On the Determination of the Forming Limits of Low-Alloy Steel Thin-Walled Tubes

João Magrinho[1*], *Pedro* Cruz[1], *Eneko* Sáenz-De-Argandoña[2], *Joseba* Mendiguren[2] and *M. Beatriz* Silva[1]

[1]IDMEC, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, Lisboa, 1049-001, Portugal
[2]Mondragon Unibertsitatea, Faculty of Engineering, Department of Mechanics and Industrial Production, Loramendi 4, Arrasate-Mondragon, Gipuzkoa, 20500, Spain

Abstract. This paper presents an innovative methodology to determine the formability limits of low-alloy steel tubes, with particular attention to the effects of the weld line on their performance. Digital Image Correlation (DIC) system, coupled with time-dependent methodologies is used to identify the onset of failure by necking and to measure the corresponding limit strains. Thickness measurements and gauge length strain analysis across cracked regions are employed to characterise the onset of fracture and to evaluate fracture limit strains. The methodology incorporates tensile tests in longitudinal and transversal directions and tube expansion tests using elastomers to generate strain loading paths and fracture strain pairs across a broad spectrum of forming conditions. These conditions range from biaxial stretching in the first quadrant to pure tension in the second quadrant of principal strain space. The unique influence of the weld line is highlighted, including its impact on both the Forming Limit Curve (FLC) and the Fracture Forming Line (FFL) plotted in the principal strain space. This study demonstrates, for the first time, the FFL of low-alloy steel thin-walled tubes, providing critical insights for optimising tube forming processes involving welded materials.

Keywords: Tube forming; Thin-walled tubes; Formability; Formability limits.

1 Introduction

The formability of low-alloy steel tubes is a critical factor in numerous industrial applications, particularly in automotive and aerospace manufacturing, where lightweight and high-strength materials are required [1]. Understanding the limits of plastic deformation before failure is essential for optimizing forming processes and ensuring structural integrity. However, determining these limits is particularly challenging for welded tubes, where the presence of a weld line introduces localized variations in mechanical properties and strain distribution [2].

In recent years, experimental techniques such as the Digital Image Correlation (DIC) systems have emerged as powerful tools for analyzing deformation and strain distributions in forming processes. Coupled with time-dependent methodologies and thickness measurements, DIC enables precise identification of the onset of necking and fracture in metal tubes under various loading conditions [3]. In this work, a novel approach is proposed to determine the formability limits of welded low-alloy steel tubes by integrating DIC and thickness measurements with time-dependent methodologies to determine the formability limits by necking and fracture from tensile tests performed in the longitudinal and transversal directions.

The effects of the weld line on both Forming Limit Curve (FLC) and Fracture Forming Limit (FFL) are examined, providing new insights into the deformation and failure mechanisms of thin-walled welded tubes. This work not only establishes, for the first time, both the FLC and FFL of such materials but also offers valuable guidance for improving forming processes and predicting failure in welded tube applications.

2 Experimentation

The investigation was conducted on a commercially low-alloy steel tube with a circular cross-section, featuring an outer radius of 20 mm and a wall thickness of 0.9 mm. The tube was manufactured through roll forming and welded using high-frequency induction welding [4].

The mechanical properties and stress-strain behaviour of the tubular material were evaluated through longitudinal and transverse (also known as “ring hoop”) tensile tests. The specimens were machined from the supplied tubes. Notably, some of the specimens in both longitudinal and transverse directions were aligned with the weld line to assess its influence on mechanical performance.

Longitudinal tensile test specimens, with a gauge length of 50 mm, were prepared in accordance with the ASTM E8/E8M-22 standard [5]. Additionally, to account for tube wall thickness variations along the circular cross-section, longitudinal specimens were extracted at every 90° along the perimeter. Transverse

* Corresponding author: joao.magrinho@tecnico.ulisboa.pt

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tensile test specimens followed a sub-size geometry of the ASTM E8/E8M standard [5]. To minimize friction between the specimen and the tool system, polytetrafluoroethylene (Teflon®) sheets were used as a lubricant. All tensile tests were conducted at ambient temperature using an Instron 5900R universal testing machine.

