

Effect of Argon Shielding-Gas Flow Rate on the Quality and Mechanical Performance of TIG-Welded AISI 316L Joints

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Abstract

Gas tungsten arc welding (GTAW), commonly known as TIG welding, is one of the most reliable techniques for joining stainless steel, producing clean joints with few defects under a gas-shielded arc. AISI 316L austenitic stainless steel, prized for its corrosion resistance and mechanical strength, is used extensively across the petrochemical, food-processing, and aerospace sectors, which makes the quality of its welded joints a matter of practical importance. This work examines how argon shielding-gas flow rate affects the mechanical performance of manually TIG-welded 316L joints. Six flow rates were tested 5, 10, 15, 17, 19, and 22 L/min with all other welding parameters held fixed, and each condition was assessed through visual inspection, liquid-penetrant testing, radiography, tensile testing, bend testing, hardness testing, and metallographic examination. A flow rate of 10 L/min gave the best overall performance among the six conditions tested, with the highest tensile strength recorded (616.1 MPa); the lowest flow rate produced lack of root fusion, while the two highest flow rates produced undercut and excess root penetration, respectively, along with a marked drop in tensile strength. Hardness, bend strength, and microstructure showed little variation across the flow rates studied, whereas tensile strength proved by far the most sensitive property to changes in flow rate. Each reported value is the average of three replicate welds, demonstrating that a flow rate of 10 L/min is best treated as a strong candidate for overall mechanical performance among the conditions tested.

Keywords: *AISI 316L; TIG welding; argon shielding gas; flow rate; radiography; tensile strength; hardness; weld quality.*

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1. Introduction and Literature Review

Sodium fast reactor coolant piping, offshore process lines, and food-grade tanks share one requirement that makes AISI 316L the default choice across all three: it has to survive years of exposure to corrosive fluids without failing at the weld [1,2]. That single requirement explains why 316L, an iron-chromium-nickel austenitic grade from the 300 series, shows up as often as it does in petrochemical and marine construction, and why the quality of its welds is scrutinized more closely than almost any other property of the finished part [3]. Joining these steels reliably is its own challenge, and among the available welding processes, gas tungsten arc welding (GTAW, or TIG) has become one of the most trusted. It can join nearly any metal or alloy, and it is used everywhere from automotive assembly to aerospace structures, food-processing equipment, and precision manufacturing [4], largely because of the quality of the weld it produces: a narrow heat-affected zone, little spatter, and minimal distortion compared with many alternative processes [5,6]. Components welded for demanding service vessels and piping carrying pressurized gases or liquids, for instance depend on the integrity of their joints for

overall safety, which is why weld quality (freedom from defects, adequate mechanical properties) is treated as a hard acceptance criterion across industrial codes and standards [7]. Getting there requires careful control of heat input, since an imbalance between current and travel speed tends to show up first at the grain boundaries in the heat-affected zone, degrading joint performance in ways that are not always visible until the part is in service [8,9,10].

Shielding gas is not incidental to this control it is one of the primary levers available to a welder. Beyond protecting the molten pool from atmospheric contamination, it directly affects arc stability and, through that, the geometry and quality of the resulting weld [11]. Ikpe et al. showed that TIG performance depends on an interacting set of variables current, arc voltage, arc length, travel speed, and electrode geometry each of which can shift arc stability and penetration [12]. Rodrigues and Loureiro went further, comparing argon, argon-hydrogen, and argon-helium shielding on austenitic stainless steel and finding that shielding gas alone changes bead geometry and the depth-to-width ratio of the weld, partly through its interaction with any activating flux present [13]. Pavan et al. extended this line of work to A-TIG welding of 316L(N), using real-time arc imaging and thermal measurement to connect shielding-gas composition pure argon, pure helium, and blends of the two directly to arc characteristics, heat-flux distribution, and penetration depth; helium-rich shielding produced measurably deeper penetration.

Related studies by Tathgir et al. and Khrais et al. reached similar conclusions about the importance of shielding conditions for penetration and microstructural development in A TIG welding, though both focused on changing gas composition or other process parameters rather than isolating the flow rate of a single gas under conventional TIG conditions [14].

A smaller but growing body of work has looked at flow rate specifically, rather than gas type. Aljufri et al. varied shielding-gas flow rate during TIG welding of 304 stainless steel and observed clear shifts in weld performance as a result [9,15]. More recently, Nigus et al. treated gas flow rate as one of several co-varied parameters alongside current and electrode diameter and identified it as a significant factor in mechanical performance. Taken together, these studies confirm that flow rate matters, but differences in material, process, and the specific combination of parameters varied make it difficult to translate their findings directly to AISI 316L under manually controlled TIG conditions [16]. For 316L specifically, the literature is somewhat richer on welding parameters in general than on flow rate in particular. Moi et al. studied TIG welding of 316L and reported how welding parameters shape mechanical performance, while Chandrasekar et al. examined activated flux and welding parameters together and their effect on the mechanical and metallurgical properties of 316L joints. Both confirm that 316L weld quality is sensitive to how the arc and weld pool form but neither isolates argon flow rate as the sole independent variable over a defined range, which is the gap this study addresses [16,17,18].

A pattern worth flagging here: several of these studies quietly settle on a flow rate near 10 L/min without ever treating it as a variable. Durgutlu fixed flow at 10 L/min while varying hydrogen content; both of Khrais et al.'s studies (2024, 2025) did the same while varying current and gas composition. Where flow rate has been treated as one of several optimized variables, the results scatter rather than converge: Moi et al. found an optimum around 8.12 L/min, Kanan settled on 15 L/min, and Ghumman et al. found their best tensile performance at the lowest rate they tested, 6 L/min. So the literature seems to agree that something near 10 L/min is safe,

without agreeing on where the real optimum sits or why which is exactly the question this study was built to answer directly, rather than as a side effect of optimizing something else.

Table 1 summarizes this body of work. Despite the consistent finding that shielding conditions affect arc behavior, penetration, and mechanical performance, the studies vary considerably in material, joint type, gas composition, and the number of parameters changed at once and the handful that do examine flow rate tend to use different base materials or track only a single response variable.

