

Welding Procedure and validation of combined SS304L and SS321 in autogenous TIG Welding with socket joint for both manual and orbital

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Abstract

This study presents a comprehensive evaluation of autogenous Tungsten Inert Gas (TIG) welding for dissimilar austenitic stainless steel socket joints between SS321 and SS304L tubes, employing both manual and orbital welding techniques. The objective is to assess weld quality, metallurgical integrity, and process feasibility for producing high-reliability dissimilar joints without filler metal, as required in aerospace, pharmaceutical, food processing, and high-purity piping applications. The dissimilar combination of titanium-stabilized SS321 and low-carbon SS304L introduces challenges such as thermal expansion mismatch, elemental diffusion, and sensitization, particularly in constrained socket geometries. Critical welding parameters, including current, pulse settings (orbital), torch angle (manual), arc length, and purge flow rate, were optimized based on tube dimensions. Both techniques achieved full-penetration welds without defects. Post-weld evaluation was conducted through visual inspection, dye penetrant testing, and metallographic analysis, while mechanical performance was assessed via hardness mapping and pressure-based leak testing. Orbital TIG welding demonstrated superior repeatability, narrower heat-affected zones, and consistent weld quality, making it suitable for automated and high-purity applications. Manual TIG welding, though operator-dependent, produced acceptable results under controlled conditions and remains advantageous for field applications. The findings confirm that autogenous TIG welding of SS321 to SS304L socket joints is feasible and capable of producing high-quality dissimilar joints when appropriate process control and joint preparation are maintained.

Keywords: TIG welding, SS321, SS304L, dissimilar welding, autogenous welding, orbital welding, socket joint, stainless steel tubing, microstructure, corrosion resistance.

1. Introduction

1.1 Overview of TIG Welding and Its Applications

Tungsten Inert Gas (TIG) welding, also known as Gas Tungsten Arc Welding (GTAW), is a high-precision fusion welding process that employs a non-consumable tungsten electrode and an inert shielding gas, typically argon or helium, to produce clean and defect-free welds. The process is characterized by excellent control over heat input, arc stability, and weld pool dynamics, making it particularly suitable for thin sections and high-integrity applications. TIG welding can be performed with or without filler metal; in autogenous mode, the joint is formed solely by melting the base materials, ensuring superior cleanliness and minimal compositional alteration. Due to these advantages, TIG welding is extensively used in aerospace, nuclear, pharmaceutical, and high-purity piping systems where weld quality and contamination control are critical.

1.2 Significance of Welding SS321 and SS304L Without Filler Rods

Autogenous welding of dissimilar austenitic stainless steels such as SS321 and SS304L is of significant industrial relevance, particularly in applications

requiring high purity and corrosion resistance. The absence of filler metal eliminates the risk of compositional mismatch and preserves the intrinsic properties of both alloys—titanium stabilization in SS321 and low carbon content in SS304L—thereby reducing susceptibility to intergranular corrosion. Additionally, filler-less welding produces smooth, oxide-free joints with minimal contamination, which is essential for hygienic and high-purity systems. However, the process presents challenges including increased susceptibility to solidification cracking, reduced joint reinforcement, and sensitivity to heat input, which may lead to microstructural degradation such as carbide precipitation or sensitization. Therefore, precise control of welding parameters, joint fit-up, and shielding conditions (including back purging) is critical to ensure weld integrity.

1.3 Research Objectives and Scope

This study aims to investigate the feasibility and performance of autogenous TIG welding of SS321–SS304L socket joints using both manual and orbital techniques. The focus is on evaluating weld quality, microstructural evolution, and mechanical integrity under filler-less conditions. Specific objectives include: (i) optimization of welding parameters to achieve

defect-free, full-penetration welds; (ii) comparison of mechanical properties such as hardness and joint integrity between manual and orbital welding; (iii) analysis of microstructural features, including heat-affected zone characteristics and phase stability; and (iv) assessment of process repeatability and suitability for high-purity applications. The scope emphasizes the viability of producing reliable dissimilar metal joints without filler metal while maintaining corrosion resistance and dimensional integrity.

2. Literature review

2.1 Review of Existing Studies on Autogenous Welding

Autogenous TIG welding of austenitic stainless steels such as SS304L and SS321 has been widely investigated for thin-walled tube applications. Studies by Sindo Kou [1] and John C. Lippold and Damian J. Kotecki [2] indicate that filler-less welding produces a fully austenitic microstructure with negligible δ -ferrite, increasing susceptibility to solidification cracking, particularly in SS304L. Sensitization due to chromium carbide precipitation in SS304L and titanium carbide (TiC) formation in SS321 under high heat input are critical concerns affecting corrosion resistance [1], [3]. Mechanical studies report joint efficiencies of approximately 85–90% for thin SS304L tubes, with orbital TIG welding demonstrating superior consistency and reduced heat-affected zone (HAZ) compared to manual welding [4], [5]. Pulsed TIG techniques further reduce HAZ width and refine microstructure [5]. However, autogenous welds may exhibit lower toughness and higher intergranular corrosion susceptibility compared to filler-added welds, often necessitating controlled heat input or post-weld treatments [6].

2.2 Welding of SS321 and SS304L: Past Research and Gaps

Existing research confirms that autogenous TIG welding of SS321 and SS304L is feasible for thin sections but presents metallurgical and performance challenges. SS321 exhibits relatively better resistance to hot cracking due to titanium stabilization, whereas SS304L is more prone to sensitization and grain boundary chromium depletion [1], [2]. Excessive heat input leads to grain coarsening, reduced ductility, and TiC precipitation, while optimized parameters and pulsed current can mitigate these effects [3], [5]. Orbital TIG welding offers improved repeatability, defect control, and compliance with high-purity standards compared to manual welding [5], [7].