Strain measurements near fracture in tensile tests were performed using a Dantec Dynamics Q-400 3D digital image correlation (DIC) system. Specimen surfaces were coated with a black speckle pattern on a white background for contrast. A single spotlight illuminated specimens to ensure adequate measurement coverage. The DIC system featured two 6-megapixel cameras with 50.2 mm focal lenses f/11, capturing images at 10 frames per second. Analysis was conducted using INSTRA 4D software with a facet size of 13 px and a spacing grid of 7 px.

3 Results and Discussion

Fig. 1 shows the stress-strain curves resulting from the sheet blank before tube forming, as well as the longitudinal and transverse tensile test specimens retrieved from the tube.

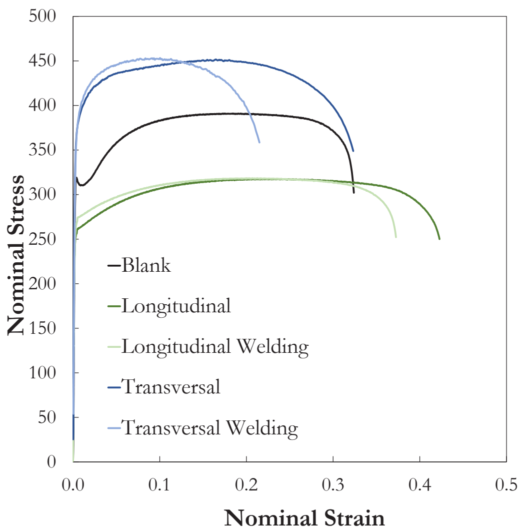

Fig. 1. Average true stress – true strain curves.

The stress-strain curves reveal distinct mechanical behaviours depending on the testing direction. The sheet blank exhibits an average response, while transverse tensile tests demonstrate higher mechanical properties compared to longitudinal tests, which, in contrast, show lower strength but greater elongation at break. The comparison between welded and base material specimens in both directions indicates similar mechanical behaviour, suggesting that the weld line does not significantly alter the overall stress-strain response. However, the base material exhibits slightly higher deformation before failure, indicating a greater ductility compared to the welded specimens.

Fig. 2 illustrates the strain loading paths, as well as the necking and fracture points obtained from the tensile tests. Theoretically, FLC and FFL were plotted in the principal strain space using the necking and fracture points, respectively. The strain loading paths exhibit a characteristic slope of -2, typical of uniaxial tensile conditions. While the necking points are consistent across all five testing conditions, the fracture points show notable differences. The sheet blank and transverse test specimens display similar fracture strain values, with the longitudinal specimens exhibiting higher fracture strains. These findings align with the stress-strain curves, where longitudinal specimens demonstrate greater elongation at break. Overall, the weld line does not significantly impact the formability of the thin-walled tube.

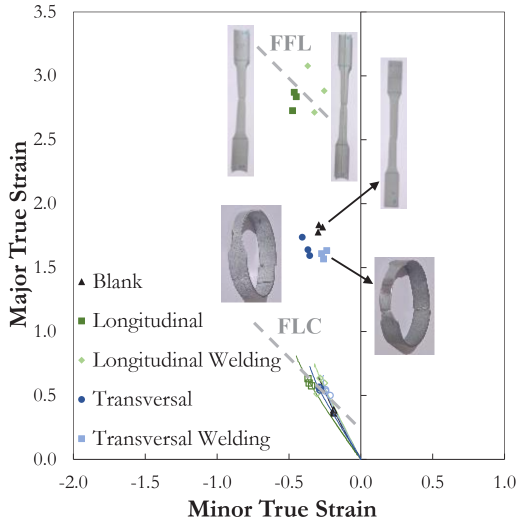

Fig. 2. Strain loading paths and necking and fracture points from tensile tests in principal strain space.

4 Conclusions

This study presents a methodology to determine the formability limits of low-alloy steel tubes, emphasizing the weld line's influence. Using Digital Image Correlation (DIC) and tensile tests in different orientations, the onset of necking and fracture were identified. Results show that transverse specimens exhibit higher strength, while longitudinal ones display greater elongation. The weld line has minimal impact on formability, with only slight differences in fracture strain between welded and base materials. These insights enhance the understanding of welded tube behaviour, aiding process optimization. Future studies should investigate formability under different stress states.

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