



Multiwire Gas Tungsten Arc-Directed Energy Deposition

Evaluation of dilution and composition gradients around changes in filler metal feed rates for a nickel-based alloy system

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Abstract

Further development of manufacturing methods and metallic alloys is crucial for creating next-generation energy production systems with enhanced strength, toughness, creep resistance, and/or corrosion resistance. For wire-based additive manufacturing (AM), wire materials are often cheaper than powdered metal, impurity contents are easier to control, deposition rates are substantially higher than those of powder-based AM, and wire arc AM is backed by decades of experience in multipass welding, cladding, and build-up repairs. To further expand the capabilities of wire arc additive manufacturing, a multiwire gas tungsten arc welding AM system was developed to independently introduce two commercially available nickel-based alloys, Alloy 617 and Alloy 740H, as weld wires into a single weld pool, thereby introducing chemical composition gradients with the intent of altering local material properties. This research analyzed weld metal dilutions and evaluated the composition profiles at different proportions of nickel alloy filler wires. The work demonstrated that multiwire gas tungsten arc-directed energy deposition can deposit graded compositions predictably via a simple mathematical analysis based on mass balance.

Keywords

- Directed Energy Deposition (DED)
- Gas Tungsten Arc Welding (GTAW)
- Gas Tungsten Arc-Directed Energy Deposition (GTA-DED)
- Wire Arc Additive Manufacturing (WAAM)
- Inconel®
- Alloy 617
- Alloy 740H
- Alloy Discovery

Introduction

Commercial power generation facilities benefit from economies of scale, and individual components, such as valve bodies, turbine casings, steam headers, and piping, are quite large, weighing thousands of kilograms with wall thicknesses potentially exceeding 75 mm (2.95 in.). These items are generally one-of-a-kind, special-order items that require extensive engineering and planning, resulting in long manufacturing lead times. Usually, these large components are cast, which, though near net shape, require ancillary components (gating, runners, sprues, risers, pouring basins, etc.). For example, a power plant valve body, ~ 2700 kg (6000 lbs), requires on the order of 7700 kg (17,000 lbs) of metal to be cast (Ref. 1), requiring about 5000 kg (11,000 lbs) to be recycled.

Additive manufacturing (AM) techniques can reduce lead time and recycle material because mold and die design are not required, and ancillary components can be eliminated. Wire-based arc methods offer deposition rates of upwards of 10 kg/h, typically higher than those of other wire-based or powder-based directed energy deposition (DED) methods, such as laser or electron beam energy sources, which have deposition rates of ≤ 1 kg/h (Refs. 2–4). Also, wire-based additive methods exhibit deposition efficiencies approaching

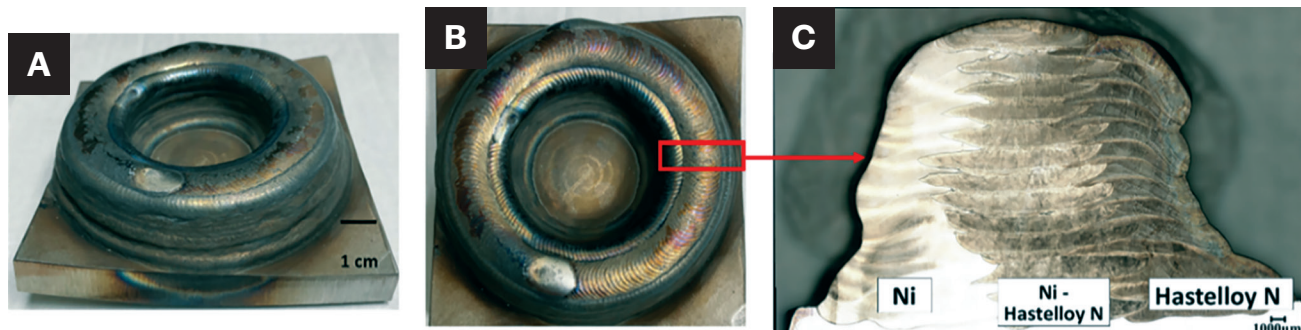


Fig. 1 — A pipe-shaped deposit graded from nickel to Hastelloy N using multiwire GMA-DED for molten salt applications: A — Side; B — top; C — cross-sectional views.

