Through-Thickness Microstructure and Mechanical Properties Evaluation of a TMCP S355ML Steel Plate

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Abstract

This study investigates the through-thickness microstructure and mechanical property variations of a 20 mm-thick thermo-mechanically controlled processed (TMCP) S355ML steel plate, commercially manufactured and intended for potential use in offshore structures. A key objective of the present work is to investigate the variations of microstructure and associated mechanical properties through the thickness, especially for the thickness effect on fatigue performance.

Metallographic analysis revealed refined ferrite grains at the plate centre (average diameter: ≈ 4.9 µm) compared to near-surface regions (≈ 6.5 µm), attributed to enhanced ferrite nucleation from microalloying precipitates and optimised cooling rates during TMCP. The centre also showed pronounced pearlite banding (average thickness: ≈ 13 µm), whereas the surface featured scattered pearlite regions (≈ 3 µm). Quantitative image analysis revealed a pearlite volume fraction of approximately 16% at the centre, compared to about 11.5% near the surface (see Fig. 1).

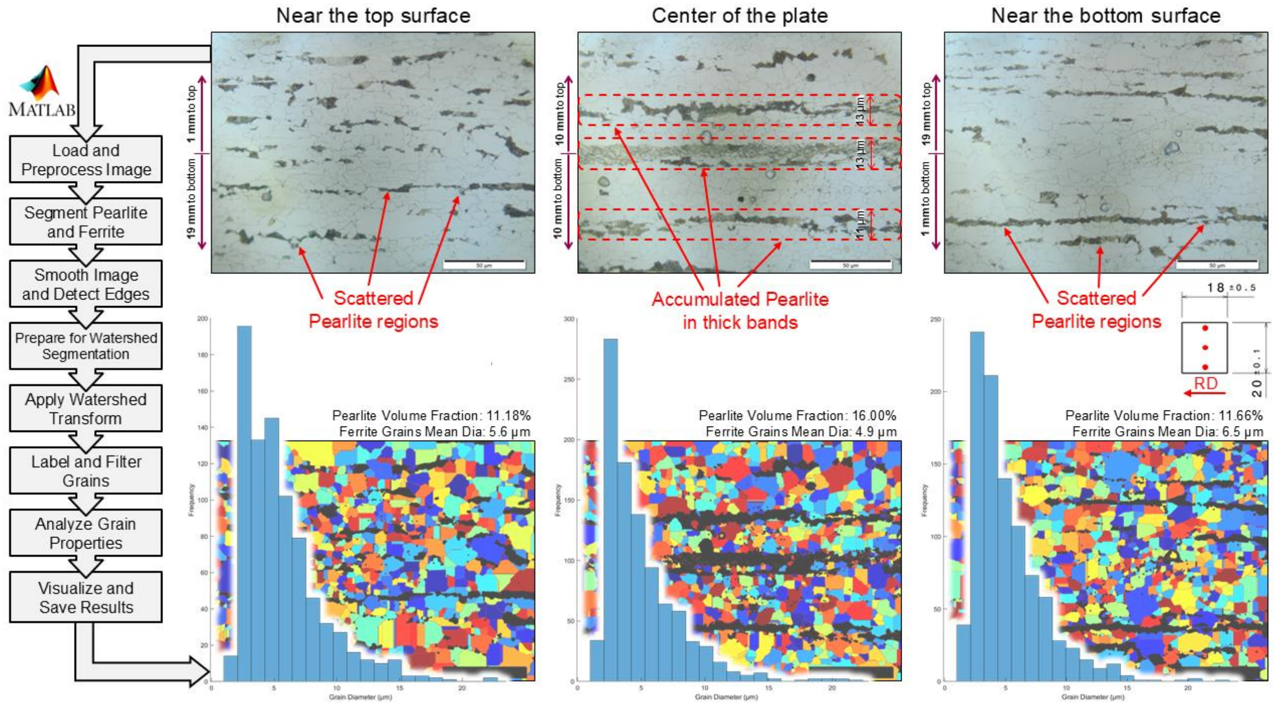

Figure 1: Ferrite grain segmentation and size distribution of a 20 mm-thick S355ML steel plate (etched for 15 s in Nital 2%), based on through-thickness metallography images processed using MATLAB

