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Exploring Electron Beam Welding Techniques for Structural Steel: Microstructural and Mechanical Characterization

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Abstract. This study investigates Electron Beam Welding (EBW) processes, both with and without material deposition. Specifically, structural steel (S355ML) with a thickness of 90mm was welded in a single pass. Microstructural analysis characterizations and mechanical tests were conducted to evaluate the welds' properties. The results demonstrate successful welding, with both defect-free and sound welds achieved. This research provides valuable insights into the efficacy of the EBW technique and its application in welding structural steel components. The ability to perform welds in a single pass suggests high potential for this technique in industrial applications requiring high-quality welds in thick materials. This study highlights the importance of electron beam welding as a reliable and effective technique in the fabrication of critical steel structures.

1 Introduction

The advancement of wind power in the future offers a substantial opportunity for supplying low-carbon energy. However, it also poses several challenges. To remain competitive, wind power must demonstrate cost-effectiveness compared to fossil fuels and other renewable energy sources, particularly solar photovoltaics.

To enhance wind energy production, offshore implementation is essential. Various types of metallic structures can be employed depending on the characteristics and depth of the seabed, such as monopiles, jackets, tension leg platforms, semi-submersible platforms, or spar buoys [1].

The wind turbine foundation has been recognized as a significant cost factor in offshore wind turbine systems. The overall cost of the foundation can reach up to 21% of the total cost of offshore wind power production. A monopile foundation, being the most prevalent and cost-effective structure for offshore wind farms, is typically suitable for relatively shallow water depths of 40 meters or less [2].

Monopiles are structures shaped like a single tube that support the wind turbine. They are manufactured from thick plates made of structural steels. The fabrication process begins with flat plates that are cut and bent to form parts of the tubes. These elements are joined together through longitudinal and radial welds. The thickness of the plates may vary depending on the application, but it is common to use plates with thicknesses around 100mm.

The costs associated with joining plates of such dimensions are high. To access the joint using arc welding torches, it is necessary to prepare a V, U or X groove joint. The space between the plates must be filled bead by bead through welding. This labor-intensive task may require several hours or even days of work for each joint, depending on the joint's characteristics and the chosen welding process.

As an alternative to conventional welding processes, methods based on high-penetration energy beams are being investigated. This approach could eliminate the need for X-groove preparations and enable rapid joining in a matter of minutes. Among these technologies, noteworthy proposals include novel approaches based on laser beams in vacuum conditions or Electron Beam Welding (EBW), a proven technology capable of penetrating large thicknesses [3].

This process is not new, but it is currently attracting interest from industrial sectors with the most demanding requirements, such as the fusion nuclear industry, which works with low-activation steels [4]. Furthermore, it is presented as a viable alternative for structural steels [5].

The high cooling rate is an intrinsic feature of the EBW process when welding large thicknesses. One potential negative consequence can be structures with high hardness and low toughness. There are studies demonstrating that toughness can be slightly improved with PWHT, [6]. However, due to the size of the parts, it is not feasible to carry out these types of treatments. Some researchers have addressed this issue by employing in-situ treatment methods using the electron beam itself, [7] However, their applicability in large thicknesses is not clear.

Therefore, for EBW to be a viable alternative, the joints must exhibit satisfactory properties without any pre- or post-welding treatment.

Another limitation of the process is the requirement for a vacuum chamber. Currently, new technologies and equipment are being developed to enable the execution of the process outside the vacuum chamber, [8].

Nevertheless, as previously mentioned, the development of the EBW process and the demonstration

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of satisfactory joint characteristics are imperative. This study provides an examination of the properties of 90mm thick specimens fabricated from S355 ML steel. Two types of joint preparations have been proposed, and a comparative analysis has been undertaken to assess the viability of this technology for implementation in monopile manufacturing.

2 Methodology

The study has been conducted with S355 ML material. It is a structural steel similar to the commonly used S355 J2 steel in the industry, with improved properties for offshore conditions. Coupons of 90mm thickness have been welded with backing in the root zone.

All the studied welds have been made using the same equipment and process conditions. The equipment was a CNC machine EBOCAM KS 110 - G300 KM installed at the facilities of ESS Bilbao.

2.1.1 Welding 90mm thickness coupons

One of the significant challenges presented by these joints is the large plate thicknessz. Therefore, before executing the joints, a process parameter optimization has been carried out. Finally, the parameters shown in the table have been selected.

