

Effects of loading angle and build direction on the tensile behavior of WAAM steel produced with ER70S-6 welding wire

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Abstract: This study investigates the effects of loading angle and build direction on the tensile properties of components fabricated through wire arc additive manufacturing (WAAM) fabricated using ER70S-6 steel. Tensile tests were conducted at four loading angles (0°, 45°, 60°, and 90°) for two build directions (flat and upright). For each loading angle and build direction, two tensile specimens were tested, and the reported values were obtained from a representative specimen for each testing condition. The results reveal that the WAAM-fabricated specimens exhibited pronounced mechanical anisotropy, with the highest tensile strength obtained when the applied load is parallel to the bead direction, followed by a considerable reduction at other loading angles. For the upright build direction, the ultimate tensile strength decreased by approximately 47% at 45° relative to that at 0°, suggesting a possible contribution from interlayer shear stresses and delamination-related failure mechanisms. An empirical model was proposed to describe the dependence of tensile strength on the loading angle, enabling the quantitative evaluation of the role of different stress components. The flat build direction exhibited more stable mechanical behavior and a lower degree of anisotropy. In addition, hardness measurements showed that the variation in hardness was mainly governed by the build direction rather than the loading angle. The obtained results provide further insight into the relationship among layered structure, stress state, and mechanical properties, thereby supporting the design and application of WAAM structures subjected to multidirectional loading conditions.

Keywords: WAAM; ER70S-6 steel; tensile strength; loading angle; build direction; anisotropy; delamination

1. Introduction

Wire Arc Additive Manufacturing (WAAM) has been regarded as one of the most promising technologies for fabricating medium- and large-scale metallic components [1], [2], [3], [4], [5], [6]. Compared with powder-based metal additive manufacturing processes [7], [8], [9], [10], WAAM offers several advantages, including a high deposition rate, low material cost, relatively simple equipment, and ease of integration with automated industrial welding systems [3], [5], [6], [11], [12], [13]. In addition, its layer-by-layer deposition process enables the fabrication of complex geometries while reducing material waste, thereby supporting more sustainable manufacturing practices.

However, the WAAM process involves repeated thermal cycles and layer-wise solidification, which may result in heterogeneous microstructures and induce anisotropy in mechanical properties [5]. For WAAM-fabricated steels, differences in thermal history, localized remelting between adjacent layers, and preferential grain growth can significantly affect strength and ductility when the applied load is oriented differently from the bead direction. Therefore, a comprehensive understanding of

mechanical anisotropy is essential for developing reliable material models and supporting structural design.

Several studies have evaluated the mechanical properties of WAAM-fabricated steels produced using different welding wires, ranging from carbon steels to stainless steels and high-strength steels [14], [15], [16], [17]. The reported results indicate that WAAM materials can achieve, or even exceed, the strength levels of conventionally manufactured steels. These studies have also demonstrated that the mechanical response can be anisotropic because of the directional characteristics introduced during deposition, particularly the differences between the bead direction and the build direction, as well as variations in interlayer bonding quality [5], [14]. Nevertheless, previous studies have focused primarily on two representative loading angles, including parallel (0°) and perpendicular (90°) to the bead direction, whereas the influence of intermediate loading angles has not yet been systematically clarified. This represents a significant limitation because, under practical service conditions, structural components are often subjected to loads acting in arbitrary directions, leading to more complex stress states than uniaxial tension alone.

From a mechanical perspective, when the applied load deviates from the principal material directions, the stress state changes from pure tension to a combined tension–shear condition, thereby altering the fracture mechanism of the material [16], [18]. Although the effects of build direction, bead direction, and interlayer bonding have been widely reported, their combined influence under intermediate loading angles has not yet been quantitatively established for WAAM steels. Therefore, the present work systematically evaluates the effect of loading angle on the tensile mechanical properties of WAAM-fabricated steel using ER70S-6 welding wire. Specimens were fabricated in two build directions and tested under different loading angles. Based on the experimental results, this study aims to characterize mechanical anisotropy and quantify the relationship between loading angle and tensile strength.

2. Material and methods

2.1 Mechanical basis of tensile behavior under different loading angles

During the deposition process, directional heat transfer, together with repeated thermal cycles between successive layers, promotes the development of columnar grain structures along the build direction, thereby inducing microstructural anisotropy [19], [20]. This microstructure, combined with heat-affected zones and the non-uniform distribution of defects, causes mechanical properties such as tensile strength and ductility to be strongly dependent on the loading angle [21].

