installation of offshore wind turbines: A technical review,* Renewable and Sustainable Energy Reviews 139 (2021) pp. 110576.
3. Liu, Dongsheng; Cheng, Binggui; Chen, Yuanyuan., *Strengthening and Toughening of a Heavy Plate Steel for Shipbuilding with Yield Strength of Approximately 690 MPa,* Metallurgical and Materials Transactions A; Vol. 44, N° 1 (2013), pp. 440-455.
4. Guo, K.; Pan, T.; Zhang, N.; Meng, L.; Luo, X.; Chai, F. *Effect of Microstructural Evolution on the Mechanical Properties of Ni-Cr-Mo Ultra-Heavy Steel Plate*. Materials 2023, 16, 1607.
5. Julio C. Gonzalez L, Wei Li, Jiang Ke, Yuantao Xu, Huiyong Pang, XueJun Jin, *Study of the impact properties and microstructure evolution in a high-strength low-alloy heavy steel*, Materials Science and Engineering: A, Vo. 819, 2021, 141404
6. Wang, Q.; Ye, Q.; Wang, Z.; Kan, L.; Wang, H. *Thickness Effect on Microstructure, Strength, and Toughness of a Quenched and Tempered 178 mm Thickness Steel Plate*. Metals 2020, 10, 572
7. K. Otani, K. Hattori, H. Muraoka, H. Kawazoe, S. Tsuruta, *Development of Ultraheavy-Gauge (210 mm Thick) 800 N/mm2 Tensile Strength Plate Steel for Racks of Jack-up Rigs*, Nippon Steel Technical Report No. 58, July 1993
8. Reprinted from: https://www.cadeler.com/en/vessels/
9. Reprinted from DNVGL-RP-0075 Nov. 2014
10. J. Billingham et al., *Review of the Performance of High Strength Steels Used Offshore*, Cranfield University, Health and Safety Executive, 2003.