Table 3. Main welding parameters

Parameter	Value
Voltage	150 kV
Intensity	200 mA
Feed rate	1,7 mm/s

Welding large thicknesses in a single pass entails a multitude of challenges that must be addressed. While aligning and centering parts for joining might appear relatively straightforward when dealing with thinner components, the task becomes considerably more intricate as thickness increases. Ensuring precise alignment of the joint parallel to the direction of the welding beam emerges as a pivotal factor in achieving optimal results. This alignment becomes increasingly critical with rising thicknesses, underscoring its significance in the welding process.

As a preventive measure against misalignment complications, joint preparation has been conducted. This involved machining two surfaces on each plate: the 90mm-thick surface, which constitutes the joint, and the surface that rests upon the welding table. By adopting this approach, it becomes feasible to ensure the precise perpendicular placement of the joint in relation to the welding table.

2.1.2 Welding joint setups

The process of electron beam welding manifests significant deviations from conventional arc welding methodologies. One notable distinction lies in its exemption from the requirement of V or X preparation, thus streamlining the formation of joints to a single pass.

Furthermore, electron beam welding showcases notable disparities in the width of the fusion zone and the extent of the heat-affected zone (HAZ) when juxtaposed with conventional welding techniques. The fusion zone and HAZ exhibit markedly diminished dimensions.

Complicating matters further is the technical challenge posed by preheating requirements. The experimental conditions, conducted within a vacuum chamber, render traditional preheating methodologies impractical. Consequently, welds are executed without any preheating.

The confluence of reduced bead width and the absence of preheating engenders a distinct cooling profile characterized by rapid thermal dissipation. This phenomenon necessitates an understanding of cooling kinetics to mitigate potential structural compromises arising from rapid solidification.

To thoroughly investigate the impact of rapid cooling and assess the potential for modifying weld properties, two distinct configurations have been examined, Fig 1:

•**Butt Welding, without filler:** This technique involves the direct fusion of materials without the addition of any supplementary substances.

•**Butt Welding with Ni foil**: In this setup, a 0.2mm thick sheet of pure nickel has been interposed between the joint surfaces. Additionally, an upper bevel has been incorporated to enhance beam penetration and optimize welding outcomes.

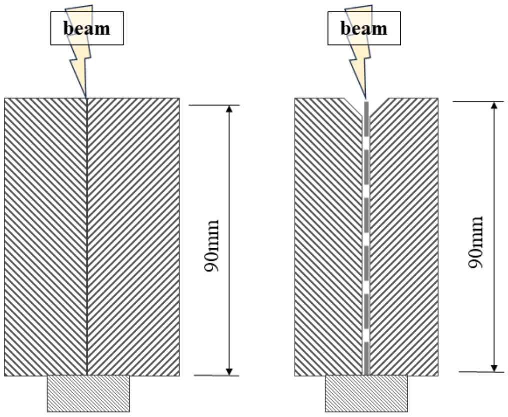

Fig. 1. Joint Setup. Left, butt welding, without filler. Right, butt welding with Ni foil.

2.1.3 Characterization

To comprehensively evaluate weld properties and assess the potential applicability of this technology in the fabrication of monopiles for supporting offshore wind turbines, a structured characterization approach has been employed:

A thorough visual assessment has been conducted to identify surface defects, evaluate weld bead geometry and uniformity, and quantify any spatter present.

Macrographs of each joint type have been captured, offering a macroscopic perspective, while micrographs of various regions within the joints, utilizing the two described configurations, have been examined to provide insights into microstructural features.

Mechanical assessments have been conducted, incorporating hardness examinations at varying depths and in pivotal regions. Furthermore, Charpy tests have been implemented to evaluate the welds' toughness properties.

3 Results and discussion

3.1.1 Visual Inspection

Sound welds have been achieved in both joint configurations studied. The two images shown in the Fig 2 depict a defect-free surface. One differentiating factor between the two joint configurations has been the amount of spatter. The coupon welded with a bevel and with a Ni foil has shown a noticeably higher number of projections. Additionally, the surface of the butt-welded coupon without Ni exhibits a more uniform surface, without irregularities in the weld bead over thickness and without undulations in the line formed between the joint and the plate surface.

Furthermore, it is noteworthy that the width of the weld bead with the addition of Ni is marginally reduced. Specifically, the width of the weld bead without Ni measures approximately 25 mm, representing a 5 mm increase compared to the width observed in the specimen without the Ni foil.