Table 1 — Multiwire GTA-DED Deposition Parameters

Parameters	Weld Conditions	
	High Heat Input	Low Heat Input
Avg. Current (A)	275	175
Voltage	12	12
Peak Current (A)	300	200
Peak Current Pulse Width (s)	0.5	0.5
Background Current (A)	250	150
Background Current Pulse Width (s)	0.5	0.5
Travel Speed (mm/min)	102	102
Electrode Type	EWL a-1.5	EWL a-1.5
Electrode Preparation	30 deg included angle, truncated	30 deg included angle, truncated
Shielding Gas	75% Ar/25% He	75% Ar/25% He
Shielding Gas Flow Rate (in./min)	12	12
Gas Cup	Size 10 (15.8-mm orifice)	Size 10 (15.8-mm orifice)
Heat Input (kJ/mm)	1.95 kJ/mm	1.24 kJ/mm

100% while powder-based DED methods generally exhibit < 50% deposition efficiency (and recycling powder can cause issues with defect generation [Refs. 5–7]). The cost of wire is also considerably less than the same alloy in powder form: e.g., Type 316L stainless steel wire costs approximately three times less than powder based on a 15 kg quantity (Refs. 8, 9). Although powder-based additive methods have the advantage of higher resolution, this is not overly important for large power generation components.

Large components were additively fabricated in the 1970s and 1980s using the submerged arc welding (SAW) process (Refs. 10–12), with Babcock and Wilcox developing a gas metal arc welding (GMAW) process referred to as “shape melting” or “free-form fabrication” (Refs. 12, 13) in the late 1980s and early 1990s. Recent additive manufacturing developments include gas metal arc directed energy deposition (GMA-DED) (Refs. 14, 15) that leverages long-established welding process knowledge and inexpensive welding equipment, essentially creating multipass welding without the

Table 2 – Composition of Materials from the Material Certifications

	Chemical Compositions (wt-%)										
	Ni	Cr	Co	Mo	Fe	Al	Ti	Mn	Si	C	Nb
Alloy 617 Substrate	54.10	22.20	11.60	8.60	1.60	1.10	0.40	0.10	0.10	0.05	–
Alloy 617 Weld Wire	54.24	21.81	11.57	9.00	1.67	1.08	0.34	0.08	0.07	0.08	–
Alloy 740H Weld Wire	50.00	24.30	20.40	0.33	0.16	1.38	1.38	0.28	0.13	0.02	1.41

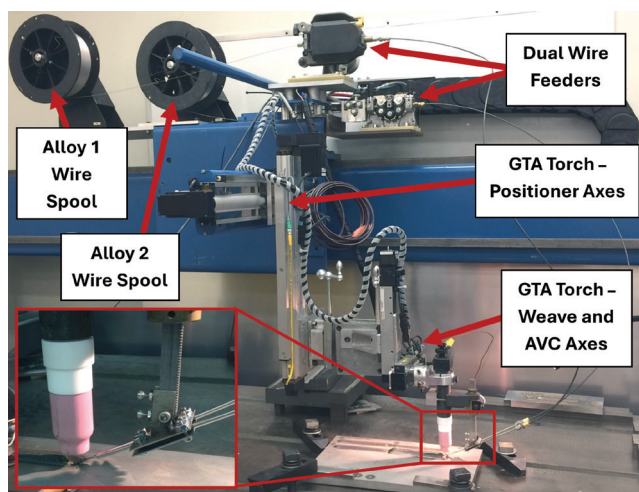


Fig. 2 – Overview of the multiwire GTA-DED system showing the dual wire feed guide relative to the GTAW torch.

constraint of a welding groove, relying on surface tension and heat flow to build net-shape or near-net-shape geometries. Wire arc additive manufacturing (either gas tungsten arc directed energy deposition [GTA-DED] or GMA-DED, [Ref. 16]) has been mostly limited to deposition using a single welding wire.

Feeding two or more wires of different composition into the weld pool allows for depositing alloys of unique composition, i.e., multiwire arc additive manufacturing. Independently varying the wire feed rates enables the deposition of functionally graded materials (FGMs) and the placement of specific alloys in desired locations without abrupt compositional changes. SAW is often used to deposit numerous electrodes into a single weld pool with deposition rates up to 300 kg/h (Ref. 13). However, a flux must be contained over the weld pool, and high heat input results in coarse, highly segregated microstructures. Additionally, some alloys may lack an appropriate flux, e.g., Inconel Alloy 740H, a high-temperature, nickel-based alloy with high levels of aluminum and titanium. Twin wire arc additive manufacturing methods via GMAW or gas tungsten arc welding (GTAW) (Refs. 17, 18) elim-

inate the need for a flux. However, the use of only two wires in these methods limits the wide range of compositional flexibility required to avoid undesirable phases. Additionally, the overall heat input with GTAW is not influenced by filler metal feed rates (i.e., a constant current process with controlled voltage) and is inherently more stable due to reduced spatter generation (i.e., composition loss) compared to GMAW.