Despite these advancements, significant research gaps remain, particularly in dissimilar autogenous welding of SS321–SS304L combinations. Limited data exist on long-term corrosion behavior, fatigue performance, and

creep resistance under service conditions. Additionally, the influence of post-weld heat treatment on microstructural stability and corrosion resistance is not fully established [6]. There is also a lack of standardized guidelines for high-purity and aerospace applications, along with minimal exploration of advanced approaches such as hybrid welding and data-driven parameter optimization.

2.3 Factors Affecting Weld Quality and Performance in TIG Welding

Weld quality in autogenous TIG welding is strongly influenced by process parameters, material characteristics, and operational practices. Heat input plays a critical role, with optimal ranges required to balance penetration and microstructural stability while minimizing sensitization and cracking [8]. Current magnitude, travel speed, and pulsed parameters significantly affect HAZ width and weld integrity [5], [9]. Material composition, particularly Cr/Ni ratio and impurity levels, governs phase balance and crack susceptibility [2], [10]. Shielding gas composition and effective back purging are essential to prevent oxidation and ensure clean weld roots, especially in tube welding [10]. Additionally, operator-controlled factors such as torch angle, arc length, and travel speed influence weld consistency. Proper control of these parameters is essential to achieve defect-free, high-quality autogenous welds in dissimilar stainless-steel systems.

3. Material Properties and Selection

3.1 Chemical Composition of SS304L and SS321

SS304L and SS321 are austenitic stainless steels derived from the 18–8 Cr–Ni system. SS304L is designed for enhanced weldability and corrosion resistance through ultra-low carbon content, while SS321 incorporates titanium stabilization for improved performance at elevated temperatures.

SS304L (UNS S30403) contains $\leq 0.03\%$ carbon, which suppresses chromium carbide precipitation during welding and eliminates sensitization in the as-welded condition. It typically consists of 17.5–19.5% Cr and 8–12% Ni, providing excellent corrosion resistance and a stable austenitic microstructure. The alloy exhibits good oxidation resistance up to $\sim 870^\circ\text{C}$, along with excellent formability and ductility.

SS321 (UNS S32100) is a titanium-stabilized grade in which Ti is added ($\text{Ti} \geq 5 \times (\text{C} + \text{N})$) to preferentially form titanium carbides, thereby preventing chromium depletion in the temperature range of $450\text{--}900^\circ\text{C}$. It contains 17–19% Cr and 9–12% Ni, with a higher carbon limit ($\leq 0.08\%$) than SS304L, resulting in improved creep strength and high-temperature stability.

3.2 Mechanical Properties and Application Relevance

SS304L exhibits a tensile strength of 485–620 MPa and yield strength ≥ 170 MPa, whereas SS321 shows slightly higher strength (tensile: 515–720 MPa, yield ≥ 205 MPa). Both alloys possess elongation $\geq 40\%$, modulus of elasticity ~ 193 GPa, and density ~ 8.0 g/cm³.

From an application perspective, SS304L is preferred for corrosion-resistant welded structures due to its immunity to sensitization without post-weld heat treatment. In contrast, SS321 is better suited for high-temperature applications such as exhaust systems, heat exchangers, and aerospace components, where resistance to intergranular corrosion and enhanced creep strength are critical.

4. Welding Techniques & Procedures

4.1 TIG Welding Setup for Autogenous Welding

TIG welding without filler rod (autogenous welding) is suitable for thin sections and precision joints, where fusion is achieved solely by melting the base metal.

The process typically employs a DC power source in DCEN mode for stainless steels, ensuring stable arc characteristics and adequate penetration. A TIG torch (air-cooled for low current, water-cooled for high current) is used with non-consumable tungsten electrodes such as thoriated or lanthanated types. For thin sections (≤ 3 mm), a 1.6 mm diameter electrode with a sharp tip ($20\text{--}30^\circ$) is preferred.



Figure 1: Autogenous weld setup

High-purity argon is used as the shielding gas, typically at flow rates of 7–12 CFH, with gas lenses recommended for improved coverage and reduced oxidation. Auxiliary components include a foot pedal for current control, proper grounding, and standard PPE (helmet, gloves, and protective clothing).

4.2 Parameter Selection for SS321–SS304L Autogenous Socket Joint

Autogenous welding of SS321 and SS304L requires strict heat input control to avoid sensitization, distortion, and lack of fusion.

Typical parameters include DCEN current with an amperage range of 40–90 A depending on thickness (1–3 mm), voltage of 10–14 V, and a short arc length ($\sim 1\text{--}2$ mm). A 1.6 mm thoriated or lanthanated tungsten electrode is recommended. Pure argon shielding (10–15 L/min) with pre-flow (0.5–1 s) and post-flow (2–3 s) is essential to prevent oxidation.

Optional pulsed current (1–2 Hz) improves heat control and weld stability. Travel speed should be moderate (3–6 cm/min) to balance penetration and heat input.