Fig. 2. Surface appearance. Left, butt welding, without filler. Right, butt welding with Ni foil.

3.1.2 Metallographic analysis

Macrographic analysis reveals welding with a very narrow melted zone and a reduced Heat Affected Zone (HAZ). Both macrographs depict a wider zone within the first 10mm of penetration from the upper surface. Both sections demonstrate joints without cracks or pores.

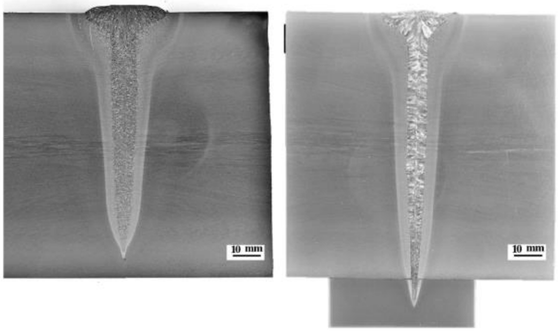

Fig. 3. Macrograph. Left, butt welding, without filler. Right, butt welding with Ni foil.

In Fig 3, a clear observation emerges: the penetration achieved with the configuration employing a nickel plate is markedly superior. Furthermore, the expansion of the weld bead proximal to the upper region is more pronounced in the directly welded specimen. Consequently, it is reasonable to infer that a portion of the beam energy is dissipated in surface melting, failing to reach adequate penetration into the root.

On the other hand, it should be mentioned that in the central area of the plates, segregations forming longitudinal lines are observed. These characteristics are not related to welding; they are typical features in plates of considerable thickness.

The Heat Affected Zone (HAZ) stands out as the most critical region in these welds; thus, the micrographic analysis has primarily concentrated on this area. Both joint configurations exhibit a comparable microstructure within the HAZ. Despite its narrow width, there is a discernible transition from a bainitic structure adjacent to the molten metal to a ferritic-perlitic structure at the interface between the HAZ and the base metal. Fig 4 depicts the microstructure of the welded coupon without the Ni sheet. This microstructure has been obtained in the HAZ at a mid-level depth of the weld bead section.

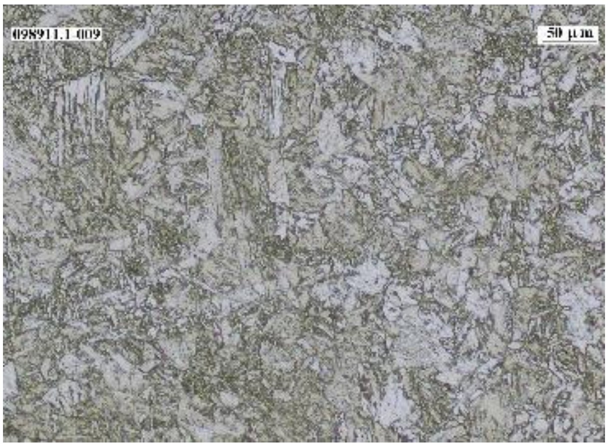

Fig. 4. Microstructure of the HAZ at mid-depth

When comparing this microstructure with that obtained in the lower region of the weld, it becomes evident that the grain size is notably smaller in the lower section, as illustrated in Fig 5. The cooling rate experienced by the material when welded using the EBW process is higher than the cooling rate achieved when employing arc welding processes. Furthermore, the ample mass available to absorb heat in thick plates, as observed in this case, facilitates rapid cooling. Moreover, the beam primarily impacts the upper region, gradually dissipating energy as it traverses the joint. Consequently, the energy absorption by the material in the lower section is diminished compared to the upper part. This rapid cooling scenario impedes grain growth, elucidating the fine grain size observed in the lower weld regions, as presented in Fig 5.

Fig. 5. Microstructure of the HAZ in the lower region.

3.1.3 SEM/EDX Analysis

To assess the diffusion of nickel across the weld profile, we conducted an analysis employing scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM/EDX).

To achieve this, we conducted both linear EDX analysis (line scan) spanning from the melted zone to the Heat Affected Zone (HAZ), as illustrated in the Fig 6.