Numerous alloys exist that optimally address either structural or corrosion requirements of components. Depositing such alloys together, as in arc cladding, effectively addresses both corrosion and structural requirements without the need to develop a new alloy. However, differences in the properties between cladding and substrate can result in unacceptable distortion and/or cracking (Refs. 19, 20). Multiwire GTA-DED can smooth sharp transitions in composition, as shown in Fig. 1, thereby reducing the severity of distortion, the potential for cracking, and the formation of undesirable brittle phases (Ref. 21).

This paper presents the results obtained from a prototype two-wire GTA-DED system, as well as the factors that affect the as-deposited composition profile. Only the relative feed rate ratios of the wires are varied for two heat input conditions. A simple dilution model was developed to predict local composition profiles arising from changes in wire feed rates and heat input.

Experimental Approach

A second wire feeder was integrated into an automated GTAW system, as shown in Fig. 2., as GTAW decouples the dependence of welding current and heat input from the weld wire feed rate unlike GMAW. The entire multiwire GTA-DED process was controlled by an internally developed LabVIEW software program. Deposits were made using pulsed GTAW with automatic voltage control (AVC) with the specific parameters shown in Table 1. The deposition rate was set to nearly 1 kg/h. This is not a maximum deposition rate for GTAW but was chosen based on equipment and sound weld procedures. Specifically, the GTAW process was chosen over other processes due to its constant current characteristics, which allow for independent control of the wire feed rate without changing other process parameters. For instance, multiwire

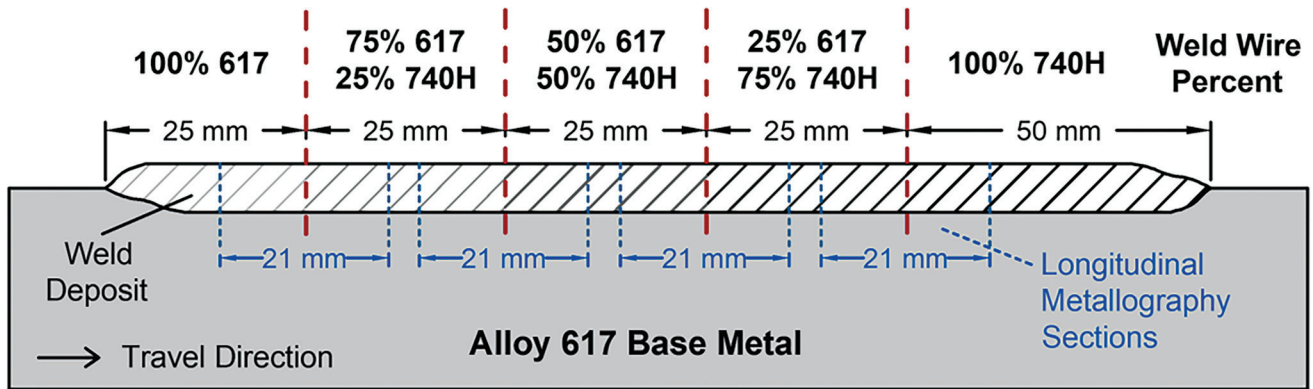


Fig. 3 — Schematic of the multiwire GTA-DED deposit showing the weld wire feed changes and metallographic sectioning locations. Samples, ~ 21 mm long, were extracted at locations containing each step change in the filler wire feed rates.

Table 3 — Weld Wire Deposition Information for Each Section of the Deposit

Variables		Wire Feed Percentages				
		100% 617 0% 740H	75% 617 25% 740H	50% 617 50% 740H	25% 617 75% 740H	0% 617 100% 740H
617 Feed Rate (m/min)		1.96	1.47	0.978	0.489	0.0
617 Deposition Rate (mm ³ /min)		2006.8	1505.1	1003.4	501.7	0.0
617 Deposition Rate (g/min)		16.8	12.6	8.4	4.2	0.0
740H Feed Rate (m/min)		0.0	0.635	1.27	1.91	2.54
740H Deposition Rate (mm ³ /min)		0.00	489.4	978.8	1468.2	1957.6
740H Deposition Rate (g/min)		0.0	3.9	7.9	11.8	15.8
Total Filler, V^{total} (mm ³ /mm)*		19.75	19.63	19.51	19.39	19.27
Total Filler (g/mm)*		0.165	0.163	0.160	0.158	0.155
Weight Fraction	617	1.00	0.76	0.52	0.26	0.00
	740H	0.00	0.24	0.48	0.74	1.00

*At a travel speed of 101.6 mm/min

GMAW or multiwire SAW are based on constant voltage power supplies that adjust the current (heat input) in response to changes in wire feed speed.

Two high-temperature, nickel-based weld wires, