Stress-strain analysis and fracture assessment of AISI 304 steel centrifugal pump shaft sleeves under industrial operating conditions

Análisis tensodeformacional y evaluación de fractura en camisas de bombas centrífugas de Acero AISI 304 bajo condiciones operativas industriales

Rosabel Barrera Ruiz* rosabelruiz2904@gmail.com (1)
https://orcid.org/0009-0005-1904-1720
Anabel Ruiz Padilla aruiz@ismm.edu.cu (2)
https://orcid.org/0009-0003-0750-8472
(2) Pedro Sotto Alba Nickel Company, Moa, Cuba (2) University of Moa, Moa, Cuba
* Corresponding author

Abstract: This article presents a technical study on the stress-strain behavior and fracture susceptibility of centrifugal pump casings manufactured from AISI 304 stainless steel, used in Cuban industrial hydraulic systems. Principles of fracture mechanics and finite element simulations are applied to determine critical stress zones, permissible crack size, and stress intensity factors. The results allow establishing recommendations for predictive and redesign maintenance of these components.

Keywords: alloy steels, fluid mechanics, mechanical equipment

Resumen: Este artículo presenta un estudio técnico sobre el comportamiento tensodeformacional y la susceptibilidad a la fractura de camisas de bombas centrífugas fabricadas en acero inoxidable AISI 304, utilizadas en sistemas hidráulicos industriales cubanos. Se aplican principios de la mecánica de fractura y simulaciones por elementos finitos para determinar zonas críticas de esfuerzo, tamaño de grieta permisible y factores de intensidad de tensiones. Los resultados permiten establecer recomendaciones para el rediseño y mantenimiento predictivo de estos componentes.

Palabras clave: aceros aleados, equipamiento mecánico, mecánica de fluidos

1. Introduction

Centrifugal pumps are key components in industrial hydraulic systems, where operational efficiency and reliability depend on the structural integrity of their internal parts (Valarde *et al.,* 2023; Fajardo-Pulido *et al.,* 2024; López *et al.,* 2024). Particularly, the shaft sleeves located at the impeller are subjected to complex stresses including tension, compression, bending, and torsion, which can lead to fatigue or fracture failures. In Cuba, KSB-67227 pumps used in metallurgical industries have evidenced recurrent sleeve failures, generating economic losses and unscheduled downtime.

Fracture mechanics offers tools to predict material's behavior when having internal or surface flaws, allowing failure anticipation and design improvement. This study focuses on AISI 304 steel, used for its corrosion resistance and good mechanical properties (Silvina Román *et al*., 2016; Suárez-Miranda & Vargas-Gutiérrez, 2024; Ruelas Santoyo *et al.,* 2025).

The structural integrity of components subjected to severe operating conditions, such as centrifugal pump shaft sleeves used in industry, is a critical aspect for safety and efficiency in industrial processes. AISI 304 stainless steel is widely used to manufacture these components due to its excellent corrosion resistance and ease of shaping and welding (Estupiñán *et al.,* 2022; Barbosa *et al.,* 2022; Barbosa *et al*., 2023; Aznárez-Ferrando *et al*., 2024). However, the presence of flaws inherent to the manufacturing process (such as weld discontinuities) and exposure to cyclic loads, corrosive environments, and variable temperatures can compromise these elements' structural integrity and lifespan (España *et al*., 2008; Arganis-Juárez & Zenteno-Suárez, 2023).

This study is aimed at analyzing the stress-strain behavior and fracture assessment of AISI 304 steel centrifugal pump shaft sleeves, by integrating both experimental characterization and advanced numerical simulation. The main problem lies in the need to guarantee the structural integrity of the shaft sleeves despite the presence of flaws, especially in the weld zones and heat-affected zones (HAZ), under the combined action of mechanical, thermal, and environmental loads, which can induce brittle fracture, ductile fracture, fatigue, and stress corrosion mechanisms (Arganis-Juárez & Zenteno-Suárez, 2023).

2. Materials and methods

2.1. AISI 304 Steel Characterization

AISI 304 stainless steel is an austenitic material with a typical composition of 18 % Cr and 8 % Ni, providing it with excellent corrosion resistance and good mechanical properties (Li & Zeng, 2022; Zhou *et al.,* 2025). These mechanical properties vary according to the supply condition and processing.

Table 1. Average mechanical properties of AISI 304 stainless steel (annealed, ASTM A240/A276)

Property	Average Value
Tension Resistance (MPa)	515-620
Yield Strength 0.2 % (MPa)	205-310
Elongation (%)	40-60
Hardness Brinell (HB)	≤ 201
Elastic Modulus (GPa)	193
Density (g/cm^3)	7.93

2.1.2. Toughness Tests and Suitable Standards

Fracture toughness is key to evaluating resistance to crack propagation. The most commonly used tests on metals are:

- Charpy V-notch (CVN) impact test: it determines the absorbed energy (ASTM E23). It is useful to characterize the ductile-brittle transition and indirectly estimate fracture toughness (ZwickRoell, 2025).

- Fracture toughness test (K_IC): it finds the stress intensity factor's critical value for fracture initiation under plane strain conditions (ASTM E399) (Ramos Morales *et al.*, 2005; Terán *et al.*, 2016; Anderson, 2017).

2.2. Sleeve Welding, HAZ Effects, and Finite Element Modeling

Shaft sleeves are often manufactured by joining tubular sections using circumferential butt welding. This process generates a heat-affected zone (HAZ) and a weld metal, whose properties can differ significantly from the base metal. The HAZ is susceptible to heterogeneous microstructures formation, grain growth, and residual stresses concentration, which can favor crack initiation and propagation (Zhang *et al.,* 2024). The welding procedure selection and heat input control are fundamental.

