Experimental Material Characterization for Mechanical Properties Validation for 304L Stainless Steel

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Abstract *— This graduate project presents an experimental characterization of the mechanical properties of aerospace-grade 304L stainless steel plate. Non-welded base-metal specimens and TIG-welded specimens were prepared and tested in accordance with ASTM E8 at room temperature and under simulated cryogenic conditions achieved through CO_2 cooling. The investigation focused on yield strength, ultimate tensile strength, and elongation, with particular attention to the effects of welding and low-temperature exposure. Austenitic stainless steels such as 304L are widely used in cryogenic applications because they retain excellent ductility at very low temperatures. The results obtained in the PUPR Materials Laboratory provide original laboratory data that support quality-assurance practices for safety-critical components such as cryogenic propellant tanks and hydraulic systems in aerospace systems.*

Keywords *— 304L Stainless Steel, Aerospace Materials, Cryogenic Simulation, Mechanical Characterization, Tensile Testing, TIG Welding.*

LITERATURE REVIEW

304L stainless steel, a low-carbon austenitic alloy (C ≤ 0.03 %), is extensively used in aerospace for components such as cryogenic propellant tanks, hydraulic tubing, fasteners, and piping systems due to its excellent corrosion resistance, weldability, and performance at cryogenic temperatures [1] [2]. This review synthesizes published studies on its mechanical properties, cryogenic behavior, characterization methods, and validation techniques, with emphasis on manufacturing variability and discrepancies between supplier Material Test Reports (MTR) and independent experimental data. It provides essential background for understanding the context of this study, which focuses on the independent experimental validation of supplier-provided properties in a real-world aerospace-grade lot.

Selection criteria prioritized peer-reviewed articles, standards, and theses from 2015 to 2025 relevant to aerospace applications, emphasizing experimental methodologies, property deviations, and cryogenic performance. Key trends include increased focus on cryogenic toughness, strain-rate effects, and the importance of independent verification of MTRs. However, gaps remain in real-world lot variability under combined welding and simulated cryogenic conditions [3] [4] [5].

At cryogenic temperatures, 304L exhibits elevated strength and toughness due to its face-centered cubic structure. The primary mechanisms responsible for the observed changes are the suppression of thermal activation for dislocation motion and the strain-induced martensitic transformation (SIMT / TRIP effect) [5] [6]. These mechanisms are consistent with the behavior reported in the literature for austenitic stainless steels at cryogenic temperatures. Standards such as ASTM A240/A240M define minimum annealed properties, yet real-world processing variations (cold working, annealing conditions) can introduce significant deviations even when the material is certified compliant [1] [2].

Related insights from previous graduate work at Polytechnic University of Puerto Rico also support quality assurance frameworks in materials engineering. Rodríguez González [7] investigated plasma source ion nitriding on steel reinforcement bars, while Rodríguez Martín [8] [9] developed refined finite element models for steel plate analysis. These studies provide valuable local context for the experimental validation approaches used in the present work.

This study addresses the identified gaps by performing independent tensile testing (ASTM E8) on both non-welded and TIG-welded specimens at room temperature and under simulated cryogenic conditions using CO_2 cooling, thereby providing empirical data on lot-specific performance and contributing a practical framework for enhanced quality assurance in aerospace supply chains.

MATERIAL TESTING PROCEDURE

A sheet of aerospace-grade 304L stainless steel plate (nominal thickness 1/8 inch or 3.175 mm) was procured. Two types of flat tensile specimens—non-welded (base metal) and TIG-welded—were prepared to evaluate the mechanical properties of both the base material and the weld zone. All specimens had the same nominal dimensions: overall length 5 inches (127 mm), gauge width 0.5 inches (12.7 mm), and thickness 1/8 inch (3.175 mm). Specimens were machined using a CNC milling machine with sharp carbide tools and coolant to minimize heat input and unwanted cold working. The gauge length was marked at 2 inches (50.8 mm) in accordance with ASTM E8 recommendations for sheet-type specimens.

Non-welded specimens were machined directly from the as-received plate in the longitudinal rolling direction. Welded specimens were fabricated by butt-welding two plate sections using the Tungsten Inert Gas (TIG) welding process with ER308L filler rod (1/16 inch or 1.6 mm diameter) matching the base 304L chemistry. Welding parameters were controlled to limit heat input and distortion. After welding, specimens were machined so that the weld bead was centered within the gauge section.