This makes it difficult to compare their results directly with the behavior of AISI 316L under controlled, single-variable conditions. The present study was designed to close that gap: it isolates the effect of high-purity argon flow rate, keeps every other welding parameter fixed, and evaluates the resulting joints using a combined non-destructive, mechanical, and metallurgical test program. Six flow rates were selected three within the standard ANSI/AWS range and three deliberately outside it to characterize behavior across, and slightly beyond, typical practice.

Table 1. Selected previous studies relevant to shielding-gas conditions and TIG welding of stainless steels

Study	Material / process	Principal variable	Main findings	Relation to present study
Rodrigues & Loureiro (2005)	Austenitic SS TIG/A-TIG	Shielding-gas type, current, activating flux	Shielding conditions altered bead geometry and penetration	Gas type, not flow rate
Tathgir et al. (2016)	Stainless steel TIG	Gas composition and activating flux	Composition changes affected penetration and weld characteristics	Composition, not flow rate
Pavan et al. (2021)	SS 316L(N) TIG	Ar-He composition, current, speed	Composition altered arc characteristics, heat distribution, penetration	Closely related mechanism; composition not flow rate
Khrais et al. (2024)	SS 316L TIG	Ar-He-N ₂ composition, current	Composition and current affected profile, penetration, microstructure	Same steel grade, composition not flow rate
Ghumman et al. (2022)	SS 316L TIG	Welding parameters	Parameters affected roughness, hardness, tensile strength	Same grade, different variable
Moi et al. (2018)	SS 316L TIG	TIG input parameters	Parameters linked to tensile performance	Same grade, different variable

Abd Rahman et al. (2022)	TIG welded joints	Argon flow rate	Flow rate linked to joint hardness	Directly relevant, narrower response set
Aljufri et al. (2024)	SS 304 TIG	Shielding-gas flow rate	Flow rate affected performance and weld characteristics	Directly relevant, different steel grade
Nigus et al. (2026)	SS 304 manual TIG	Current, electrode diameter, gas flow	Combined parameters affected mechanical/microstructural response	Related process, multi-parameter design

2. Experimental Work

2.1 Base Material and Joint Design

Two plates of AISI 316L austenitic stainless steel, each 50 mm wide, 100 mm long, and 3 mm thick, were welded with a 1.6 mm root gap between them, as shown in Fig. 1. Table 2 lists the chemical composition of the 316L base metal and of the ER-316L filler wire used, with the minimum and maximum limits for each element. A square butt joint was chosen for its balance of economic efficiency and suitable weld characteristics.

Table 2a. Chemical composition limits of the 316L base metal

Grade	C %	Mn %	Si %	P %	S %	Cr %	Mo %	Ni %	N %
316L Min	—	—	—	—	—	16.0	2.00	10.0	—
316L Max	0.03	2.0	0.75	0.045	0.03	18.0	3.00	14.0	0.10

Table 2b. Chemical composition limits of the ER-316L filler wire

Grade	C %	Mn %	Si %	P %	S %	Cr %	Mo %	Ni %	N %	Cu %
Min	0.02	1.0	0.3	—	—	16.0	2.00	11.0	—	—
Max	0.03	2.5	0.65	0.03	0.03	18.0	3.00	14.0	0.10	0.75

2.2 Preparation for Welding

Preparation proceeded in two stages: first, machining and cleaning the base plates into a joint configuration, and second, setting up the welding machine and its principal variables (electrode, current type, shielding gas, and flow rate). The joint area and filler wire were degreased and cleaned of paint and rust well beyond the expected heat-affected zone, using a liquid cleaner, emery paper, and a wire brush.

Three specimens were welded at each of the six flow rates under otherwise identical conditions, for a total of 18 welded specimens. This replicate design was adopted to give a statistically more robust picture of how the shielding gas affects joint quality than a single specimen per condition could provide; the value reported for each flow rate throughout this paper is the mean of its three replicates, giving six condition-level results for analysis.

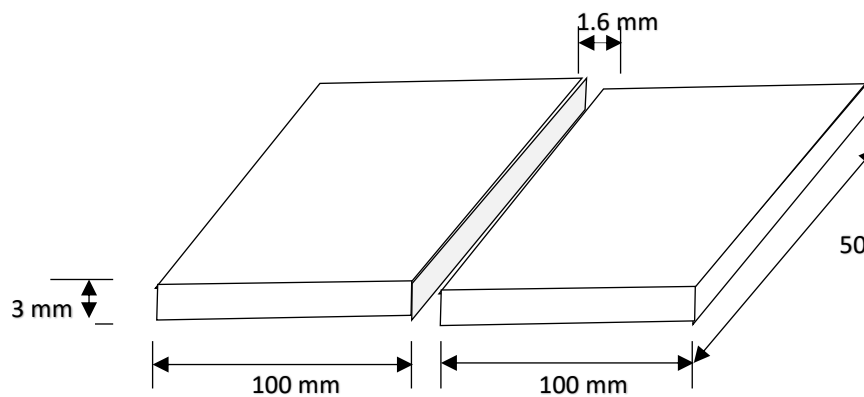


Fig.1. Weld joint configuration and dimensions

A tungsten electrode doped with 2% thorium oxide (EWTh-2 per AWS classification, red colour code) was used with direct current, chosen for its favourable arc-starting behaviour and stable arc support with stainless steel.

Table 3. Electrode sizes for the welding current range used

DCEP (reverse polarity), A	DCEN (straight polarity), A	Electrode diameter (mm)	Electrode diameter (in.)
15–30	70–90	2.4	0.093

High-purity argon (99.998%) was used as the shielding gas, chosen for its relatively easy ionization, ease of arc initiation, and its status as the only commercial gas that produces a cleaning action on stainless steel. Welding practice otherwise followed ANSI/AWS guidance, except that argon flow rate was deliberately varied — to 5, 10, 15, 17, 19, and 22 L/min — well beyond the standard's recommended 5.7–11.9 L/min at the upper end, so that three of the six conditions tested (17, 19, and 22 L/min) intentionally probed outside normal practice to characterize the limits of acceptable performance.