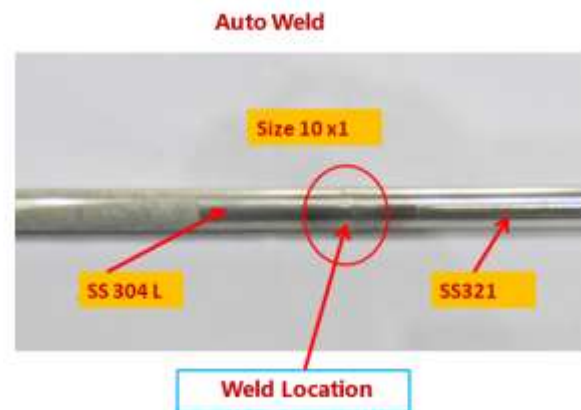


Figure 2: Orbital weld

Proper joint preparation (cleaning, tight fit-up) and back purging are critical to prevent oxidation (“sugaring”). During welding, a short arc and controlled movement are maintained, followed by slow cooling and, if required, post-weld passivation.

4.3 Manual vs. Automated TIG Welding

Manual TIG welding relies on operator skill for arc control, torch angle ($10\text{--}15^\circ$), and travel speed, offering flexibility for complex joints and low-volume production. However, it is prone to variability, tungsten contamination, and heat distortion.



Figure 3: Manual weld Setup

Automated TIG welding (orbital, robotic, or carriage-based) provides high precision, repeatability, and consistent heat input through pre-programmed parameters and closed-loop control systems. It is preferred for critical applications and high-volume production but involves higher initial cost and lower flexibility.

In practice, manual TIG is suitable for prototyping and repair work, whereas automated TIG is preferred for thin-walled tubes, pressure vessels, and aerospace-grade welds.

4.4 Safety and Quality Control

TIG welding of stainless steels requires strict safety and quality control measures. Key safety practices include the use of PPE, proper ventilation (to control Cr/Ni fumes), secure grounding, and leak-free shielding gas systems. Automated systems additionally require guarding of moving parts and emergency controls.

Quality control involves pre-weld cleaning and fit-up, in-process monitoring of heat input and shielding gas, and post-weld inspection. Visual inspection (acceptable light straw coloration), dye penetrant testing, and radiographic testing are commonly used. For corrosion-sensitive applications, additional tests such as ferroxyl testing and passivation are recommended.

5. Evaluation of Weld Quality

The quality of autogenous TIG welds in SS321–SS304L joints is assessed using visual inspection, non-destructive testing (NDT), and mechanical evaluation to ensure structural integrity and defect-free welds.

5.1 Visual Inspection

Visual inspection is performed at three stages:

Pre-weld: Ensure proper fit-up (gap ≤ 0.05 mm), adequate socket engagement ($\sim 1.5 \times$ wall thickness), and complete removal of contaminants using solvent cleaning.

In-process: Maintain stable weld pool and arc conditions. Heat tint is used as an indicator of oxidation;

light straw/yellow is acceptable, while blue/grey indicates excessive oxidation and reduced corrosion resistance.

Post-weld: Examine weld surface and root using magnification or borescope. Acceptance criteria include absence of cracks, undercut (>0.1 mm), lack of fusion, and excessive concavity. Weld profile should be smooth with minimal discoloration (\leq light yellow) and controlled root depression (≤ 0.2 mm).

5.2 Non-Destructive Testing (NDT)

Radiographic Testing (RT): Used for detecting internal defects such as porosity, cracks, inclusions, and lack of fusion. It provides high sensitivity but involves higher cost and radiation safety requirements.

Dye Penetrant Testing (PT): Effective for detecting surface-breaking defects such as cracks and porosity in non-porous materials.

RT is preferred for internal integrity assessment, while PT is commonly used for surface defect evaluation.

5.3 Mechanical Testing

Tensile Testing: Conducted as per ASTM E8 and AWS B4.0 to evaluate weld strength and ductility. Typical ultimate tensile strength is ~ 515 MPa for SS321 and ~ 485 MPa for SS304L, with elongation ≥ 35 –40%. Failure generally occurs in the heat-affected zone (HAZ) due to microstructural changes.

Hardness Testing: Vickers microhardness is used to assess HAZ variations. SS321 typically exhibits higher HAZ hardness (~ 220 HV) due to TiC formation, whereas SS304L shows more uniform hardness (~ 180 HV). Excessive hardness may indicate reduced corrosion resistance.

6. Case Studies and Experimental Results

Autogenous TIG welding of SS321–SS304L socket joints requires precise control of heat input and parameters to prevent sensitization, carbide precipitation, and lack of fusion.

6.1 Material Selection and Certification

SS304L and SS321 are austenitic stainless steels from the 18–8 Cr–Ni system. SS304L (low carbon $\leq 0.03\%$) offers superior weldability and resistance to sensitization, while SS321 (Ti-stabilized) provides improved resistance to intergranular corrosion at elevated temperatures (450–900°C).