In addition, the formation of crystallographic texture and directionally oriented lamellar structures in WAAM materials also contributes to enhanced mechanical anisotropy. Previous studies have shown that WAAM-fabricated materials often exhibit pronounced anisotropy in both microstructure and mechanical properties due to the heterogeneous distribution and preferred orientation of crystalline structures [22]. Fundamentally, the presence of crystallographic texture, namely the preferential orientation of grains, makes the mechanical properties direction-dependent, particularly in materials fabricated through layer-wise deposition processes.

Figure 1 illustrates the mechanism of stress-state transformation in a WAAM material element subjected to tensile loading at a loading angle measured with respect to the bead direction. In this study, the bead direction refers to the deposition path of the welding wire, whereas the build direction corresponds to the layer stacking direction. The interlayer plane is defined as the interface at which two successive deposited layers bond during the WAAM process. Owing to its layer-by-layer fabrication characteristics, WAAM materials exhibit preferred material directions, including the bead direction and the build direction [23]. When the applied load is not aligned with these

directions, the stress state within the material becomes more complex than that under pure uniaxial tension. The nominal tensile stress σ applied at an angle θ with respect to the bead direction can be resolved into normal and shear stress components. Here, θ is defined as the angle between the loading direction and the bead direction (x -axis), while the y -axis represents the build direction and is normal to the interlayer plane. Assuming a uniaxial stress state, the stress components can be determined using the classical stress transformation equations, as expressed in Equation (1).

$$\sigma_x = \sigma \cos^2 \theta, \sigma_y = \sigma \sin^2 \theta, \tau_{xy} = \sigma \sin \theta \cos \theta \quad (1)$$

where σ_x and σ_y are the normal stress components along the bead and build directions, respectively, and τ_{xy} is the shear stress component acting on the interlayer plane. Figure 1 schematically illustrates the relationship between the loading direction, bead direction, interlayer plane, and the corresponding stress components described by Eq. (1). The shear stress reaches its maximum at $\theta = 45^\circ$, resulting in a combined normal-shear stress state that may promote sliding and crack propagation along the interlayer region. At $\theta = 0^\circ$, $\tau_{xy} = 0$ and the applied stress is carried along the bead direction. At $\theta = 90^\circ$, the shear stress also becomes zero, while the normal stress across the interlayer plane reaches its maximum value ($\sigma_y = \sigma$). Thus, the relative contributions of normal and shear stresses vary with the loading angle and may contribute to the orientation-dependent tensile behavior of the WAAM material.

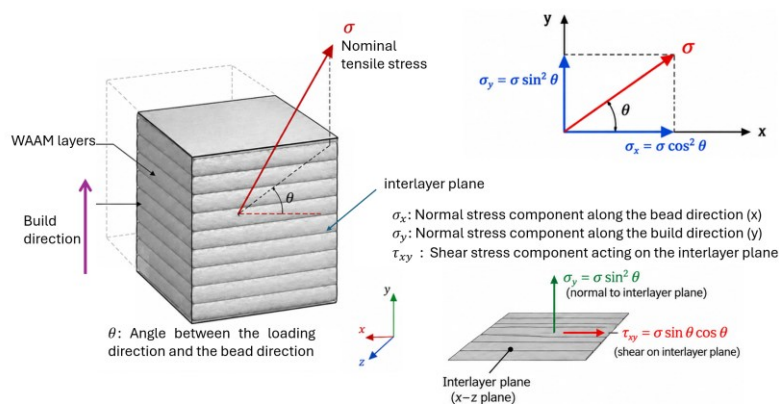


Figure 1. Stress state in a WAAM material element

Based on the stress decomposition analysis presented above, an empirical model was developed to describe the relationship between ultimate tensile strength f_u and loading angle θ . Previous studies have reported clear orientation-dependent mechanical behavior in anisotropic materials [24], [25]. The first two terms represent the contributions associated with the principal loading directions, while the term $\sin^2 \theta \cos^2 \theta$ follows the angular dependence of the squared normalized shear stress, $(\tau_{xy}/\sigma)^2$, defined in Eq. (1). The proposed model is expressed as follows:

$$f_u(\theta) = A \cos^2 \theta + B \sin^2 \theta - C \sin^2 \theta \cos^2 \theta \quad (2)$$

where A and B represent the tensile strengths at $\theta = 0^\circ$ and 90° , respectively, and C is an empirical coefficient accounting for the additional strength reduction at intermediate loading angles. The parameters A , B , and C , expressed in MPa, were estimated by least-squares fitting of the experimental UTS data.