Mechanical testing across five slices through the thickness demonstrated that the plate centre exhibited higher yield and tensile strength, rationalised by the Hall-Petch effect (based on ferrite grain size), and higher pearlite volume fraction. Nano-indentation testing is employed through the thickness to evaluate local hardness and modulus and to further validate the presence of strengthening gradients. Tensile testing was conducted using an Instron extensometer and digital image correlation (DIC), enabling full-field strain mapping to evaluate local deformation and strain heterogeneity. Additionally, scanning electron microscopy (SEM) is used to examine the fracture surfaces of tensile specimens to identify dominant fracture modes and failure-dominant microstructural features across the thickness of the plate.

It is found that through-thickness gradients in microstructure and mechanical properties of S355ML steel exist. Effective characterisation and control of these through-thickness gradients are helpful to optimise structural performance and reliability of large-scale welded assemblies, including monopiles and jacket structures in OWT applications. A key future step in the present work is to develop thermo-metallurgical-mechanical models for predicting the measured through-thickness microstructure variations and relating these to mechanical behaviour (e.g., yield and ultimate strength, ductility, and fatigue strength) for up-scaling of cost-effective structures in renewable energy infrastructure.

Possible Sessions

13. Metals and Microstructure, 15. Nano & Micromechanical Testing, 19. Optical & DIC Techniques

Introduction

Offshore wind turbine (OWT) structures demand high-performance materials capable of withstanding corrosive marine environments and cyclic mechanical loading. S355ML, a thermo-mechanically controlled processed (TMCP) steel, is widely used due to its strength, weldability, and cost-effectiveness. However, the heavy thicknesses typically used in OWT components (up to 100 mm) exhibit through-thickness heterogeneities in both microstructure and mechanical performance. This inhomogeneity is accounted for in design codes for support structures (e.g., brittle fracture analysis, thickness effect in fatigue).

Understanding of these variations better is therefore helpful to optimise the design of large offshore structures by taking away conservative approaches. Grain size, pearlite distribution, dislocation density, and precipitation behaviour often vary across the thickness due to differences in cooling rates and micro-alloy segregation. These features influence yield and tensile strength through mechanisms like Hall-Petch strengthening, precipitation hardening, strain hardening capacity, and fatigue strength.

This study characterises a commercially-manufactured 20 mm-thick S355ML steel plate using metallography, nanoindentation, and mechanical testing (tensile, extensometer-based strain tracking, and DIC) at five through-thickness locations. Post-failure SEM analysis of fractured tensile specimens is also performed to explore ductile versus brittle failure features and correlate them with local microstructural differences. Particular attention is paid to the quantification of pearlite volume fractions, which revealed a higher concentration at the centre, supporting the observed mechanical property trends. The goal is to map microstructure-property relationships to identify methods for optimising TMCP of ferritic-pearlitic steels for cost-effective upscaling of OWT structures.

Conclusion

This comprehensive investigation revealed microstructural and mechanical property gradients across the 20 mm thickness of the TMCP S355ML steel plate.

Centre regions exhibited finer ferrite grains and thicker pearlite bands, reflecting slower cooling and stronger segregation effects. The pearlite volume fraction at the centre was found to be about 16%, significantly higher than the 11.5% measured near the surface.

Tensile and yield strength were higher at the centre, correlating with finer ferrite grains, higher pearlite volume fraction, and potential micro-alloy precipitation.

This study demonstrates that the TMCP process influences the through-thickness uniformity of microstructural and mechanical properties. The observed variations provide insight into the thickness size effect in fatigue design of such structures, which could be particularly beneficial for the upscaling of renewable energy infrastructure.

References

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