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THE DETERMINATION OF MECHANICAL PROPERTIES BY TENSILE TESTING OF HARDFACING WEAR PLATES

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Abstract: *This study examines the impact of weld row orientation on the mechanical properties of hardfacing wear plates, which are produced by applying a wear-resistant overlay onto S355MC structural steel using the flux-cored arc welding (FCAW-S) process. The research specifically investigates the tensile performance of specimens with weld orientations of 0°, 45°, and 90°. The objective is to determine which weld orientation optimally preserves stress transfer while minimizing performance losses in high-load conditions. The results underscore the critical role of weld alignment in influencing the mechanical response of wear-resistant overlays. This insight paves the way for future research aimed at incorporating additional influencing factors, such as the thermal effects induced during welding and strategies for minimizing the heat-affected zone (HAZ).*
Keywords: *wear, hardfacing, welding, FCAW-S, mechanical properties.*

1. INTRODUCTION

Tribology is the discipline that investigates the interactions between contacting surfaces, focusing on the phenomena of friction, wear, and lubrication. Wear, which involves material loss or deterioration at contact areas, is a critical factor influencing the service life of mechanical components, ranging from the nanoscale to the macroscopic scale [1]. The degradation of machine components leads to reduced performance and necessitates periodic shutdowns for replacement, generating additional costs. In this context, industries across various sectors are focusing on the development of advanced materials and optimized manufacturing technologies to enhance wear resistance and extend the operational lifespan of components in demanding environments [2].

Wear-resistant plates are produced by depositing a protective coating onto a metallic substrate using advanced coating technologies. The primary objective and key advantage of these plates is to extend the operational life of components by increasing the hardness of the applied layer, thereby reducing maintenance time and costs [3]. Due to these properties, the demand for such materials has significantly increased, as they are widely used in applications subject to abrasive wear, making them essential in industries such as ceramics, cement, asphalt, and mining [4]. Additionally, they play a crucial role in agriculture and the petrochemical industry [5], [6], [7].

The manufacturing process of these plates involves the application of a protective layer through welding, using flux-cored wire and a portal-type welding machine [8], [9]. The key welding parameters include: welding current, wire feed speed, travel speed of the welding torch, and weld bead width [10]. Furthermore, the orientation of weld beads – which can be linear or sinusoidal – significantly influences the final properties of the deposited layer, determining the mechanical strength and structural behavior of the material.

This paper presents a comparative analysis of the tensile mechanical behavior of wear-coated specimens with linearly arranged weld beads. The study investigates how weld bead orientation affects mechanical properties, particularly tensile strength values. By analyzing stress-strain behavior, stress distribution, and the heat-affected zone (HAZ), this research aims to identify optimal welding configurations to improve the mechanical performance of wear-resistant materials. The findings will provide practical insights for enhancing the durability and reliability of materials used in high-stress applications.

2. MATERIALS AND METHODS

To assess the tensile strength of the metallic material, testing was conducted in compliance with the ISO 6892-1 standard. This internationally recognized standard defines precise procedures for tensile testing, ensuring uniformity and accuracy in the evaluation of the mechanical properties of metallic materials under controlled conditions, typically at ambient temperature. By adhering to this standardized methodology, results can be reliably compared across different materials and studies, enhancing the consistency and reproducibility of mechanical performance assessments.

The base material used for the hardfacing wear plate is S355MC, a high-strength, low-alloy (HSLA) steel, widely employed in structural applications due to its excellent formability, weldability, and mechanical resilience. The selected material has a thickness of 6 mm and was obtained through a hot-rolling process, which enhances its mechanical properties by refining the grain structure and improving its homogeneity and strength. S355MC exhibits an engineering stress range between 430 MPa and 550 MPa, making it well-suited for applications that require a balance between high strength and ductility.

The chemical composition of S355MC, as certified by the manufacturer, adheres to strict quality standards to ensure performance consistency and compliance with industrial requirements. The elemental composition, including carbon, manganese, and other alloying elements, is detailed in Table 1, demonstrating how these constituents contribute to the steel's mechanical strength, toughness, and processability [11], [12]. The controlled chemical composition aligns with industry standards, confirming its suitability for hardfacing applications and subsequent mechanical testing.

Table 1.