The mechanical response of WAAM materials is therefore influenced by both the build orientation and the stress state associated with the loading angle. Evaluating the tensile behavior at different

loading angles is important for understanding the anisotropic response of the material and supporting its structural design and engineering applications.

2.2 Experimental setup

The experimental procedure was carried out according to the workflow shown in Figure 2, which includes WAAM deposition, specimen preparation, and mechanical testing.

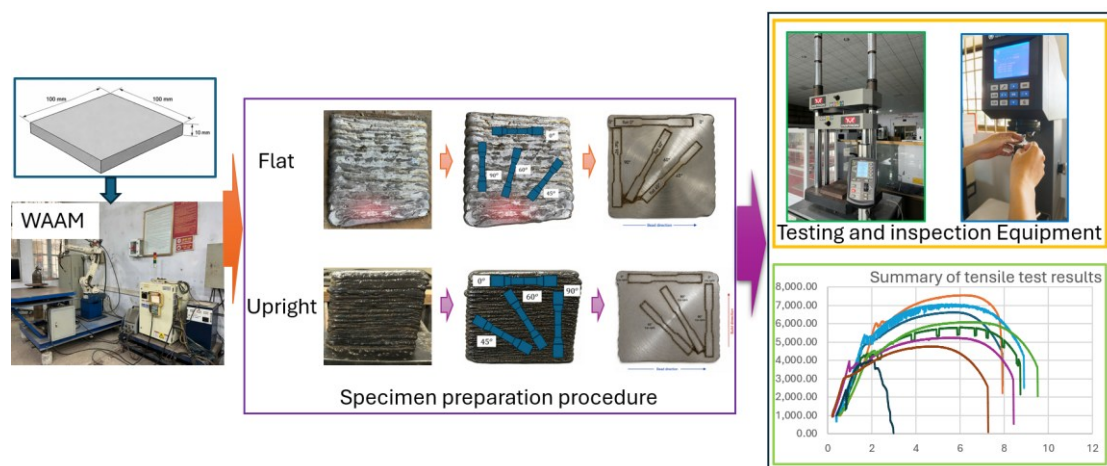


Figure 2. Experimental workflow for WAAM specimen fabrication and mechanical testing

The material used in this study was commercial ER70S-6 low-carbon steel welding wire with a diameter of 1.2 mm, conforming to AWS A5.18. The nominal chemical composition provided by the manufacturer is presented in Table 1. The relatively high manganese and silicon contents in the welding wire enhance deoxidation capability, improve arc stability, and reduce the formation of defects in the deposited metal. In the as-welded condition, the weld metal exhibits a minimum yield strength of approximately 420 MPa, a minimum ultimate tensile strength of approximately 500 MPa, and an elongation of not less than 22%, making it suitable for the fabrication of low-carbon steel structures as well as WAAM applications.

Table 1. The composition of ER70S-6

Component	Content (wt.%)
Carbon	0.06 – 0.15
Manganese	1.40 – 1.85
Silicon	0.80 – 1.15
Sulfur	≤ 0.035
Phosphorus	≤ 0.025
Copper	≤ 0.50
Nickel	≤ 0.15
Chromium	≤ 0.15
Molybdenum	≤ 0.15
Vanadium	≤ 0.03
Iron	Bal

The WAAM experimental system used for specimen fabrication is shown in Figure 3. The system consists mainly of a robotic arm, a MIG welding unit, a welding nozzle, a wire-feeding system, and a shielding gas supply. During deposition, the robotic arm controls the movement of the welding nozzle along the programmed path, while the MIG welding unit supplies the welding current and

continuously feeds the wire to form successive deposited layers. The shielding gas is supplied through the welding nozzle to protect the molten pool during deposition.