The Finite Element Method (FEM) was used to simulate the shaft sleeve's stress-strain behavior, including weld zones and typical flaws (circumferential cracks). Solid and contact elements were used to represent the interaction with the fluid. Mesh quality is critical; the mesh was refined in stress concentration zones (crack edges) and metrics such as skewness and orthogonality were evaluated (Rodríguez & Mollehuanca, 2021; Sánchez Mateo, 2024).

Representative loading scenarios were simulated (impact, internal pressure, thermal fluctuations). The shaft sleeve-fluid interaction was modeled with contact elements, considering pressure transfer and flow-induced vibrations (Rojas Suárez *et al.,* 2021).

2.3. Failure Assessment Criteria: CEGB R6 and BS 7910

The release-to-service assessment was performed following international standard procedures using the Failure Assessment Diagram (FAD):

- CEGB R6: it combines the analysis of fracture toughness (Kr) and proximity to plastic collapse (Lr) to determine a cracked component safety (Budden & Sharples, 2015; TWI, 2004).

- BS 7910/PD 6493: it provides detailed guidance for assessing defects in welded metallic structures, integrating the FAD approach (Budden & Sharples, 2015; TWI, 2004).

These procedures allowed for determining whether a flaw is acceptable under the anticipated loading and operating conditions or not.

3. Results and discussion

3.1. Critical Stress Zones

FEM simulations revealed that the highest stress concentrations occur in three specific regions:

1. In the weld interior (weld metal), where the geometric change of the join and residual stresses generate an up-to-3.2 stress concentration factor (Kt), reaching Von Mises stress values of 350 MPa under combined loading (pressure + axial).

2. In the HAZ, particularly on the shaft sleeve's outer side, where the heterogeneous microstructure (presence of deformation-induced martensite and possible sensitization) reduces toughness. Here, stresses reach 310 MPa, exceeding the material's yield strength in that state (estimated at 240 MPa).

3. At the front of the circumferential crack, especially at its edges, where a stress singularity with values exceeding 600 MPa occurs, although they are plastically relaxed.

These zones coincide with the failure locations reported in KSB-67227 pumps maintenance reports.

3.2. Stress Intensity Factors (K)

Stress intensity factors K_I was calculated for different crack depths (a) in the HAZ, considering a semi-elliptical surface fissure (a/2c ratio = 0.2) (Table 2).

Table 2. K_I variation according to crack depth

Crack depth	K_I (MPa√m)	Observation
0.5	32	Safe regime
1	58	Safe
1.5	78	Close to the limit (HAZ)
2	95	Outlimits K_{IC} HAZ (90)
2.5	112	Unstable propagation

The failure condition occurs when K_I \geq K_{IC}. For the base material (unwelded), K_{IC} is 120 MPa√m, which would allow cracks up to 2.2 mm without immediate propagation. However, in the HAZ, with K_{IC} reduced to 90 MPa√m, the critical value is reached with a = 1.6 mm.

The intensity factors obtained confirm that the predominant fracture mode is Mode I (tensile opening), since the maximum principal stresses are perpendicular to the circumferential weld plane.

3.3. Permissible Crack Size

The maximum acceptable flaw size for a safety factor of 1.5 on the design load was determined by using the FAD diagram according to BS 7910, the K_{IC} and yield stress values (\sigma_{ys} = 240 MPa for the HAZ, 290 MPa for the base material).

After applying an additional safety factor of 2 on the load, and considering the stress corrosion sensitivity under stress, the following permissible crack size are established:

- 1.8 mm depth for flaws in the HAZ.

- 2.5 mm for the base material.

Ultrasonic or dye penetrant inspections should detect cracks ≥ 1.0 mm to act preventively.

The combination of FEM and the FAD approach allowed quantifying that, under normal operating conditions, moderate flaws (under 1.5 mm) in the HAZ are acceptable. However, the presence of deformation-induced martensite (caused by poor welding practices or cold working) reduces the effective toughness, shifting the assessment points towards the unsafe region of the diagram. Furthermore, stress corrosion in chloride environments (common in Cuban industrial waters) can reduce K_{IC} to 50 MPa√m, making even micro-cracks critical.

The results validate shaft sleeves can operate reliably if a predictive maintenance plan is implemented based on periodic inspection of critical zones (welding and HAZ) and welding quality control (heat input ≤ 1.5 kJ/mm, controlled cooling). For future redesigning, it is recommended to increase the local thickness in the welded join or change to a steel with higher toughness, such as AISI 316L.

4. Conclusions

The analysis demonstrates that the structural integrity of AISI 304 steel centrifugal pump shaft sleeves depends on the interaction between material properties, weld quality, the presence of flaws, and loading and environmental conditions. The application of fracture mechanics (FAD), combined with FEM simulations and normative criteria (R6, BS 7910), enables a comprehensive fitness-for-service assessment.

For moderate flaws in welds, the acceptance points are within the FAD curve under the studied conditions. However, factors such as deformation-induced martensite or sensitization increase the risk in the HAZ. The implementation of the proposed redesigning and predictive maintenance strategies is crucial to maximize these components' reliability and lifespan.

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Rosabel Barrera Ruiz: Conceptualization/Formal data analysis/Data curation /Methodology/Investigation/Writing - original draft

Anabel Ruiz Padilla: Data and content curation/Methodology/Supervision/Writing - review and editing