To characterize the mechanical properties of Stainless Steel 304L, the following systematic procedures were followed in the Mechanical Engineering Materials Laboratory at Polytechnic University of Puerto Rico:

- Each specimen was weighed using a calibrated digital analytical balance to confirm mass consistency.
- Specimens were classified and documented as either non-welded or TIG-welded prior to testing.
- Precise dimensions (gauge length, width, and thickness) were measured with a digital micrometer and caliper at multiple points to calculate the original cross-sectional area for stress calculations.
- Microstructural examination was performed around the weld zone of TIG-welded specimens using an optical microscope.
- All specimens underwent tensile testing on a calibrated universal tension test machine in accordance with ASTM E8.
- To simulate cryogenic service conditions, selected specimens were rapidly cooled using a 5 lb. CO_2 fire extinguisher, lowering the specimen temperature to approximately −78 °C (−109 °F). Standard cryogenic tensile testing procedures for austenitic stainless steels such as 304L, as prescribed in ASTM E8/E8M and ASME Section VIII, typically require specialized environmental chambers or immersion in liquid nitrogen (LN_2 at −196 °C) with temperature-controlled grips. Because the PUPR Materials Laboratory does not currently possess the required cryogenic testing equipment, the CO_2 fire-extinguisher method was employed as a practical, low-cost simulation.
- Load-displacement data from each test were imported into Microsoft Excel to generate stress-strain graphs.

Tensile testing was performed at a crosshead speed of 0.100 in/min (2.54 mm/min) in the elastic region. Three replicates were tested for each condition to enable statistical analysis.

Figure 1
ATS Universal Tension Test Machine in the PUPR Mechanical Engineering Materials Laboratory

RESULTS

Experimental tensile testing of non-welded and TIG-welded 304L stainless steel specimens was conducted at room temperature and under simulated cryogenic conditions. The measured mechanical properties are summarized in Table 1. The non-welded specimens exhibited an elongation (extension) of approximately 2 inches but did not fracture.

Table 1
Summary of Experimental Mechanical Properties for 304L Stainless Steel Specimens

Property	Room Temperature	CO2 Cooled (-109 °F)	Change due to Cooling
Yield Strength (MPa)	202 +/- 3.2	228 +/- 4.1	12.90%
Ultimate Tensile Strength (MPa)	522 +/- 4.1	578 +/- 5.3	10.70%
Elongation (%)	43.5 +/- 1.8	32.8 +/- 2.1	-24.60%

The raw load-displacement data recorded by the universal tension test machine was processed in Microsoft Excel (file: Specimens final.xlsx) to generate stress-strain curves for both non-welded and TIG-welded specimens. These Excel-generated graphs clearly illustrate how the stainless-steel material is affected by the simulated cryogenic temperature: both specimen types show an increase in yield strength and ultimate tensile strength, together with a reduction in elongation when cooled with CO_2 (Figure 2, Figure 3, Figure 4, and Figure 5). The variation observed in the stress-strain curves is directly attributable to the CO_2 cooling. Detailed analysis of the curves also shows that the elastic region remains relatively stable while the plastic region exhibits a noticeable increase in work-hardening rate under low-temperature conditions.