Table 4. Welding parameters used in this study

Welding variable	Value / description
Filler metal size (mm)	1.6–3.2
Filler metal type	ER-316L
Shielding gas purity	Argon, 99.998%
Shielding-gas flow rate (L/min)	5, 10, 15, 17, 19, 22
Nozzle size (mm)	9.5
Preheat, min	16 °C
Interpass temperature, max	260 °C
Welding position	Flat
Material thickness (mm)	3.0–3.2
Joint design	Square butt joint

Root gap (mm)	1.6
Current (A)	70–90
Polarity	DCEN
Arc voltage (V)	8–12
Travel speed	56 cm/min
Electrode type	EWTh-2

3. Testing Methods

Each welded joint went through a full inspection sequence: non-destructive testing first (visual inspection, liquid-penetrant testing, and radiography), followed by destructive testing (tensile, bend, hardness, and microstructure). Specimens for the destructive tests were machined to ASTM dimensions before testing.

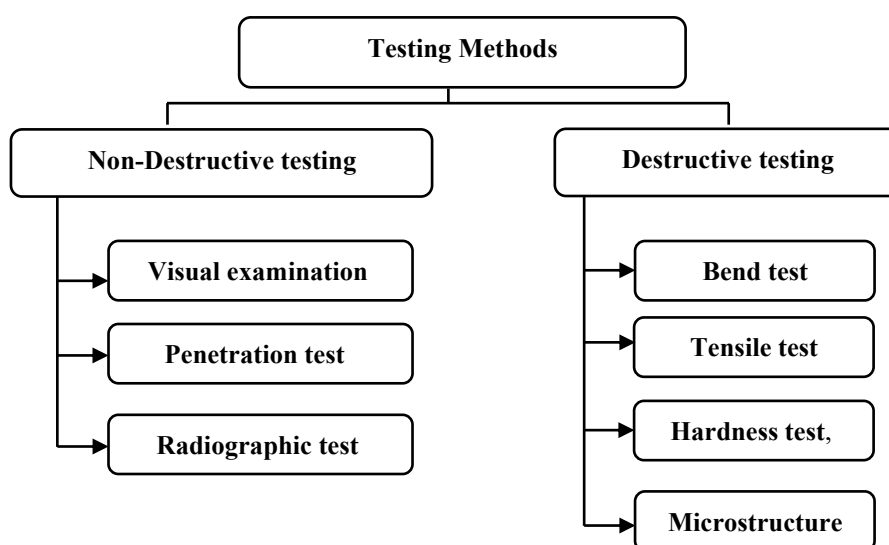


Fig. 2. Testing Methods



Fig. 3- Method for measuring the flow rate of inert gas during the welding process

Visual inspection came first simple and inexpensive, but only as good as the inspector performing it, and dependent on adequate visual acuity, lighting, training, and a documented procedure. Each joint was inspected before, during, and after welding. Liquid-penetrant testing

followed ASTM E165-02: MR-68C penetrant was applied and left to dwell for at least 20 minutes, removed with MR-85 cleaner, allowed to air-dry for 10–20 minutes, and then developed with MR-70 for an initial 5 minutes before a second inspection 20 minutes later. Radiography followed ASTM A370/96, using a 200 kVA X-ray source positioned opposite the film cassette across the weld root. Brinell hardness testing (ASTM A370/96) used a 150 kg load held for at least 15 seconds, with indentations spaced no closer than 2.5 indentation diameters apart. Four indentations were taken in each of the weld metal, HAZ, and base-metal zones per specimen, and the maximum, minimum, and mean were recorded for each zone.



Fig. 4- Hardness test

Tensile testing (ASTM A370/96) used flat specimens 3 mm thick with a 200 mm overall length and a 60 mm gauge section (60 mm² cross-section), measuring 0.2% proof strength, ultimate tensile strength, elongation, and reduction of area. Bend testing (ASTM A370/96) used 200 × 20 × 3 mm specimens to assess the ductility of the weld metal and adjacent HAZ. For microstructural examination, specimens from the HAZ and weld-metal regions were sectioned, hot-mounted at approximately 200 °C under pressure, ground through successively finer silicon-carbide grits (180 to 1200), polished with diamond paste on soft cloth, and etched with ferric chloride solution to reveal microstructural detail.

4. Results and Discussion

Each welded plate was inspected visually before being sectioned into ASTM-specified test coupons; any coupon whose defects exceeded permissible limits, or that failed to meet minimum property requirements, was excluded from further analysis.

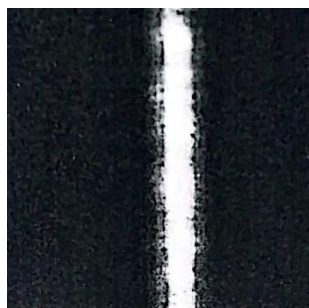
By visual Inspection All welded joints, across the full range of flow rates tested, presented an acceptable surface appearance with no visible discontinuity severe enough to disqualify a specimen from subsequent testing. This held consistently regardless of flow rate, which suggests that changes in argon flow rate within the tested range did not produce surface defects large enough to be caught by eye. Visual inspection is, of course, only a first screen; it says nothing about what might be happening beneath the surface. Also, by Penetrant testing found no surface-breaking discontinuities at any of the six flow rates- no cracks, no other indications open to the surface. This is consistent with the visual results and, taken together, the two methods agree that flow rate had no detectable effect on surface integrity over the range tested.

4.1 Radiographic Examination

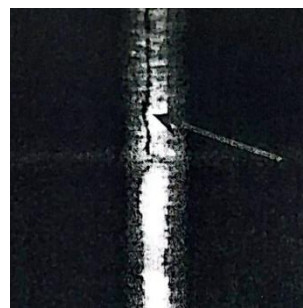
Radiography told a different story. Where visual and penetrant testing found nothing, internal examination revealed clear, flow-rate-dependent differences: lack of fusion at 5 L/min, no detectable internal defects at 10, 15, or 17 L/min, undercut at 19 L/min, and excess root penetration at 22 L/min. Table 5 summarizes these findings.