Chemical composition of the material S355MC and overlay [%]

Material / Element	S355MC	Tubular wire
Mn	0,68	0,20
C	0,08	5,50
B	-	0,03
Ti	0,02	-
Si	0,01	1,30
Cr	-	29,50
S	0,01	-
Al	0,03	-
Nb	0,02	-
P	0,01	-
Fe	R	R

The wear-resistant overlay, characterized by a hardness range of 58 to 62 HRC, is applied through a welding process and has a deposited thickness of 3 mm. To manufacture the wear-resistant plates, from which the test specimens were extracted, the self-shielded flux-cored arc welding (FCAW-S) process was employed. This welding technique is particularly advantageous for hardfacing applications due to its use of a tubular electrode filled with a flux core, which generates protective shielding gases during the welding process. This self-shielding capability eliminates the need for an external shielding gas supply, making it an ideal choice for outdoor or harsh environments, where maintaining a stable shielding gas coverage can be challenging [8].

In addition to its operational flexibility, the FCAW-S process ensures efficient deposition of the wear-resistant layer with minimal dilution, thereby preserving the integrity of the hardfacing material. This results in a highly durable and abrasion-resistant overlay, providing consistent protection against wear and impact, which is crucial for applications operating under severe mechanical and environmental conditions [13], [14], [15].

The chemical composition of the flux-cored wire used in the welding process, which consists of ferro-alloy powder mixtures, is detailed in Table 1. These alloying elements play a critical role in enhancing the mechanical properties, wear resistance, and overall performance of the deposited overlay.

The methodology illustrated in Fig. 1 involves the application of the wear-resistant weld overlay in parallel rows of equal width, each measuring 23 mm, oriented along the rolling direction of the base material. Following the welding process, the test specimens were extracted using a precision cutting technique, with their dimensions detailed in Fig. 2.

The samples were produced using an H-Frame automated welding machine (Fig. 3), applying the FCAW-S welding process (which stands for Flux-Cored Arc Welding with a Self-shielding wire). The primary welding parameters utilized were a voltage of 28 V, current intensity of 280 A, wire feed speed of 3.30 m/min, and a Z-axis travel speed of 0.20 m/min. These parameters are within the range recommended by the wire manufacturer, ensuring optimal welding conditions and adherence to established safety and performance standards.

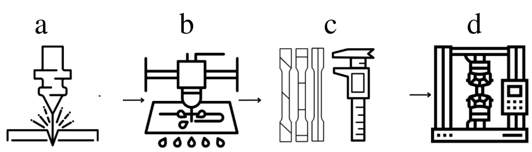

Fig. 1. Steps to perform the analysis: a – specimen welding, b - specimen cutting, c - specimen measurement, d - uniaxial tensile test.

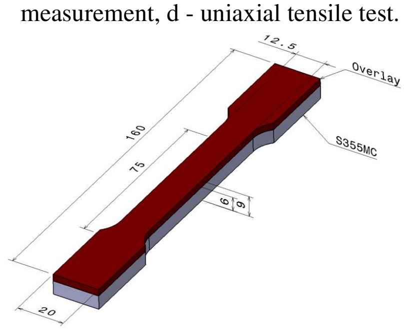

Fig. 2. Hardfacing specimen dimensions.

Fig. 3. H-Frame welding machine.

During the cutting process, particular attention was given to the orientation of the specimens to ensure accurate representation of different weld alignments. As a result, three distinct specimen types were prepared:

1. 0° specimens (aligned with the welding direction) – These were cut such that their length remained parallel to the direction of the weld beads.
2. 45° specimens (diagonal orientation) – These were extracted at an angle of 45° relative to the weld bead alignment.
3. 90° specimens (perpendicular orientation) – These were cut so that their length was perpendicular (at a 90° angle) to the welding direction.

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After qualitative inspection and dimensional verification of the specimens, uniaxial tensile tests were performed to fracture, in accordance with standardized testing procedures. The tests were conducted at room temperature, using a tensile testing speed of 15 mm/min, ensuring controlled and consistent evaluation of the mechanical performance of the wear-resistant overlays.

The tensile tests were performed using an INSTRON 5587 universal testing machine (Fig. 4), which features a static load capacity of 300 kN. This high-precision system enables the accurate determination of mechanical properties, including yield strength and ultimate tensile strength, in full compliance with the ISO 6892-1 standard.

Fig. 4. Uniaxial tensile test on INSTRON 5587.