Tube specifications used:

- SS304L: $\text{Ø}10 \times 1$ mm
- SS321: $\text{Ø}10 \times 1$ mm with end step ($\text{Ø}1$ & depth 0.5mm)

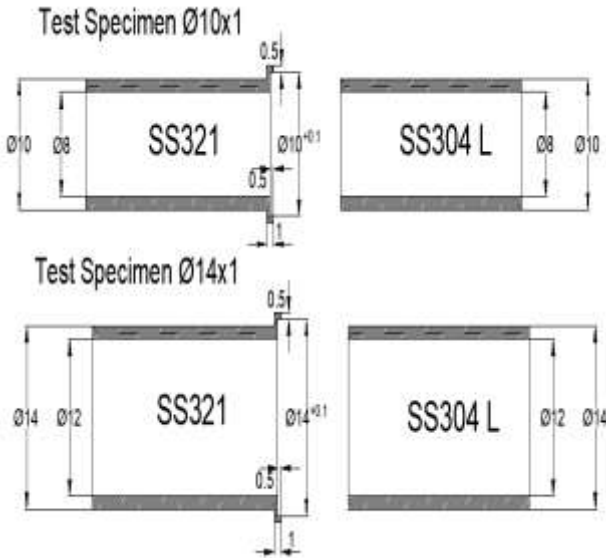
Socket or stepped Configuration



Figure 4:

Stepped or Socket type configuration

Dimension of Stepped Configuration



SS 304 L

QUALITY CONTROL (Materials) QUALITY CONTROL & NON-DESTRUCTIVE EVALUATION GROUP SYSTEM RELIABILITY & QUALITY ASSURANCE								
MATERIAL ACCEPTANCE CERTIFICATE								
MAC No.	VIS16/20							
Date:	31.12.2020							
1.0 Material Description & P.O. Details:								
1.1 Material	AISI 304, Tubes							
1.2 Condition	Bright Annealed							
1.3 Size	OD20 x WT 1.0 x 500 mm							
1.4 Quantity	1 No							
1.5 Application:	Developing							
1.6 P.O. No. & Date:								
1.7 Supplier:	M/V. Ramanani Metals & Tubes Ltd., Annamalai							
1.8 Quality Check/Specification No.	ASTM A213/A213M & QAP No. ITY/4029000740/A213 Rev 04, dt: 08.02.2020							
2.0 Feasibility Details:								
2.1 Cast/Blot supplier:	Nanamani							
2.2 Cast/Blot Heat No.	RSC28							
2.3 Raw Material Code (RMC No.):	10687							
2.4 Finished products Heat/Batch No.	Batch-1							
TEST RESULTS								
2.0 Visual and Dimensional Inspection: Satisfactory								
2.1 Chemical Composition:								
Specification	C	Si	Mn	P	S	Ni	Cr	Fe
Min	-	-	-	-	-	8.0	18.0	
Max	0.035	1.0	2.00	0.045	0.03	12.0	20.0	Bal
Result	0.015	0.29	1.89	0.03	0.005	8.30	18.25	
2.2 Mechanical Properties: Solution annealed at 1042°C - Rapid cooling:								
Specification (min)	UTS (Mpa)	0.2% PF (Mpa)	% Elongation (GL-50mm)	Hardness (HPS-Nel)				
	485	170	35	90				
Result	652.06	256.25	62	64-68				
2.3 Hydrostatic Pressure test:	Satisfactory							
2.4 Edley Current Test:	Satisfactory							
2.5 Metallurgy Examination:	Satisfactory; Grain size ASTM No. 8-8							
2.6 Inclusion Rating:	Satisfactory							
2.7 NDT Test:	Satisfactory							
2.8 Flattening & Flaring Test:	Satisfactory							
2.9 Non-Conformance Details:	-							
DISPOSITION:								
The above materials have been accepted as per specification and approved procedure.								
Signature:	V. Venkatesh							
Name:	Vertha Venkatesh							

Figure 5: SS304L Material Certificate

Material Certificates:

SS321

QUALITY CONTROL (Materials) QUALITY CONTROL & NON-DESTRUCTIVE EVALUATION GROUP SYSTEM RELIABILITY & QUALITY ASSURANCE								
MATERIAL ACCEPTANCE CERTIFICATE								
MAC No.	VIS25/20							
Date:	31.12.2020							
1.0 Material Description & P.O. Details:								
1.1 Material	AISI 321, Tubes							
1.2 Condition	Bright Annealed							
1.3 Size	OD 20 x WT 1.0 x 500 mm							
1.4 Quantity	1 No							
1.5 Application:	Developing							
1.6 P.O. No. & Date:								
1.7 Supplier:	M/V. Ramanani Metals & Tubes Ltd., Annamalai							
1.8 Quality Check/Specification No.	ASTM A213/A213M & QAP No. ITY/4029000740/A213 Rev 04, dt: 08.02.2020							
2.0 Feasibility Details:								
2.1 Cast/Blot supplier:	Nanamani							
2.2 Cast/Blot Heat No.	RSC28							
2.3 Raw Material Code (RMC No.):	10687							
2.4 Finished products Heat/Batch No.	Batch-1							
TEST RESULTS								
2.0 Visual and Dimensional Inspection: Satisfactory								
2.1 Chemical Composition:								
Specification	C	Si	Mn	P	S	Ni	Cr	Fe
Min	-	-	-	-	-	8.0	17.0	
Max	0.08	1.0	2.00	0.040	0.03	12.0	20.0	Bal
Result	0.02	0.43	1.77	0.03	0.002	9.11	17.28	0.22
2.2 Mechanical Properties: Solution annealed at 1042°C - Rapid cooling:								
Specification (min)	UTS (Mpa)	0.2% PF (Mpa)	% Elongation (GL-50mm)	Hardness (HPS-Nel)				
	515	205	35	90				
Result	673.86	250.32	62.40	65-75				
2.3 Hydrostatic Pressure test:	Satisfactory							
2.4 Edley Current Test:	Satisfactory							
2.5 Metallurgy Examination:	Satisfactory; Grain size ASTM No. 8-8							
2.6 Inclusion Rating:	Satisfactory							
2.7 NDT Test:	Satisfactory							
2.8 Flattening & Flaring Test:	Satisfactory							
2.9 Non-Conformance Details:	-							
DISPOSITION:								
The above materials have been accepted as per specification and approved procedure.								
Signature:	V. Venkatesh							
Name:	Vertha Venkatesh							

Figure 6 : SS321 Material Certificate

6.2 Selection of Welding Parameters

Welding parameters were determined based on thinner tube thickness (t) and heat input control.