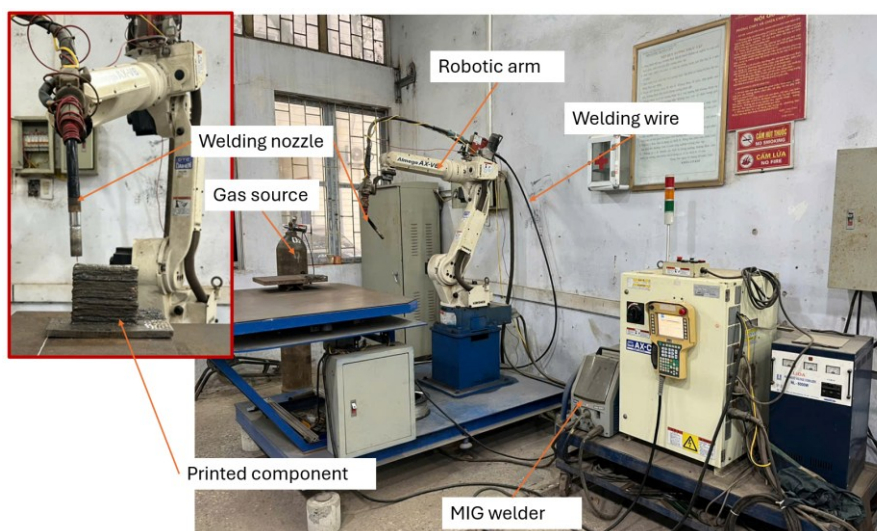


Figure 3. WAAM experimental setup used for specimen fabrication

The printed blanks were fabricated in the form of plates with nominal dimensions of 100×100×10 mm using the WAAM process in two different build directions in order to evaluate the effect of build direction on the mechanical properties of the material. Two WAAM plates were fabricated for each build direction (flat and upright). Tensile specimens at loading angles of 0°, 45°, 60°, and 90° were extracted from each plate. Consequently, two tensile specimens were tested for each loading angle and build direction, and a representative specimen was used for the reported values. The maximum difference in UTS between the two specimens tested under the same condition was 8%, which is considerably smaller than the variation caused by the loading angle. The main printing parameters used in this study are presented in Table 2.

Table 2. Process parameters used for WAAM

Parameter	Value
Welding current	175 A
Arc voltage	24 V
Travel speed	35 cm/min
Shielding gas flow rate	20 L/min
Wire diameter	1.2 mm

After completion of the printing process, the deposited material blocks were machined into tensile specimens using wire electrical discharge machining (wire EDM) in order to minimize thermal deformation and ensure geometrical accuracy. The tensile specimens were extracted at different loading angles relative to the bead direction, namely 0°, 45°, 60°, and 90° (Figure 4). For each build direction, eight tensile specimens were prepared (two specimens for each loading angle), resulting in a total of 16 tensile specimens for the two build directions. The selection of these loading angles enables the evaluation of the mechanical anisotropy of WAAM materials, which arises from differences in interlayer bonding and crystallographic growth direction during solidification [5], [26], [27]. After cutting, the specimens were finished by milling and grinding to achieve the required dimensions before tensile testing.

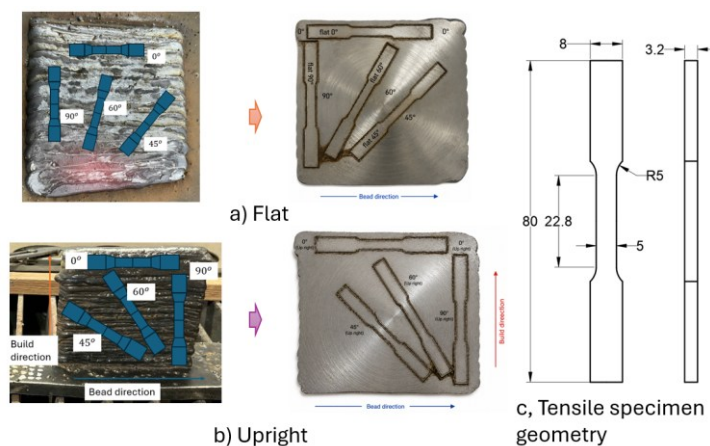


Figure 4. Direction of specimen cutting from WAAM printed blocks

Tensile tests were conducted using an Instron Satec 300DX static hydraulic universal testing machine (300 kN capacity) in accordance with ASTM E8/E8M-08. The tests were performed under displacement control at a constant crosshead speed of 1 mm/min. Axial strain was estimated from the crosshead displacement and the initial gauge length, as no extensometer was used, i.e., $\epsilon = \Delta L / L_0$, where ΔL is the crosshead displacement and $L_0 = 22.8$ mm is the length of the reduced section (Figure 4c). Engineering stress was calculated from the applied load and the initial cross-sectional area of the reduced section (5×3.2 mm). Since the crosshead displacement also includes the elastic deformation of the machine and grips, the strain is somewhat overestimated, mainly in the elastic region. The strain values were therefore used only for comparison between specimens, whereas the ultimate tensile strength is not affected. All specimens fractured within the reduced gauge section, with no fracture observed at the shoulders or gripping regions. Two specimens were tested for each build direction and loading angle, and representative values were reported.