Table 5. Radiography results by flow rate

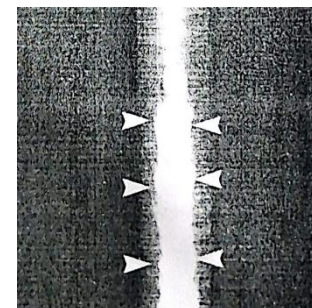
No.	Flow rate (L/min)	Remarks
1	5	Lack of root fusion
2	10	OK
3	15	OK
4	17	OK
5	19	Undercut
6	22	Excess root penetration



Under cut



Lack of root fusion



Excess root penetration

Fig. 5- Radiography test results

The pattern is symmetric: defects appear at both ends of the tested range and disappear in the middle. This is broadly consistent with prior work connecting shielding conditions to weld-pool behavior — Rodrigues and Loureiro linked shielding-gas conditions to bead geometry in austenitic steel, and Pavan et al. showed that shielding-gas composition changes arc characteristics and heat distribution during A-TIG welding of 316L(N) - though neither study varied flow rate under conventional TIG conditions the way this one does. No arc-temperature or current-density measurements were taken here, so these radiographic differences should be read as evidence that internal weld condition changed with flow rate, not as confirmation of a specific arc mechanism behind that change. A possible explanation for defects at higher flow rates is the development of gas-stream turbulence: past some threshold, adding more shielding gas doesn't shield better it just stirs the gas stream up. Jeyaprasanth et al., reviewing TIG process guidance more generally, note that excess flow rate creates turbulence right at the nozzle exit, which works against the gas envelope rather than reinforcing it. That lines up with undercut and excess penetration showing up at 19 and 22 L/min here, though it's worth saying plainly that this study didn't measure gas-stream turbulence directly — the mechanism is borrowed from established practice, not demonstrated in this data.

4.2 Hardness

Base-metal hardness varied somewhat between specimens, from 153 to 162.5 HB; weld-metal hardness ranged from 157.5 to 182.5 HB, and HAZ hardness from 157.5 to 176.0 HB. Table 6 gives the full results.

Table 6. Brinell hardness results across all zones

No.	Flow rate (L/min)	Base metal (HB)	Weld metal (HB)	HAZ (HB)
1	5	153	160.7	165.5
2	10	155.5	177.7	160.2
3	15	157	165.9	172.0
4	17	159.5	165.2	176.0
5	19	159.5	157.5	174.5
6	22	162.5	182.5	157.5

Unlike radiography, hardness barely moved with flow rate. The HAZ ran consistently harder than the base and weld metal, but weld-metal values stayed close to the base metal throughout, and the overall spread was modest. Hardness, in other words, was a much less sensitive indicator of flow-rate effects than the internal weld condition captured by radiography.

Aljufri et al. (2024), working with 304 stainless steels, reported a broadly similar pattern: mean hardness of 99.712, 105.522, and 106.704 HBW at 8, 13, and 18 L/min, respectively different numbers, given the different steel grade, but the same qualitative sensitivity of hardness to flow rate. Tathgir et al. (2016) reported essentially no change in microhardness across their TIG and A-TIG conditions, which despite testing a different material system fits the same general picture: hardness tends to be a blunt instrument for detecting shielding-gas effects unless the underlying thermal and metallurgical conditions shift substantially. Assefa et al. (2022) offer a useful statistical anchor here: in their Taguchi-based study of TIG-welded stainless steel, an ANOVA attributed about 8.52% of the variance in hardness to gas flow rate a real but modest effect, dwarfed by the contribution of welding current.

Its worth being upfront that the literature doesn't agree on which zone should be hardest in the first place. Durgutlu found weld metal consistently softer than both the HAZ and base metal, across every gas condition he tested. Moi et al. and Boumerzoug and Delaunois found the opposite weld metal (or fusion zone) the hardest of the three. And a study cited within Boumerzoug and Delaunois's own paper found the base metal hardest of all. Three studies, three different orderings. Table 6's own pattern weld metal edging out the HAZ at 10 and 22 L/min but not at the other four rates isn't an odd result needing explanation; it's just one more data point in a body of evidence that never settled on a consistent ordering to begin with. One plausible reason hardness moved so little here: current, travel speed, and pass count were all held fixed across every flow rate tested, and those three variables are what mainly set the thermal cycle a joint goes through and, downstream of that, the grain structure it ends up with. Since the welding current, travel speed, and transition conditions were kept constant, no significant changes in heat input between different flow-rate conditions are expected. Tensile strength doesn't get that same protection, since it responds directly to whether the weld actually fused properly which is exactly what varied with flow rate here, as the radiography already showed.