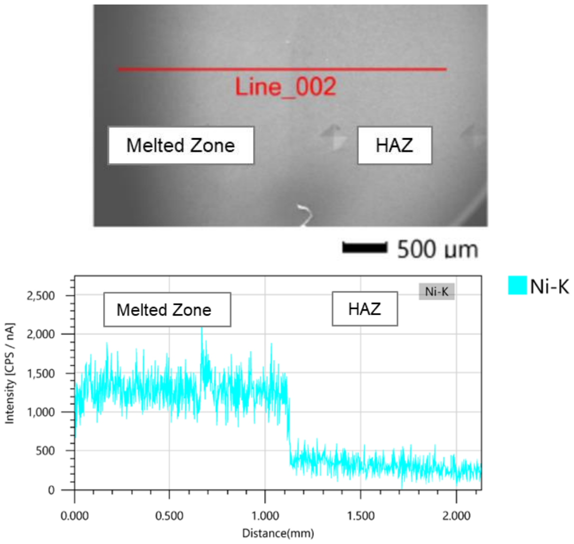

Fig. 6. Superior, Line scan location. Inferior, Ni content.

The results indicate that the Ni foil is uniformly distributed within the melted zone. However, nickel does not diffuse, and its absence is observed in the HAZ.

3.1.4 Hardness characterization

In order to assess hardness in both types of configurations HV 10 hardness testing was performed according to EN ISO 9015-1, three hardness lines with fifteen measurement points, spaced 1,5 mm apart on each coupon, have been obtained. The hardness lines were obtained at depths of -2mm, -45mm, and -75mm from the surface. The results are shown in Fig 7 with the average values and standard deviations obtained at each point. It is observed that the variability observed in points further from the weld center is higher than that observed at the center. This phenomenon is due to the differences in hardness that the starting coupons possess. Their surface layer has hardness values significantly higher than the hardness values in the interior of the coupons.

Both coupons exhibit a typical hardness profile in welds. The values observed in the base material and in the HAZ are similar for both configurations. This result is expected since both coupons were welded with the same materials and process parameters. However, a significant difference is observed in the fusion zone, Fig 7. The coupon welded without any filler material shows hardness values close to the base material, with a maximum observed value of 206 HV. The addition of Ni foil has led to an increase in hardness, reaching a maximum value of 347 HV.

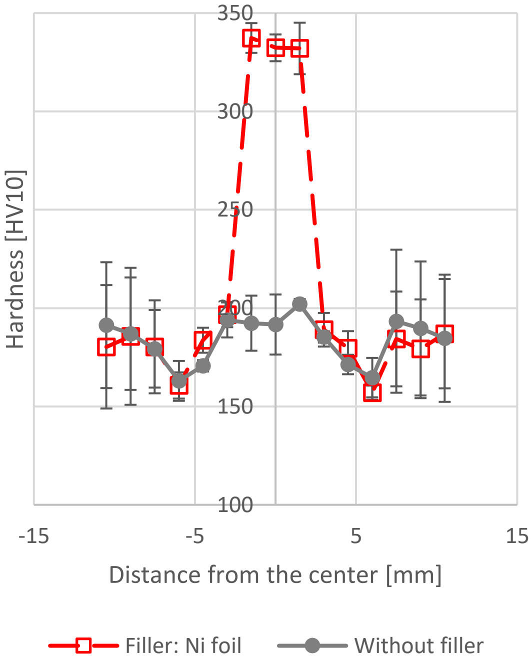

Fig. 7. Hardness values.

High hardness values are considered detrimental in welds as they can indicate material brittleness. ISO 15614-1 standard defines the maximum permissible value for welding of S355ML steel without heat treatment. This maximum value is 380HV. According to DNV-OS-C401, materials exposed to anaerobic environments or those subjected to cathodic protection must have a hardness value not exceeding 350 HV. Therefore, it is considered that the welds studied in this work meet this requirement.

3.1.5 Charpy impact test

The monopiles supporting wind turbines in marine environments can be subjected to low temperatures. In order to assess the weld toughness at low temperatures, Charpy tests have been conducted at -40°C according to EN ISO 9016. Two sets of three specimens have been extracted from the central zone of each coupon. This testing procedure has been repeated for two welding zones: the fusion zone and the heat-affected zone, as shown in Fig 8. To critically evaluate the results, EN ISO 15614-1 standard has been employed, defining a minimum acceptable value of 27 J at -40°C.

In the melted zone, the impact test results obtained from the coupon without filler material exhibit high variability. Additionally, very low values have been observed in half of the specimens: 9 J, 10 J, and 8 J. Therefore, if the joints have impact requirements, this configuration would not be suitable. However, it has been demonstrated that a 0.2mm Ni foil is sufficient to significantly improve these characteristics. Although the variability remains high, the minimum observed value has been 115 J, which greatly exceeds the required minimum.