The hardness of the WAAM specimens was determined on the Rockwell B scale (HRB) using a Wilson Hardness Rockwell 574 hardness tester, as shown in Figure 5. The test was conducted in accordance with ASTM E18. To ensure the reliability of the results, hardness measurements were performed at multiple locations on the specimen surface, avoiding regions near the edges, defects, or heat-affected zones induced by machining. For each specimen, at least five hardness measurements were obtained at different surface locations, and their arithmetic mean was calculated.

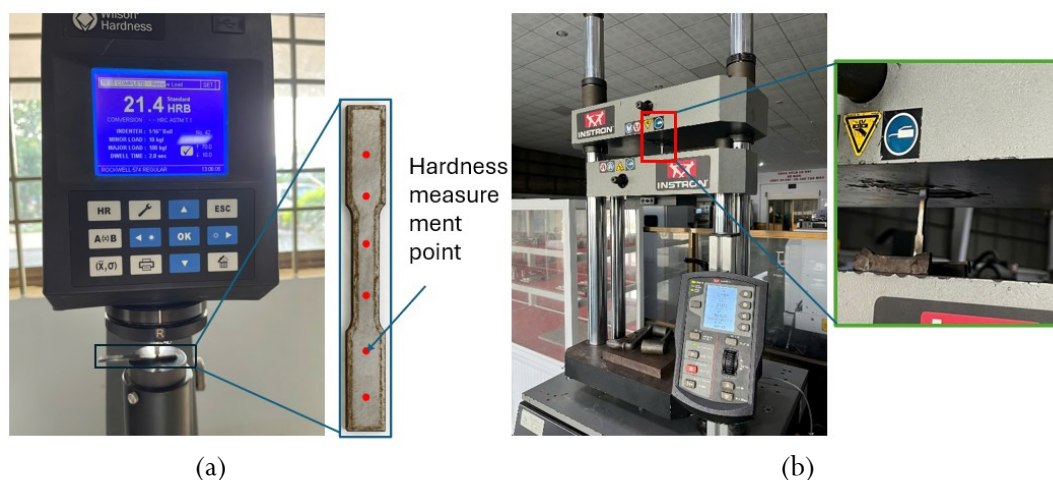


Figure 5. Experimental equipment: (a) Rockwell hardness tester (Wilson Hardness) and (b) universal testing machine (Instron) for tensile testing

3. Results and discussion

3.1 Tensile behavior under different loading angles

Figure 6 presents the stress–strain curves of the WAAM specimens tested at different loading angles for the two build directions (flat and upright). For clarity, one representative curve is shown for each condition. All specimens exhibited the typical deformation stages of metallic materials, including a linear elastic region, transition to plastic yielding, and plastic deformation until fracture. The pronounced differences in ultimate stress, initial slope, and post-peak softening behavior indicate the strong influence of loading angle and build direction on the mechanical response.