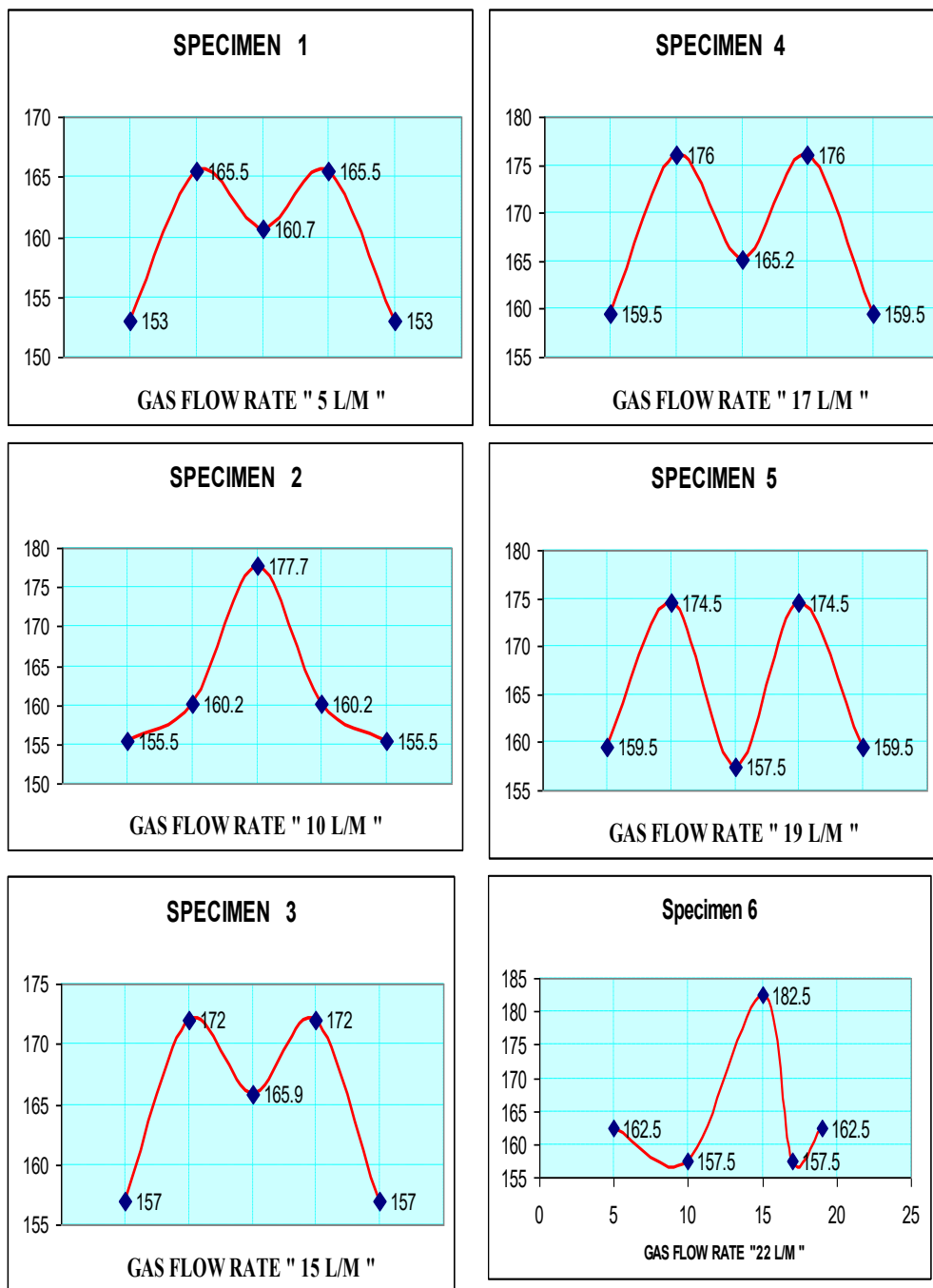


Fig. 6- Hardness test results for all samples

4.3 Tensile Strength and Elongation

Tensile properties responded far more clearly to flow rate than hardness did, as Table 7 shows.

Table 7. Tensile test results across all flow rates

No.	Flow rate (L/min)	Tensile strength (MPa)	Yield strength (MPa)	Elongation (%)	Reduction of area (%)
1	5	512.7	343.6	24.35	46.66
2	10	616.1	370.2	62.55	59.97
3	15	595.9	365.9	49.93	55.73
4	17	601.5	361.6	51.92	58.45
5	19	574.9	343.0	47.17	54.40
6	22	506.6	336.0	22.83	32.16

The joint welded at 10 L/min came out on top by every tensile measure: 616.1 MPa in tensile strength and 62.55% elongation, both the highest recorded. Performance at 15 and 17 L/min stayed close behind (595.9 and 601.5 MPa, with elongations of 49.93% and 51.92%), while the three conditions flagged by radiography 5, 19, and 22 L/min all showed reduced tensile strength (512.7, 574.9, and 506.6 MPa) and lower elongation to match. The weakest specimen overall was welded at 22 L/min, closely followed by 5 L/min, and both sit at opposite ends of the flow-rate range, linked to excess root penetration and lack of fusion respectively. That the radiographic and tensile results line up so closely is worth pausing on: it means two independent test methods, measuring completely different things, are pointing at the same underlying story. That does not mean every drop in tensile strength can be attributed to a specific radiographic indication in a strict cause-and-effect sense this study was not designed to isolate the contribution of each defect type individually but the correspondence between the two datasets gives real weight to the conclusion that flow rate, not measurement noise, is driving the pattern.

This sensitivity of tensile performance to welding conditions echoes what Moi et al. (2018) and Ghumman et al. (2022) and Mofid et al. (2025) found for 316L joints under varying TIG parameters more generally, and it lines up numerically with Aljufri et al. (2024), who reported mean tensile stress rising from 44.72 N/mm² at 8 L/min to 49.69 N/mm² at 18 L/min in 304 stainless steel a smaller absolute range, but the same upward trend with increasing flow rate. Assefa et al. (2022) go a step further: their ANOVA assigned gas flow rate 29% of the variance in tensile strength, second only to welding current among the parameters studied, and notably found the same non-monotonic pattern seen here, with tensile strength rising to a peak at a mid-range flow rate before falling off again at higher flows. That two independent studies, on different materials and joint configurations, both land on a mid-range optimum rather than a monotonic trend is a reassuring sign that the pattern reported here is not an artifact of this particular experimental setup.