To ensure uniform force distribution, the specimens were securely mounted using precision grips, minimizing misalignment and preventing premature failure due to improper clamping. A constant strain rate was applied throughout the testing process, ensuring accurate data acquisition and minimizing variability between tests.

The machine's advanced control and data acquisition system provided real-time monitoring of force-displacement behavior, ensuring high reliability and reproducibility of the experimental results. This setup allowed for a comprehensive analysis of the influence of weld row orientation on the tensile properties of the wear-resistant overlays, offering valuable insights into their mechanical performance under load.

3. RESULTS

The experimental investigation generated engineering stress-strain curves for each of the five specimen sets, providing a comprehensive analysis of the influence of weld row orientation on the tensile properties of the hardfacing wear plates. The primary objective was to evaluate how different weld alignments affected the mechanical response of the material under tensile loading.

As illustrated in Fig. 5, the average stress-strain curves corresponding to the 0°, 45°, and 90° weld orientations relative to the applied tensile force are presented. These curves are compared against the reference curve of the base material (S355MC), which was obtained from specimens cut along the rolling direction of the sheet metal. This reference serves as a benchmark, representing the unaffected mechanical properties of the substrate material, thereby enabling a direct comparative assessment of the impact induced by weld deposition and orientation on the overall tensile behavior of the wear-resistant overlay.

Specimens with weld rows aligned parallel to the tensile force direction (0° orientation) exhibited a notable reduction in mechanical performance compared to the base material. Specifically, the tensile modulus decreased by 44.05%, while elongation at break was reduced by 35.73%. These findings suggest that the presence of weld beads significantly compromises both stiffness and ductility, as opposed to the uniform microstructure of the base material, which inherently offers greater resistance to deformation.

When the weld rows were inclined at 45° to the tensile force direction, mechanical performance deteriorated further. The tensile modulus declined by 44.23%, whereas elongation at break dropped drastically by 60.51%. This substantial reduction is likely due to the introduction of stress concentration points, which restrict the material's ability to accommodate plastic deformation and exacerbate the risk of premature failure under tensile loading.

The 90° orientation, where the weld rows were perpendicular to the applied tensile force, exhibited the most pronounced degradation in mechanical properties. The tensile modulus decreased by 47.54%, while elongation at break showed a drastic reduction of 72.5%. This result underscores the detrimental impact of transverse weld bead alignment, which hinders efficient stress transfer and promotes localized weaknesses at the weld interfaces. The inability of the material to uniformly distribute stress in this configuration accelerates crack initiation and propagation, ultimately leading to early failure.

These findings highlight the critical influence of weld row orientation on the tensile behavior of hardfacing wear plates, emphasizing the need for optimized welding strategies to enhance the mechanical integrity and durability of wear-resistant materials in high-stress applications.

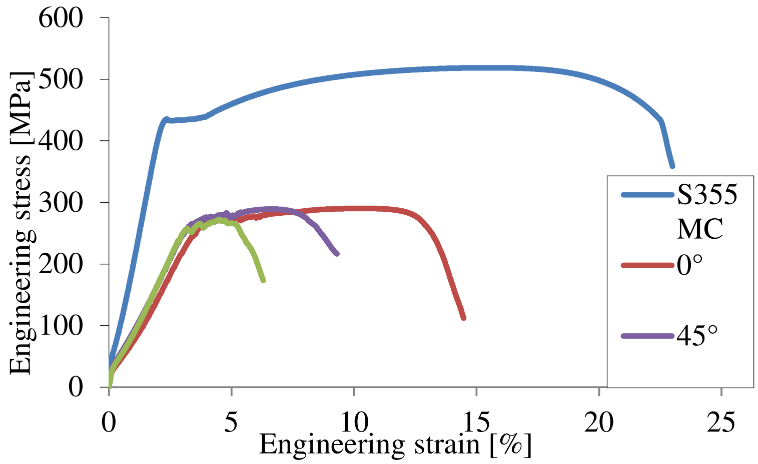

Fig. 5. Engineering stress vs. engineering strain curves for hardfacing wear plate and base material.

The base material, tested along its rolling direction, demonstrated superior mechanical properties, characterized by a high modulus of elasticity and notable ductility, as evidenced by its extended strain before failure. These enhanced mechanical characteristics can be attributed to the uniform microstructure of the material (Fig. 6), which ensures consistent load distribution and resistance to deformation.