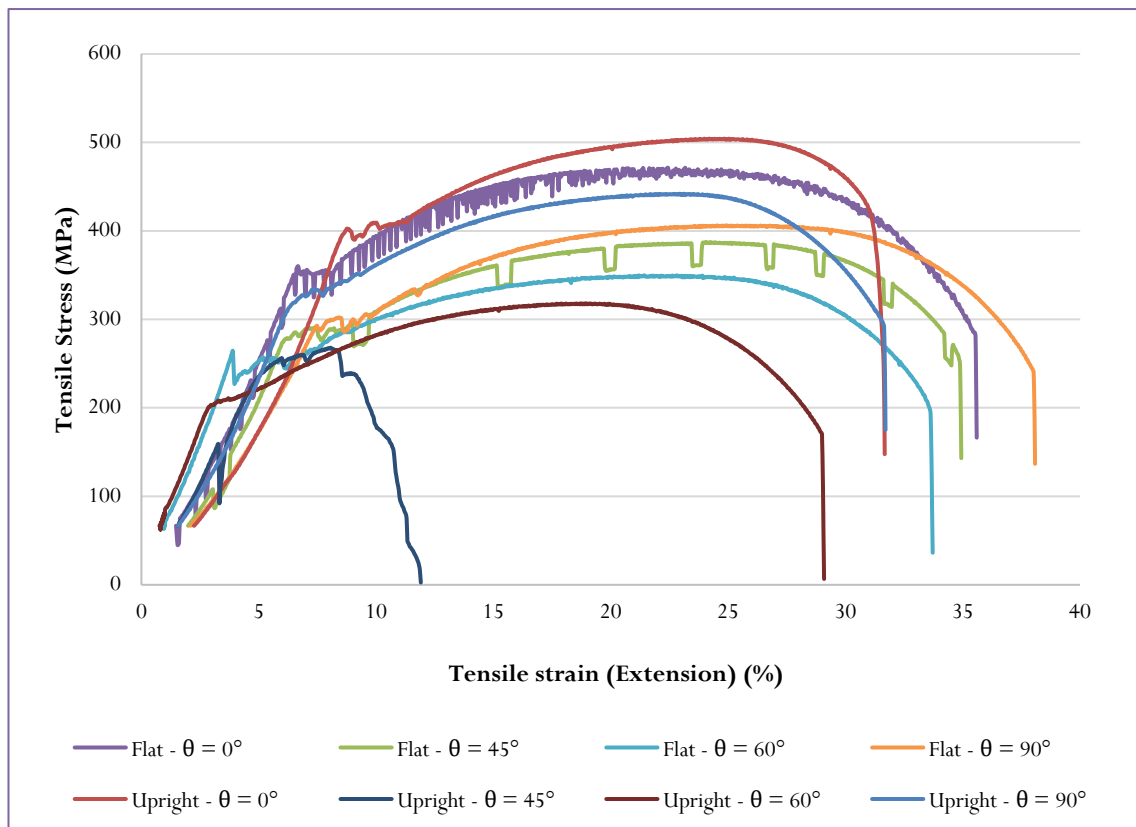


Figure 6. Stress–strain curves of WAAM specimens for flat and upright build directions at different loading angles

Specimens loaded at 0° (i.e., parallel to the bead direction) exhibited the highest tensile strength. This can be attributed to the continuity of the material structure along the deposition direction, which enables the applied stress to be effectively transferred along the beads. In contrast, as the loading angle increased, particularly at intermediate angles of 45° and 60° , the tensile strength decreased markedly. This trend reflects the transition from a pure tensile stress state to a combined tension–shear stress state, as discussed in the theoretical framework.

Notably, the specimens loaded at 45° generally showed the lowest tensile strength. This observation is consistent with the mechanical analysis, as the resolved shear stress reaches its maximum magnitude at this angle, potentially promoting interlayer sliding and fracture. For the upright specimens, the ultimate tensile strength reached approximately 504 MPa at $\theta = 0^\circ$, where the applied load was parallel to the bead direction. As the loading angle increased to 45° , the ultimate tensile strength decreased to approximately 268 MPa, corresponding to a reduction of approximately 47% relative to the UTS at 0° , i.e., $(504 - 268)/504 \times 100\%$. Subsequently, at 60° , the tensile strength partially recovered to about 318 MPa and further increased at 90° approximately 442 MPa.

Figure 7 shows the fitting results of the $f_u(\theta)$ model against the experimental data of the WAAM specimens, revealing a clear dependence of ultimate tensile strength on loading angle and build direction. Overall, the fitted model reproduced the observed dependence of ultimate tensile strength on loading angle, namely the minimum at 45° and the recovery at 60° and 90° , particularly for the upright build direction, where the fitted curve showed close agreement with the measured values (maximum deviation of 8.4 MPa, or 2.6%, at 60°). This trend was well described by the following equation (3).

$$f_{u,\text{upright}}(\theta) = 503.19\cos^2 \theta + 445.09\sin^2 \theta - 799.30\sin^2 \theta \cos^2 \theta \quad (3)$$

Equation (3) represents the fitted form of Eq. (2) for the upright specimens. The obtained coefficients reproduce the pronounced reduction in UTS at intermediate loading angles, consistent with the experimental trend shown in Figure 7.