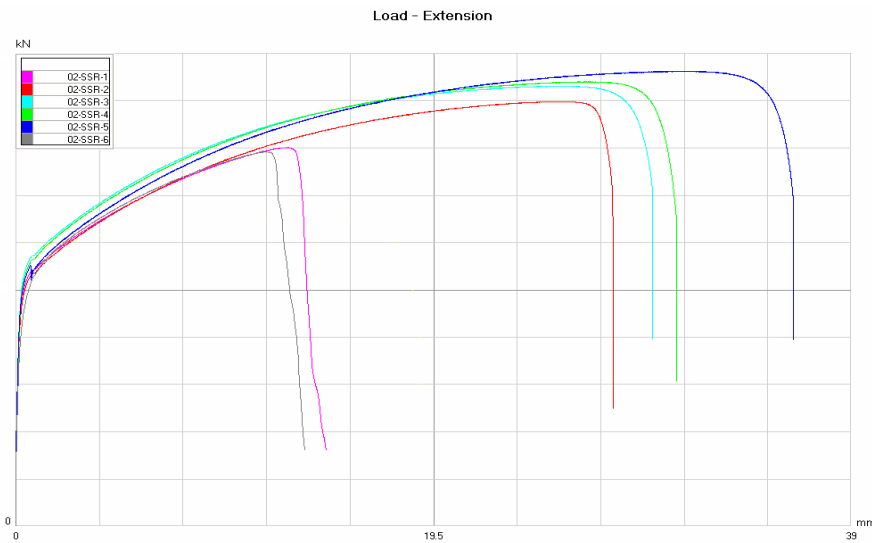


Fig. 7. Tensile test results for all samples

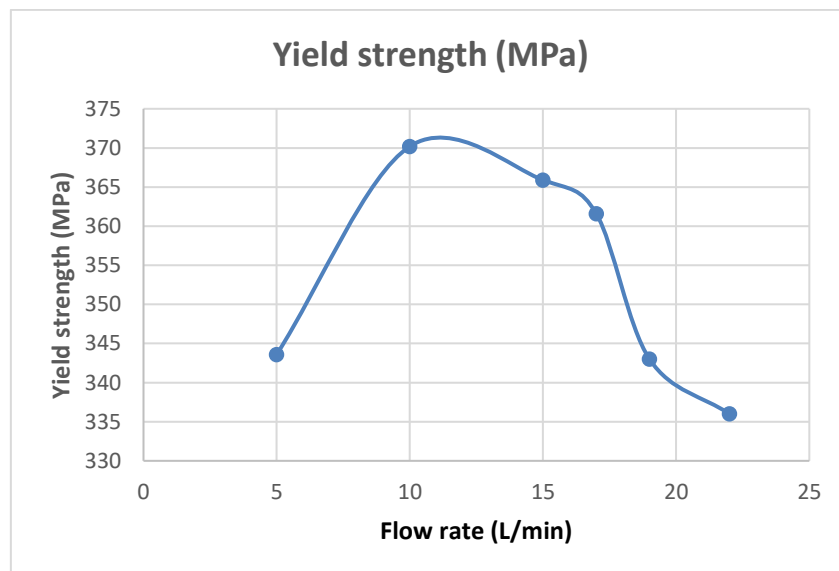


Fig. 8. Yield strength vs. argon flow rate.

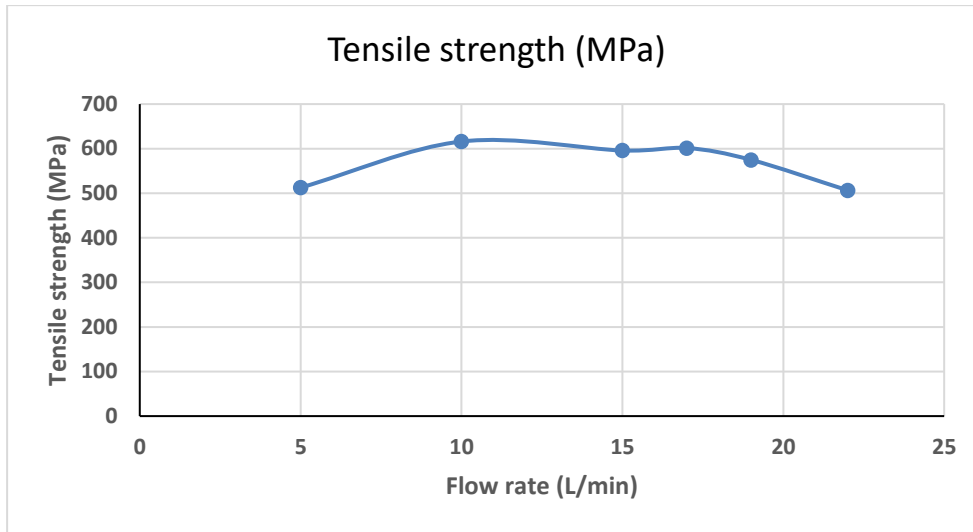


Fig. 9. Tensile strength vs. argon flow rate.

The 616.1 MPa peak recorded here sits in familiar territory: Durgutlu, welding 316L at a fixed flow rate of 10 L/min while varying hydrogen content instead, saw tensile strength range from 612 to 695 MPa depending on gas mixture. Kanan, running a full parameter study with flow rate as one of several variables, found a comparable peak of 605-615 MPa at an optimal flow rate of 15 L/min. Moi et al. push the case for flow rate's importance further than either of those: in their ANOVA, gas flow rate came out as the single most influential factor on tensile strength ahead of welding current with strength peaking at a mid-range flow of 9 L/min within their 6-12 L/min window. Ghumman et al., working with the same steel and a similar design, found the opposite shape entirely: their best tensile strength came at the lowest flow rate they tested (6 L/min), dipped at the middle setting, and only partly recovered at the highest. So even among studies that agree flow rate matters, there's no agreement on what the response curve actually looks like — rising, falling, or peaking in the middle depends on which study you read. Flow rate's contribution to tensile-strength variance across these studies runs anywhere from about 7% to 29%, never irrelevant, but never the whole story either. That inconsistency is itself a reasonable justification for a study like this one, where flow rate is examined on its own rather than folded into a multi-factor design where its individual effect is hard to isolate.

4.4 Bend Test

Three specimens per flow rate were bent to 180° with no separation, tearing, or cracking observed in any of them; measured bend strength ranged narrowly from 28.5 to 31.6 MPa, comfortably within the known range for 316L. Every specimen passed, at every flow rate the bend test simply did not distinguish between conditions the way tensile testing and radiography did. That is a real result in its own right: whatever internal changes are driving the tensile and radiographic differences, they were not severe enough to compromise bend ductility over the range studied.

Table 8. Bend test results by flow rate

Specimen	Flow rate (L/min)	Area (mm ²)	Max. load (kN)	Max. strength (MPa)	Remarks
1	5	60	1.74	28.9	No cracks
2	10	60	1.79	28.5	No cracks
3	15	60	1.89	31.6	No cracks
4	17	60	1.85	31.1	No cracks
5	19	60	1.71	29.8	No cracks
6	22	60	1.80	30.1	No cracks