Additionally, the absence of weld-induced stress concentrations eliminates potential weak points, allowing the material to maintain structural integrity and exhibit optimal mechanical performance under tensile loading.

Figure 7 presents a comparative analysis of the maximum tensile stress values for the three types of weld row orientations (0°, 45°, and 90°) against the average value of ultimate tensile strength of the base material, which was recorded as 518.8 MPa. This value serves as reference point for evaluating the reduction in tensile performance caused by the orientation of the weld rows in the hardfacing wear plates.

For specimens with weld rows aligned at 0° to the applied tensile force, the maximum tensile strength experienced a reduction of 228.5 MPa, indicating a significant decline in strength compared to the base material. This decrease is further amplified in specimens where the weld rows are oriented at 45°, with the tensile strength dropping by 229.44 MPa.

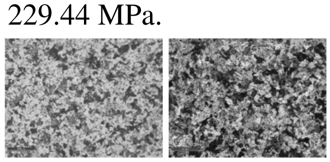

Fig. 6. Microstructure of base material.

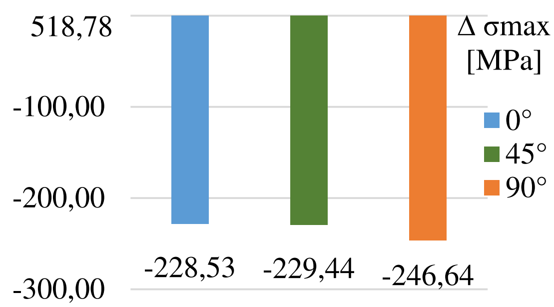

Fig. 7. Comparison of the average of maximum values of ultimate tensile strength for the three types of orientations.

The slightly greater reduction in this configuration suggests that the angular alignment impairs stress transfer efficiency, leading to localized stress concentrations that weaken the material's resistance to tensile loading.

The most substantial deterioration in mechanical performance was observed in specimens with weld rows perpendicular to the tensile force (90° orientation), where the ultimate tensile strength decreased by 246.6 MPa. This finding highlights the critical impact of transverse weld orientations, which hinder effective load distribution and promote early failure mechanisms, such as crack initiation and propagation along the weld interfaces.

The experimental data emphasize the direct correlation between weld orientation and tensile performance, demonstrating that as the alignment of weld rows becomes increasingly perpendicular to the applied force, the ultimate tensile strength progressively declines.

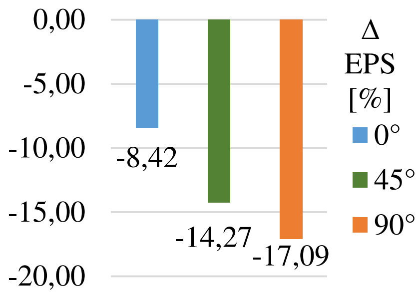

Fig. 8. Percentage variation in elongation at fracture (ΔEPS).

Additionally, figure 8 presents a comparative analysis of the percentage reduction in elongation at break (EPS) for the three weld orientations, relative to the base material, further illustrating the influence of weld alignment on ductility. Among the tested configurations, the 0° orientation exhibited the smallest reduction in elongation, with a decline of 8.4%, indicating that weld rows parallel to the tensile force preserve a substantial portion of the base material's deformation capacity. Conversely, the 45° orientation resulted in a more pronounced reduction of 14.3%, which can be attributed to the stress concentration effects introduced by the angular alignment. This configuration likely disrupts uniform plastic deformation, increasing the likelihood of premature failure. The most severe reduction in elongation at break was observed in specimens with 90° weld alignment, where the EPS decreased by 17.1%. This result underscores the detrimental impact of transverse weld rows, which impede effective stress distribution and limit plastic deformation, ultimately leading to reduced ductility and premature material failure.

Figure 9 presents a visual representation of the tensile specimens tested under various conditions, classified according to weld row orientation and material type. The specimens are systematically categorized as follows:

(a) represents the base material (S355MC), which serves as the reference sample, tested along its rolling direction to provide a benchmark for mechanical performance.

(b) corresponds to specimens with weld rows aligned parallel to the applied tensile force (0° orientation), allowing for the evaluation of stress transfer efficiency along the weld bead direction.

(c) includes specimens with weld rows oriented perpendicular to the tensile force (90° orientation), a configuration that significantly influences stress distribution and mechanical response.