- Peak Current: $I_p = K \cdot t$, where $K = 32-38$ A/mm (orbital) and $36-42$ A/mm (manual)
- Background Current: $I_b = 0.25-0.30 \cdot I_p$
- Frequency: 200-300 Hz (orbital), 2-5 Hz (manual)
- Duty Cycle: 35-45%
- Heat Input Constraint: ≤ 0.25 kJ/mm (SS321 critical)
- Arc Voltage: 11 to 13 volt

Heat input control:

$$HI = \frac{0.7 \cdot I_{avg} \cdot V}{V_s}$$

V_s = Travel speed ; V = Arc voltage

Typical settings:

- **Manual:** $I_p \approx 42A$, $I_b \approx 17A$, 2 Hz
- **Orbital:** 40-48 A peak current, travel speed ~90 mm/min

Shielding: 100% Argon with back purging ($O_2 < 50$ ppm).

6.3 Pre- and In-Process Inspection

- Pre-weld: Ensure fit-up gap ≤ 0.05 mm, proper socket engagement ($\sim 1.5 \times$ thickness), and contamination-free surfaces.
- During welding: Maintain short arc (~ 1.5 mm), stable weld pool, and controlled travel speed. Tack welding is performed prior to full weld.

6.4 Post-Weld Inspection and Testing

6.4.1 Visual Inspection

- Clean weld surface and inspect for defects (cracks, undercut, discoloration).
- Acceptable color: light straw/yellow.

6.4.2 NDT Evaluation

- Radiographic Testing (RT): Detects internal defects (porosity, cracks, lack of fusion).

- Dye Penetrant Testing (PT): Liquid Penetrant Inspection (LPI) was carried out to identify surface-breaking discontinuities on the test specimen. A visible red dye penetrant system was employed for the inspection. The consumables used in the present work were SKL-SP1 visible penetrant, SKD-S2 non-aqueous developer, and SKC-1 cleaner/remover. Results were found satisfactory.

NON DESTRUCTIVE TESTING FACILITY(NDTF) SYSTEMS RELIABILITY GROUP									
RADIOGRAPHY INSPECTION REPORT									
Ref No	NDTF X-RAY:615/2025	Date	09-04-2025						
Job Name	WPS for SS304L to SS321 (Steepl configuration)	OD and Thickness	10x1						
Project Name	Developing	Surface Condition							
Part Identification	WPS SS 321 to SS 304L / NVK Orbital-1 to 6	Percentage of Insp.	100% weldments						
Stage of Inspection	After Weld	Application	Aerospace						
Film	D4	Acceptance standard	TCV13054						
Technique	II	Material	SS304L & 321						
X-Ray Machine details	KV	mA	FFD(m)	Screen (mm)	Exposure Time (min)	Dev Time (min)	Dev Temp(°C)	Density	Sensitivity
MEDEQUIP(1.0 X 1.0)	90	12	1	0.1	02:00	5	20	2.3	2%
Sl. No.	JOB IDENTIFICATION	OBSERVATION	REMARKS						
1	NVK Orbital-1	No Significant Defect	Acceptable						
2	NVK Orbital-2	No Significant Defect	Acceptable						
3	NVK Orbital-3	Pore ≈ 0.2 mm - 1 No	Acceptable						
4	NVK Orbital-4	No Significant Defect	Acceptable						
5	NVK Orbital-5	No Significant Defect	Acceptable						
6	NVK Orbital-6	No Significant Defect	Acceptable						
Interpreted by		Prepared By		Engineer,QNDTD					
AYYASAMY P. BOOBALAN C		AYYASAMY P		KAMESH GURU G					
To: Shri San BALAMOCHAN P									

Figure 7: RT – Orbital Weld

NON DESTRUCTIVE TESTING FACILITY(NDTF) SYSTEMS RELIABILITY GROUP									
RADIOGRAPHY INSPECTION REPORT									
Ref No	NDTF X-RAY:616/2025	Date	09-04-2025						
Job Name	WPS for SS304L to SS321 (Steepl configuration)	OD and Thickness	10x1						
Project Name	Developing	Surface Condition							
Part Identification	WPS SS 321 to SS 304L / NVK Manual-1 to 6	Percentage of Insp.	100% weldments						
Stage of Inspection	After Weld	Application	Aerospace						
Film	D4	Acceptance standard	TCV13054						
Technique	II	Material	SS304L & 321						
X-Ray Machine details	KV	mA	FFD(m)	Screen (mm)	Exposure Time (min)	Dev Time (min)	Dev Temp(°C)	Density	Sensitivity
MEDEQUIP(1.0 X 1.0)	90	12	1	0.1	02:05	5	20	2.3	2%
Sl. No.	JOB IDENTIFICATION	OBSERVATION	REMARKS						
1	NVK Manual-1	No Significant Defect	Acceptable						
2	NVK Manual-2	No Significant Defect	Acceptable						
3	NVK Manual-3	No Significant Defect	Acceptable						
4	NVK Manual-4	No Significant Defect	Acceptable						
5	NVK Manual-5	No Significant Defect	Acceptable						
6	NVK Manual-6	No Significant Defect	Acceptable						
Interpreted by		Prepared By		Engineer,QNDTD/SRG					
AYYASAMY P. BOOBALAN C		AYYASAMY P		KAMESH GURU G					
To: Shri San BALAMOCHAN P									