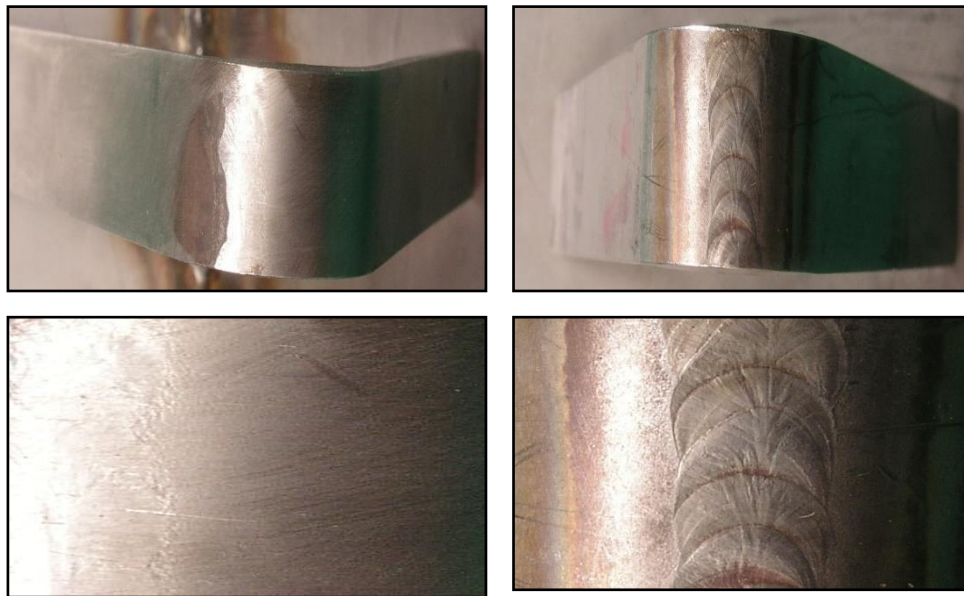


Fig. 10. Bend test results

4.5 Metallographic Examination

Microstructural examination was performed at magnifications of $\times 200$ and $\times 500$ for the welded joints. No cracking was found along grain boundaries, and no tearing defects appeared in the weld metal at any of the welded joints. Grain size in the fusion zone ran from roughly 55 to 100 μm , close to the 50–100 μm range measured in the base metal, no major differences were resolved by the optical microscope at the magnifications used. Nor does the absence of a difference at this magnification rule out finer-scale changes in phase distribution or local composition that would need SEM or EDS to resolve.

This limited microstructural response tracks the limited hardness response reasonably well both point toward flow rate having a comparatively muted effect on the metallurgy of the joint, even

where radiography and tensile testing show a clear one. Put differently, the effect of argon flow rate under these conditions was easier to see through internal-defect detection and mechanical testing than through conventional optical metallography.

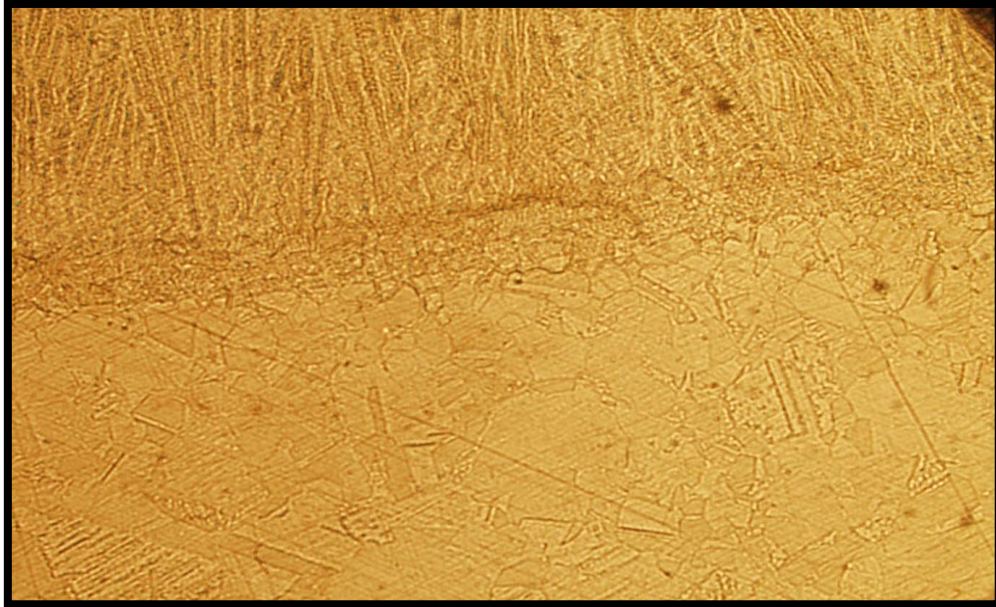


Fig. 11 Microstructure of base metal & HAZ for samples welded at 5 L/min.

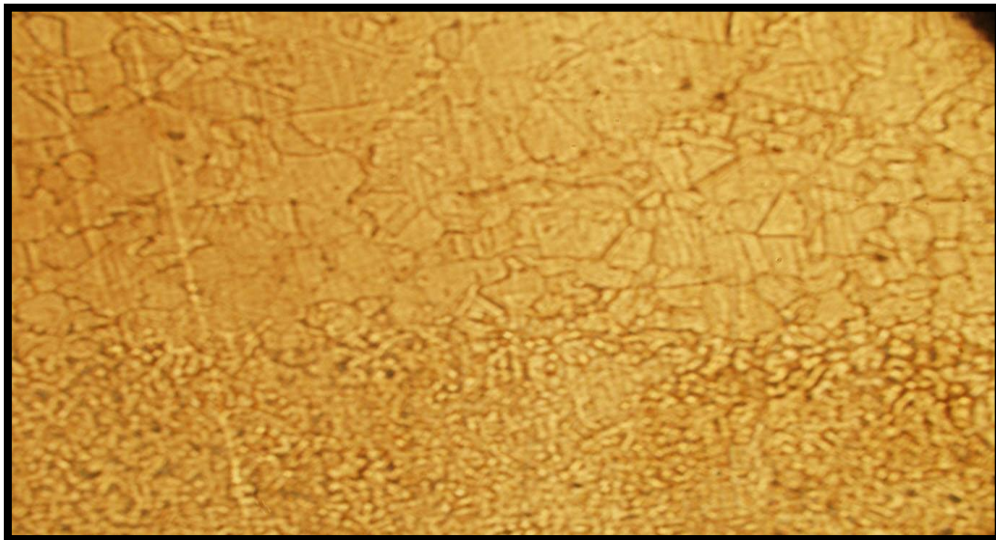


Fig. 12. Microstructure of base metal & HAZ for samples welded at 19 L/min.