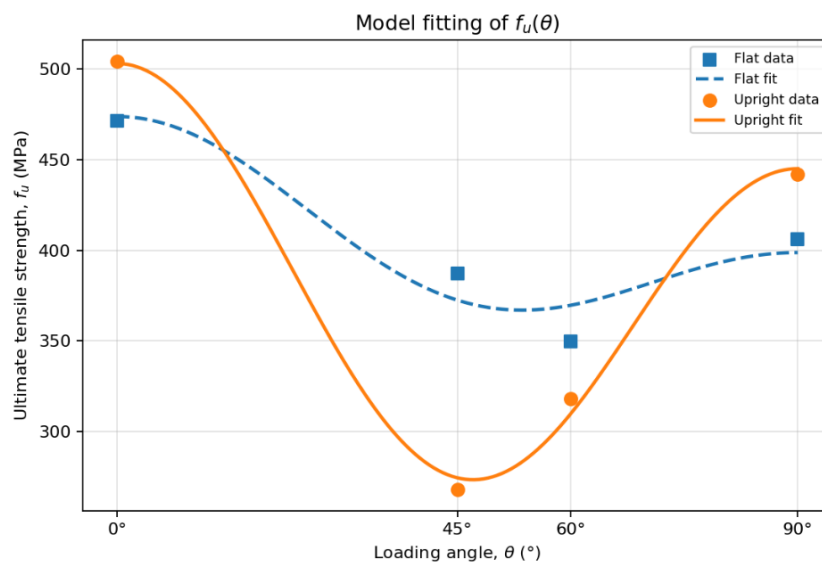


Figure 7. Experimental data and fitted curves

For the upright specimens, the fitted model yielded a coefficient of determination of $R^2 = 0.997$. Since three parameters were fitted to four loading angles, this value describes the measured trend within the tested range rather than confirming the predictive capability of the model. The large value of the parameter C indicates the dominant influence of the shear stress component at intermediate loading angles. In fact, at $\theta \approx 45^\circ$, the shear stress $\tau = \sigma \sin \theta \cos \theta$ reaches its maximum value, which may promote interlayer sliding and delamination and thereby contribute to the substantial reduction in tensile strength. Meanwhile, the upright stress-strain curves exhibited an abrupt post-peak stress drop, reflecting a more brittle fracture mechanism associated with the rapid propagation of cracks through weakly bonded interlayer regions.

In contrast, the flat specimens exhibited a lower degree of anisotropy. The ultimate tensile strength ranged from 350 to 471 MPa, with the highest value obtained at $\theta = 0^\circ$ (~ 471 MPa) followed by a moderate reduction at the intermediate loading angles. The UTS–loading angle relationship for the flat specimens, obtained by fitting Eq. (2) to the experimental data, is given by Equation (4).

$$f_{u,\text{flat}}(\theta) = 473.89\cos^2 \theta + 398.73\sin^2 \theta - 255.42\sin^2 \theta \cos^2 \theta \quad (4)$$

With $R^2 = 0.913$ (maximum deviation of 19.9 MPa, or 5.7%, at 60°). The significantly lower value of C compared with that of the upright build direction indicates a weaker influence of the

shear stress component, reflecting a more uniform stress distribution within the structure. This can be attributed to the fact that, in the flat build direction, the applied load is mainly transferred along the beads, thereby reducing the role of interlayer interfaces and limiting shear-induced failure mechanisms. In addition, the stress–strain curves of the flat specimens showed a more gradual post-peak stress reduction, indicating more uniformly distributed plastic deformation and a more ductile fracture mechanism. This result indicates that the mechanical behavior of WAAM materials can be considered analogous to that of laminated composite materials, in which strength is strongly dependent on the loading angles relative to the build direction.

3.2 Hardness distribution

The Rockwell hardness (HRB) results of the WAAM specimens are presented in Figure 8. The hardness values showed only minor variations with loading angle compared with the tensile strength, indicating that hardness is less sensitive to changes in loading angles. However, a pronounced difference was observed between the two build directions. The average hardness of the upright specimens (~22.7 HRB) was higher than that of the flat specimens (~19.9 HRB), corresponding to an increase of approximately 14%. This indicates that the build direction has a certain influence on the resistance of the material to localized plastic deformation.