Figure 8: RT – Manual Weld

NON DESTRUCTIVE TESTING FACILITY(NDTF) SYSTEMS RELIABILITY GROUP			
LIQUID PENETRANT INSPECTION REPORT			
Ref No:NDTF/DP/892/2025	Date	10-04-2023	
Job Name	WPS for SS304L to SS321 (Stepped configuration)	Project Name	Developing
Part Identification	WPS SS 321 to SS 304L / NVK Orbital-1 to 6	OD and Thickness	10x1
Penetrant	SKL-SP1	Stage of Inspection	After weld
Developer	SKD-S2	Surface Condition	
Cleaner	SKC-1	Percentage of Temp.	100% weldments
Dwell time	10 Minutes	Application	Aerospace
Surface temperature	Ambient		
Sl. No.	JOB IDENTIFICATION	OBSERVATION	REMARKS
1	NVE Orbital-1	No Surface defects noticed	Acceptable
2	NVK Orbital-2	No Surface defects noticed	Acceptable
3	NVK Orbital-3	No Surface defects noticed	Acceptable
4	NVK Orbital-4	No Surface defects noticed	Acceptable
5	NVK Orbital-5	No Surface defects noticed	Acceptable
6	NVK Orbital-6	No Surface defects noticed	Acceptable
BOOBALAN C Interpreted by		BOOBALAN C Prepared By	KAMESH GURU G Engineer
To: Shri Sanj BALAMOHAN P			

Figure 9: PT – Orbital Weld

NON DESTRUCTIVE TESTING FACILITY(NDTF) SYSTEMS RELIABILITY GROUP			
LIQUID PENETRANT INSPECTION REPORT			
Ref No:NDTF/DP/891/2025	Date	10-04-2023	
Job Name	WPS for SS304L to SS321 (Stepped configuration)	Project Name	Developing
Part Identification	WPS SS 321 to SS 304L / NVK Manual-1 to 6	OD and Thickness	10x1
Penetrant	SKL-SP1	Stage of Inspection	After Weld
Developer	SKD-S1	Surface Condition	
Cleaner	SKC-1	Percentage of Temp.	100% weldments
Dwell time	10 Minutes	Application	Aerospace
Surface temperature	Ambient		
Sl. No.	JOB IDENTIFICATION	OBSERVATION	REMARKS
1	NVK Manual-1	No Surface defects noticed	Acceptable
2	NVK Manual-2	No Surface defects noticed	Acceptable
3	NVK Manual-3	No Surface defects noticed	Acceptable
4	NVK Manual-4	No Surface defects noticed	Acceptable
5	NVK Manual-5	No Surface defects noticed	Acceptable
6	NVK Manual-6	No Surface defects noticed	Acceptable
BOOBALAN C Interpreted by		BOOBALAN C Prepared By	KAMESH GURU G Engineer
To: Shri Sanj BALAMOHAN P			

Figure 10: PT – Manual Weld

6.4.3 Tensile Testing

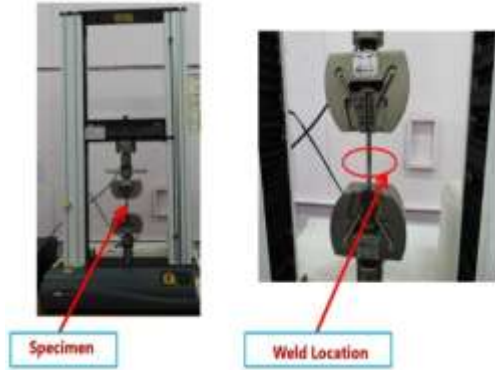
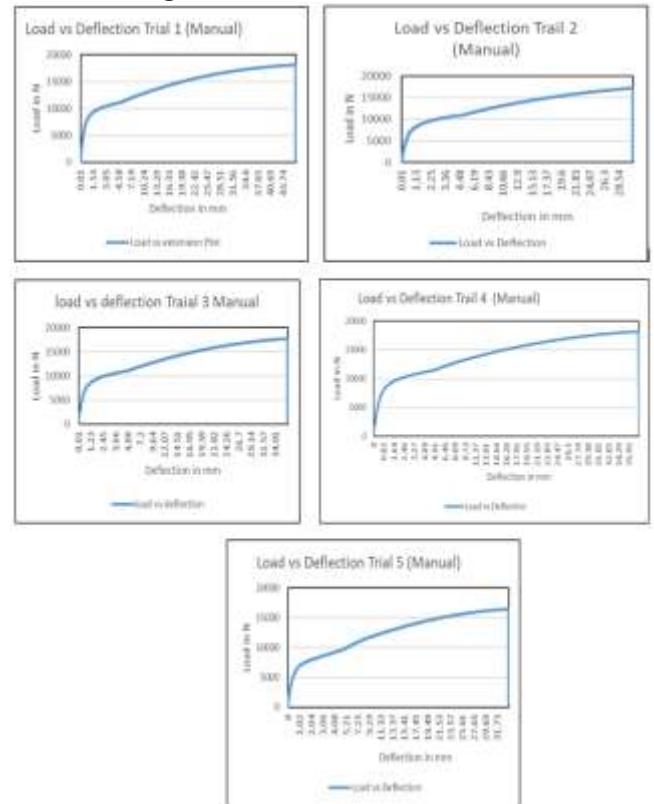


Figure 11: Tensile Test



A tensile test on a welded tube is a destructive mechanical test used to determine the tensile strength, yield strength, elongation, and fracture location of the welded joint and base material. It helps assess weld quality and mechanical integrity, especially for pressure-containing or critical piping applications.