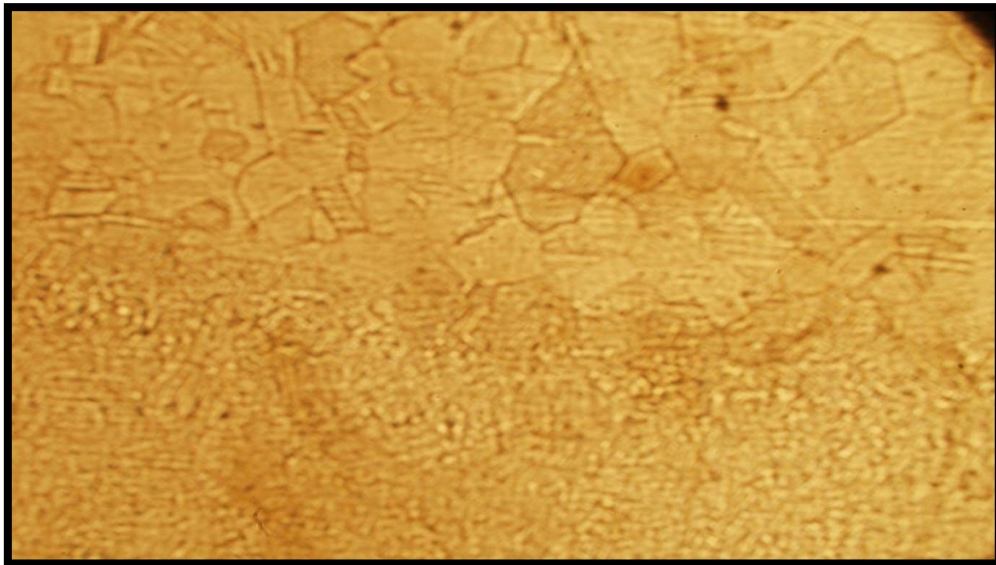


Fig. 13. Microstructure of base metal & HAZ for samples welded at 22 L/min.

4.6 Discussion

Bringing the results together, the picture that emerges is one of uneven sensitivity: argon flow rate clearly affected some properties and barely touched others. Surface inspection (visual and penetrant testing) found nothing at any flow rate.

Radiography, by contrast, drew a sharp line: clean joints at 10, 15, and 17 L/min, and specific, identifiable defects at 5, 19, and 22 L/min. Tensile testing followed the same line almost exactly, with the highest strength and elongation at 10 L/min and the weakest performance at the flow rates flagged by radiography. Hardness, bend testing, and metallography, meanwhile, showed comparatively little variation across the same range. The practical takeaway is that flow rate's effect on this joint configuration shows up mainly in internal weld condition and tensile performance, not in the properties a surface inspection or a hardness test would catch. A joint could pass visual inspection, hardness testing, and the bend test at 19 or 22 L/min and still carry the undercut or excess penetration that radiography and the tensile test picked up. That is the practical argument for not relying on any single test method to clear a shielding-gas condition for service. The broader pattern here shielding-gas conditions shaping TIG weld formation and mechanical performance matches the literature cited above; the specific numbers are naturally tied to the material, joint configuration, welding procedure, and flow-rate range used in this study. Within that scope, the joint welded at 10 L/min performed best overall, combining a clean radiograph with the highest tensile strength and elongation recorded in the study. That conclusion rests on considering radiography and tensile testing together, rather than on any single measured property in isolation.

5. Conclusions

This study examined how argon shielding-gas flow rate affects the quality of manually TIG-welded AISI 316L joints. The following conclusions can be drawn from the experimental results:

1. Argon flow rate affected weld-joint quality in AISI 316L, but the effect was far from uniform across evaluation methods it showed up clearly in internal weld condition and

- tensile properties, while visual inspection, penetrant testing, hardness, bend testing, and metallography all showed comparatively limited sensitivity over the range studied.
2. Neither visual inspection nor liquid-penetrant testing detected any surface-breaking discontinuity at any of the six flow rates tested (5–22 L/min). The differences between flow conditions were therefore driven by internal weld condition, not by detectable surface defects.
 3. Radiography showed a clear dependence of internal weld condition on flow rate: lack of fusion at 5 L/min, no detectable internal defects at 10, 15, or 17 L/min, undercut at 19 L/min, and excess root penetration at 22 L/min. The mid-range flow rates produced the most consistently sound internal weld condition.
 4. Tensile properties responded more clearly to flow rate than any other property measured. The highest tensile strength (616.1 MPa) and elongation (62.55%) were obtained at 10 L/min; the weakest performance occurred at 5 and 22 L/min (512.7 and 506.6 MPa, respectively), matching the flow conditions flagged by radiography.
 5. Hardness varied only modestly across the six conditions. Base-metal hardness ranged from 153 to 162.5 HB across specimens, weld-metal hardness from 157.5 to 182.5 HB, and HAZ hardness from 157.5 to 176.0 HB, with no clear trend tied to flow rate.
 6. All welded specimens passed the 180° bend test without visible cracking at every flow rate tested, showing no measurable difference in bend performance across the range studied.
 7. Metallographic examination found no major microstructural differences within the resolution used. Grain size in the fusion zone ranged from approximately 55 to 100 μm , close to the 50–100 μm range measured in the base metal.
 8. Taking radiography and tensile results together, 10 L/min produced the best overall response among the six flow rates tested, combining a radiograph with no detectable internal defects with the highest measured tensile strength and elongation.

6. Future Studies

The results point to a few concrete next steps that follow directly from what was and was not observed here, rather than a generic research agenda:

- a) Narrowing the flow-rate grid between 10 and 17 L/min, in steps of 1–2 L/min rather than the 5–7 L/min steps used here, to pin down where the tensile-strength peak actually sits, since the current data only bracket it between 10 and 17 L/min.
- b) Repeating the tensile and hardness measurements with enough replicates per flow rate to run a one-way ANOVA on the actual specimen-level data — the 18 specimens welded for this study were averaged into six condition-level means, but the raw per-specimen values were never tested for significance.
- c) Adding a basic corrosion test (salt-spray or potentiodynamic polarization) specifically at 5, 19, and 22 L/min, since these are the three conditions where radiography already found a defect, and it is an open question whether the same defects also compromise corrosion resistance.

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