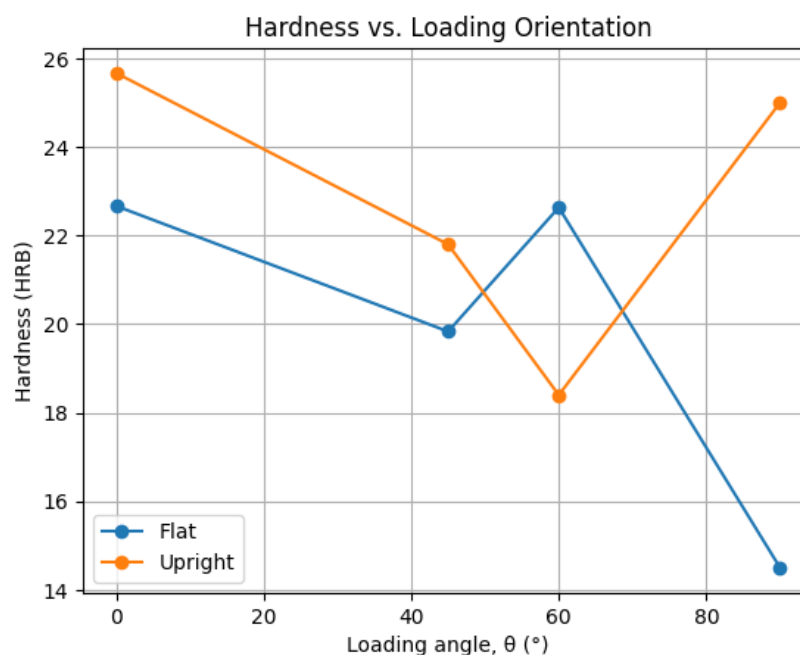


Figure 8. Variation in Rockwell B hardness (HRB) with loading angle (θ) for flat and upright WAAM specimens

This difference may be attributed to the different thermal histories experienced during the WAAM process. In the upright build direction, the deposited layers are repeatedly reheated by subsequent layers, resulting in repeated thermal cycles that promote microstructural refinement and increase the dislocation density. These factors contribute to the increased hardness of the material. In addition, the larger thermal gradient along the build direction may also lead to a locally higher cooling rate, which may be associated with grain refinement through the Hall–Petch strengthening mechanism [14].

In contrast, in the flat build direction, the degree of heat accumulation and the number of reheating cycles are lower, resulting in a relatively coarser and more uniform microstructure. Consequently, the flat specimens exhibited lower hardness values with less variation. However, the variation in

hardness with loading angle was still considerably smaller than that observed for tensile strength. This indicates that hardness mainly reflects the local microstructural characteristics of the material, whereas tensile strength is more strongly governed by interlayer bonding quality and the overall stress state. This distinction may help explain why the upright build direction exhibited higher hardness values but did not necessarily correspond to superior tensile load-bearing capacity. Although no direct fracture or microstructural characterization was performed in the present study, this interpretation is based on the observed mechanical response and the stress-state analysis.

4. Conclusion

This study investigated the effects of loading angle and build direction on the tensile mechanical properties of WAAM-fabricated ER70S-6 steel. The results showed that the material exhibited pronounced anisotropy, with the highest tensile strength obtained when the applied load was parallel to the bead direction ($\theta = 0^\circ$) followed by a significant reduction at intermediate loading angles. This reduction was particularly evident in the upright build direction, where the tensile strength decreased by approximately 47% at $\theta = 45^\circ$ relative to that at $\theta = 0^\circ$. This trend is consistent with an increased contribution from resolved interlayer shear stresses at intermediate loading angles, although the associated fracture mechanisms require direct confirmation by fractographic and microstructural analyses, which were not performed in the present study. The proposed empirical model successfully described the dependence of tensile strength on loading angle with a high coefficient of determination for the upright specimens ($R^2 \approx 0.997$). The fitted parameter C captured the additional strength reduction at intermediate loading angles. Compared with the upright build direction, the flat build direction exhibited more stable mechanical behavior and a lower degree of anisotropy. In addition, Rockwell hardness was less sensitive to loading angle but was affected by printing orientation, with the upright specimens showing higher hardness values due to repeated thermal cycling and microstructural refinement. However, hardness did not directly correlate with tensile strength, indicating that the failure behavior of WAAM materials is mainly governed by interlayer integrity and the overall stress state. These findings improve the understanding of the tensile behaviour of WAAM-fabricated ER70S-6 steel under the investigated build directions and loading angles and may provide useful guidance for similar WAAM applications.

Author's declaration

Author contribution

Nguyen Thien Nhut: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft. **Nguyen Tan No:** Investigation, Resources, Data curation. **Cao Le Anh Kiet:** Investigation, Validation, Visualization. **Nguyen Van Cuong:** Conceptualization, Methodology, Supervision, Project administration, Writing – original draft, Writing – review & editing. All authors have read and agreed to the published version of the manuscript.

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Data availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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Conflict of interest

The authors declare that they have no competing interests.

Ethical clearance

Not Applicable

AI statement

This manuscript presents original research conducted by the authors and has been proofread by an English language expert. No generative AI tools were used to produce the text or figures. The authors take full responsibility for the accuracy and integrity of all content presented in the manuscript.

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