- **Manual Weld:** Ultimate load ~16-17 KN
- **Orbital Weld :** Ultimate load ~17-18 KN
- Failure typically occurs in the HAZ.

Results:

MATERIALS TESTING LABORATORY
SR-M&NDT

Test Report

Report No: SR-M&NDT/MTL/TE 31/25 Req. 30-05-2025

Ref: Request dated: 21-05-2025 (MIL/113/25)

Test: Tensile at RT

Material	: S3321+S3304L (As per request)
Condition	: Sq. Bar with upset
Specimen Type	: Ø10x1 mm tube
Application	: For evaluation purpose

Sl. No	Specimen Idtn. No.	Ultimate Load (kN)	Remarks
1	Orbital Trial-1	18.83	Failed at S3304L side
2	Orbital Trial-2	17.95	Failed at S3321 side
3	Orbital Trial-3	19.20	Failed at S3304L side
4	Orbital Trial-4	17.24	Failed at HAZ
5	Orbital Trial-5	18.60	Failed at S3304L side
6	Manual Trial-1	18.09	Failed at S3321 side
7	Manual Trial-2	17.15	Failed at HAZ
8	Manual Trial-3	17.68	
9	Manual Trial-4	18.11	
10	Manual Trial-5	16.40	

To: Mr. BALASUBRAJ P

Figure 12: Tensile Test – Ultimate Failure Loads

Load vs Deflection Plot for manual weld
Figure 13: Tensile Test – Manual Weld

Load vs Deflection Plot for orbital weld

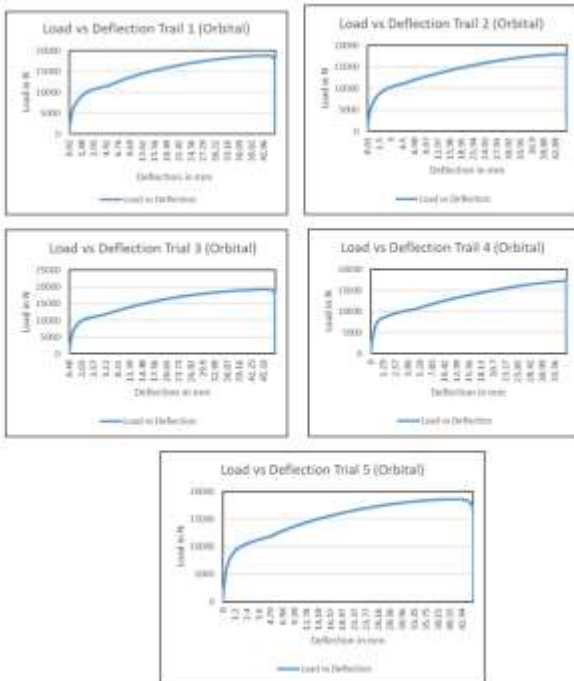


Figure 14: Tensile Test – Orbital Weld

6.4.4 Pressure Test and Leak Test for Weld Location Qualification

Pressure and leak tests were carried out to qualify the identified weld location for pressure-retaining service. The test article was pressurized in a controlled manner up to the specified pressure and held for the required duration to assess weld integrity. Subsequently, leak testing was performed at the designated leak check pressure to evaluate the weld region for any leakage indications. The observed results were compared with the applicable qualification criteria.

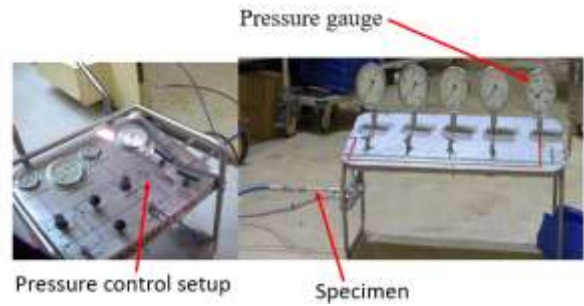


Figure 15: Hydro test

SL.NO	Weld	Hydro Test in bar	Pneumatic test With Water immersion in bar	Observation
1	Orbital Weld	750 bar	120 bar	Found satisfactory
2	Manual Weld	750 bar	120 bar	Found satisfactory

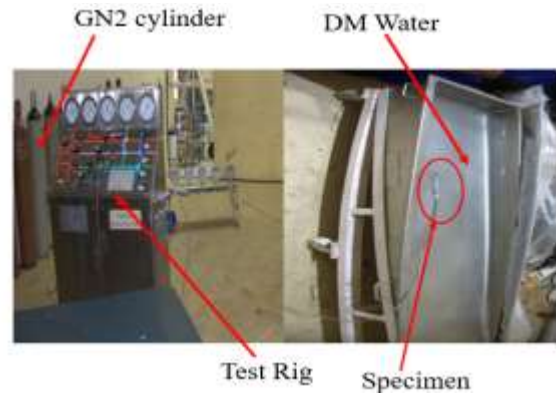


Figure 16: Pneumatic test with Water immersion

6.4.5 Micro & Macro analysis of weld

Macro examination is done at low magnification after polishing and etching. Microstructure is observed using optical microscopy after etching.