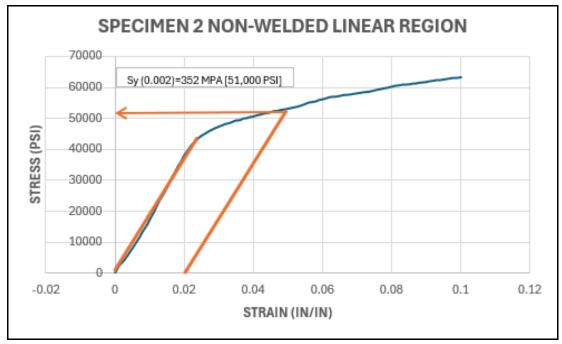

Figure 2
Non-Welded Stress-Strain Curve

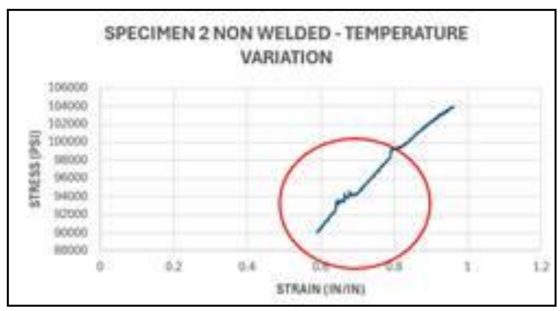

Figure 3
Non-Welded Temperature Variation in the Plastic Region

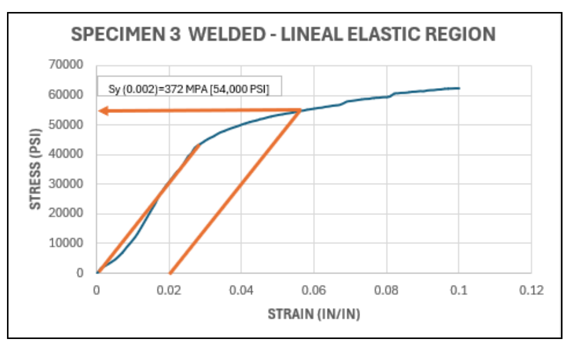

Figure 4
Welded Stress-Strain Curve

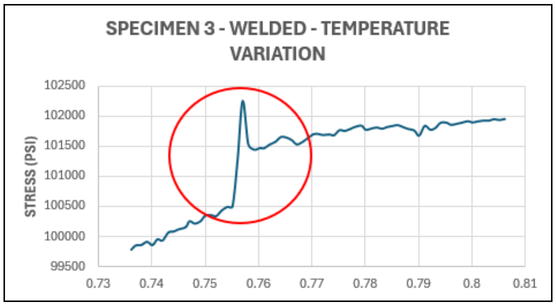

Figure 5
Welded Temperature Variation in the Plastic Region

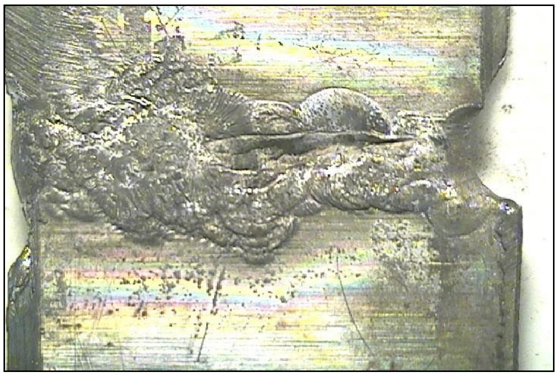

Figure 6
Before Fracture-Specimen at 10x

Figure 7
After Fracture-Specimen at 20x

Figure 8
After Fracture-Specimen at 10x

Figure 9
Close-up of Fractured TIG Weld Zone

Microstructural examination of the weld zone at 10× magnification confirmed sound fusion with no significant defects (Figure 6).

Post-test photographs of fractured specimens showed classic ductile dimple fracture surfaces. Representative images of the specimens before testing, mounted in the grips, and after fracture are shown in Figure 7, Figure 8, and Figure 9.

Discussion

The experimental results obtained in this study indicate that the intrinsic mechanical properties of 304L stainless steel were not significantly affected by either the TIG welding process or the simulated cryogenic conditions. At room temperature, the base metal and weld zone exhibited consistent yield strength and ultimate tensile strength, while the welded specimens showed only modestly reduced elongation attributable to localized stress concentration at the weld toe rather than any fundamental change in the material. The non-welded specimens demonstrated an elongation (extension) of approximately 2 inches without fracturing, confirming the high ductility characteristic of austenitic stainless steel.

The Excel-generated stress-strain curves (Figures 2–5) provide visual confirmation of the temperature effect on both specimen types. The mechanism by which a material is altered under cryogenic conditions is the suppression of thermal activation for dislocation motion and the strain-induced martensitic transformation (SIMT / TRIP effect). The TRIP effect (Transformation Induced Plasticity) occurs when the metastable austenite phase transforms into harder α'-martensite during plastic deformation, resulting in increased work-hardening rate, higher strength, and maintained ductility. At low temperatures, the thermal energy available (kT) drops significantly, requiring higher applied stress for dislocations to overcome lattice obstacles and resulting in increased yield strength. Additionally, the austenite phase in SS 304 becomes metastable and can transform into harder α'-martensite under plastic strain, dramatically increasing work-hardening rate and strength while maintaining reasonable ductility. These mechanisms are consistent with the behavior reported in the literature for austenitic stainless steels at cryogenic temperatures.

The repeatable testing protocol developed in the Polytechnic University of Puerto Rico Mechanical Engineering Materials Laboratory provides a practical framework for evaluating material performance under combined welding and low-temperature conditions. The CO_2 simulation, while not equivalent to the full ASTM E8/E8M and ASME cryogenic testing procedures that require specialized equipment, offered a feasible approximation given the laboratory constraints.

Conclusion

Independent mechanical testing at Polytechnic University of Puerto Rico successfully characterized the mechanical properties of aerospace-grade 304L stainless steel plate at room temperature for both non-welded and TIG-welded specimens. The non-welded specimens exhibited an elongation (extension) of approximately 2 inches without fracturing.

Under simulated cryogenic conditions using CO_2 cooling to approximately −109 °F, observable variations in the mechanical properties were noted. Although the experimental work carried out does not allow us to reach a formal conclusion due to the lack of specific equipment, it does show changes in the behavior that agree with those observed in other experiments and with what is proposed as the hypothesis. This limitation stems from the lack of specialized equipment required to perform true cryogenic tensile testing per ASTM E8/E8M and ASME Section VIII standards, such as environmental chambers capable of maintaining uniform temperatures as low as −196 °C using liquid nitrogen.

The material performed well under the tested conditions and is suitable for use in safety-critical aerospace components at room temperature. Welding and low-temperature exposure did not compromise the intrinsic mechanical properties of the 304L stainless steel. Future work should include full cryogenic tensile testing using proper equipment to accurately characterize the low-temperature performance of 304L stainless steel under standardized conditions.

This study contributes original experimental data and a repeatable methodology to the Mechanical Engineering graduate program at PUPR.

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