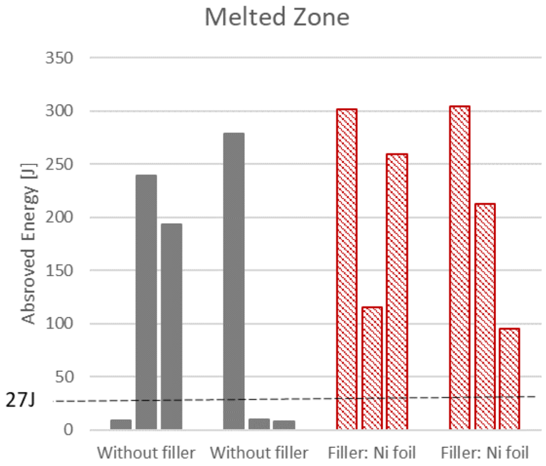

Fig 8. Charpy test in the melted zone.

The results in the HAZ zone are shown in the Fig 9. Notably, in the welded coupon without the filler material, no fracture toughness values fall below the threshold of 27J. However, there is a discernible presence of relatively lower values within this range. Such observations, when compounded with the observed high variability, introduce a potential concern regarding the adequacy of material toughness. Similarly, the Ni filler-incorporated coupon exhibits comparable trends, with instances of fracture toughness values falling below the specified threshold, indicating a need for further investigation and potential remediation strategies.

These results are consistent with the spectroscopic measurements observed. Nickel does not diffuse towards the HAZ, and the process conditions are very similar for both joint configurations. Therefore, no differences in hardness or toughness measurements are observed between the two types of joints studied.

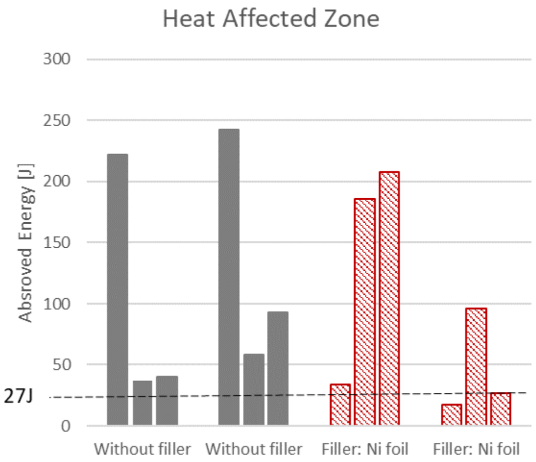

Fig 9. Charpy test in the HAZ.

While the Ni sheet has shown promise in enhancing toughness properties within the melted zone, noteworthy improvements in the HAZ have yet to be observed.

4 Conclusion

The fabrication of monopiles for offshore applications necessitates the welding of structural steels like S355 ML, often of substantial thicknesses. This study investigates the viability of EBW as an alternative to conventional arc welding processes. Welding experiments were conducted on 90mm thick S355 ML coupons using EBW technology, with a focus on comparing joint properties under two distinct configurations. One configuration employed a butt joint with straight edges and no filler material, while the other utilized a butt joint with a Ni foil interposed between the layers to be joined, along with a bevelled top surface.

The findings can be summarized as follows:

- Defect-free welds were achieved, although complete penetration was observed only in the coupon welded with the Ni foil and bevel.
- The melted zone exhibited a narrow profile, with the width of the weld bead being broader in the upper region.
- The HAZ appeared narrow, showcasing a microstructural transition from bainitic to ferritic-perlitic phases.
- Grain refinement was evident, particularly in the lower region, indicative of rapid cooling rates.
- The Ni foil added to the second coupon is uniformly distributed within the molten metal but does not diffuse into the HAZ.
- Hardness measurements aligned with EN ISO 15614-1 standards, albeit a notable increase in hardness was noted in the melted zone with the incorporation of the Ni foil.
- Welding without filler material resulted in joints with diminished toughness, a deficiency remedied by the addition of the Ni foil.
- Importantly, the toughness of the material in the HAZ remained unchanged with the inclusion of the Ni foil.

In summary, the results suggest that EBW holds promise as a viable alternative to conventional welding processes. However, the challenge of addressing material toughness in the HAZ warrants further investigation in future studies.

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