Manual Weld



Observations

- i) Top bead width 3.3mm, bottom bead width 2.5mm
- ii) HAZ width is 0.70mm (SS304 side), 0.8mm (SS321 side)
- iii) ASTM Grain Size Number at parent portion is 6.0-6.5, HAZ 5.0-5.5 (SS 304 side), parent portion is 7.5-8.0, HAZ 6.5-7.0 (SS 321 side)

Result:

No Micro Porosities and cracks

Orbital Weld



Observations

- i) Top bead width 3.66mm, bottom bead width 3.68mm
- ii) HAZ width is 0.84mm (SS304 side), 0.74mm (SS321 side)
- iii) ASTM Grain Size Number at parent portion is 5.5-6.0, HAZ 5.5-6.0 (SS 304 side), parent portion is 9.5-10.0, HAZ 6.5-7.0 (SS 321 side)

Result:

No Micro Porosities and cracks

6.5 Real-World Applications

Autogenous TIG welding is widely used for thin stainless-steel components:

- SS321: Aerospace exhaust systems, high-temperature piping
- SS304L: Food processing, pharmaceutical, and cryogenic systems

6.6 Comparative Analysis

- SS321: Higher strength, moderate HAZ sensitization risk due to Ti interactions
- SS304L: Better corrosion resistance and weldability due to low carbon
- Both exhibit comparable ductility, with SS304L showing more uniform weld quality

6.7 Defects and Mitigation

- Hot cracking: Reduce heat input, use high-purity shielding gas
- Porosity: Ensure proper cleaning and gas flow
- TiC depletion (SS321): Limit heat input, rapid cooling
- Sensitization: Maintain low heat input and controlled cooling
- Liquation cracking: Avoid excessive current and high interpass temperature

7. Challenges and Solutions

Autogenous TIG welding of SS304L–SS321 socket joints presents challenges related to material composition, heat input control, and joint configuration. Key issues and mitigation strategies are summarized below.

7.1 Common Issues in Autogenous TIG Welding

1. Porosity and Center-line Defects

Challenge:

Porosity in SS321 arises due to low sulfur content reducing weld pool fluidity and gas escape. Titanium interactions with oxygen/nitrogen can form inclusions, leading to micro-porosity.

Solutions:

Use controlled sulfur content ($\approx 0.005-0.02\%$), ensure high-purity shielding gas with proper purging, and maintain consistent gas coverage. Orbital welding improves shielding uniformity and reduces defect formation.

2. Inconsistent Penetration and Fusion

Challenge:

Variable heat input and fit-up gaps in socket joints lead to uneven penetration, burn-through, or lack of fusion, especially in thin sections.

Solutions:

Maintain precise fit-up (gap ≤ 0.075 mm), optimize current and pulse parameters, and use controlled travel speed. Orbital systems provide real-time parameter control, improving penetration consistency.

7.2 Manual vs. Orbital Welding Performance

Manual TIG welding is flexible but dependent on operator skill, leading to variability in arc stability, bead uniformity, and higher defect rates. In contrast, orbital TIG welding ensures high repeatability, lower defect

rates (<1%), and higher productivity due to automated control of welding parameters. Orbital systems are particularly advantageous for thin tubes and confined geometries.

7.3 Strategies for Defect Minimization

1. Joint Preparation and Fit-Up

Ensure square-cut tube ends with minimal gap (≤ 0.1 mm), proper alignment (± 0.05 mm), and contamination-free surfaces. Burr removal and controlled material composition (Ti and S levels) are critical for weld quality.

2. Thermal Management

SS321: Controlled preheating (≈ 150 – 175°C) and limited interpass temperature ($\leq 100^\circ\text{C}$) to reduce cracking and Ti-related effects.

SS304L: Rapid cooling post-weld to prevent sensitization.

Pulsed Welding Optimization:

SS321: Higher peak current (≈ 80 – 90 A) with lower pulse frequency (2–3 Hz)

SS304L: Lower peak current (≈ 60 – 70 A) with slightly higher frequency (3–4 Hz)

Overall, defect minimization in autogenous TIG welding depends on strict control of fit-up, shielding environment, and heat input, with orbital welding offering superior consistency for critical applications.

8. Conclusion & Recommendations

8.1 Conclusion

Autogenous TIG welding of SS321–SS304L socket joints, using both manual and orbital methods, demonstrates good weldability due to similar austenitic structures and thermal compatibility.

Manual welding produced acceptable welds under controlled conditions; however, variability in penetration, bead profile, and internal oxidation was observed due to operator dependency and purge limitations. In contrast, orbital welding provided superior consistency, uniform penetration, minimal oxidation, and narrower heat-affected zones (HAZ), reducing sensitization risks.

Non-destructive testing (RT and PT) confirmed defect-free welds, and no adverse metallurgical interactions were observed at the dissimilar interface. Mechanical properties met standard requirements, though the absence of filler metal slightly reduced joint ductility. With proper post-weld cleaning and passivation, satisfactory corrosion resistance was achieved.

8.2 Recommendations

- Prefer orbital TIG welding for critical and high-purity applications requiring repeatability and superior weld quality.
- Ensure high-purity argon shielding and back purging to prevent oxidation, especially at the weld root.
- Apply post-weld pickling and passivation to restore corrosion resistance.
- Maintain controlled heat input to minimize sensitization and preserve mechanical integrity.
- Use skilled operators for manual welding with strict parameter control.
- Develop and qualify WPS/PQR specific to SS321–SS304L autogenous joints.

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