(d) represents specimens with weld rows inclined at 45° to the tensile force, a condition that introduces angular stress concentrations, affecting both strength and ductility.

This classification enables a comparative analysis of the effects of weld orientation on tensile behavior, facilitating a deeper understanding of the mechanical performance of hardfacing wear plates under different loading conditions. A better understanding of heat dissipation and microstructural transformations could lead to enhanced process control, ensuring improved wear resistance and mechanical stability in demanding applications [1], [16], [17].

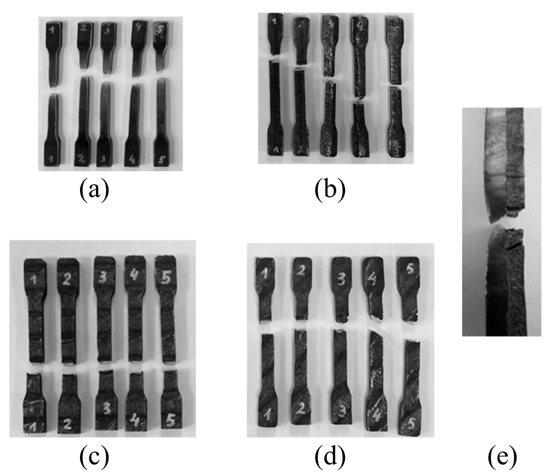

Fig. 9. Broken specimens after uniaxial tensile tests (a) – (d); detail view of broken specimen (e).

4. CONCLUSIONS

The experimental findings, achieved using specified welding parameters, indicate that weld row orientation plays a critical role in determining the mechanical performance of hardfacing specimens under tensile loading. Among the tested configurations, specimens with weld rows aligned parallel to the tensile force direction (0° orientation) exhibited the least reduction in mechanical properties compared to the base material. This suggests that a parallel weld alignment promotes more efficient stress transfer, thereby reducing degradation in key parameters such as tensile strength and elongation at break. These results underscore the importance of weld orientation optimization in maintaining the structural integrity and durability of wear-resistant materials.

Conversely, specimens with weld rows oriented at 45° and 90° exhibited more pronounced reductions in mechanical performance, with the 90° orientation resulting in the most severe deterioration. The findings highlight the adverse effects of non-parallel weld alignments, which create stress concentration zones, disrupt load distribution, and significantly impair the material's ability to withstand deformation. These observations confirm that transverse and angular weld bead configurations compromise the mechanical efficiency of hardfacing layers, reinforcing the necessity of weld alignment optimization to enhance material durability and resistance to tensile stress.

For future research, further investigation into additional factors influencing the mechanical behavior of hardfacing materials is recommended. In particular, the thermal effects induced during the welding process should be analyzed, especially their impact on the microstructure and mechanical properties of the base material. Understanding the interaction between welding heat and the cooling system is essential for optimizing process parameters and mitigating potential thermal damage.

Additionally, assessing the effectiveness of the cooling system during welding could provide valuable insights into minimizing the heat-affected zone (HAZ), which directly influences the hardness and overall mechanical integrity of the deposited layer. Addressing these aspects will contribute to the refinement of welding techniques, ensuring enhanced performance, reliability, and long-term stability of hardfacing materials in high-stress industrial applications.

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Determinarea caracteristicilor mecanice prin încercarea la tracțiune a tablelor placate

Rezumat: Acest studiu analizează impactul orientării rândurilor de sudură asupra proprietăților mecanice ale tablelor sudate, realizate prin aplicarea unui strat rezistent la uzură pe oțel structural S355MC, utilizând procesul de sudare cu electrod tubular (FCAW-S). Cercetarea prezintă în mod specific performanța la tracțiune a epruvetelor cu orientări ale sudurii de 0°, 45° și 90°. Obiectivul este de a determina care orientare a rândurilor de sudură asigură cel mai eficient transfer al forțelor, minimizând în același timp pierderile de performanță în condiții de sarcină ridicată. Rezultatele subliniază rolul esențial al aliniamentului sudurii în influențarea comportamentului mecanic al tablelor rezistente la uzură. Această perspectivă deschide calea pentru cercetări viitoare care să includă factori suplimentari, precum efectele termice generate în timpul sudării și strategii pentru minimizarea zonei influențate termic (HAZ).

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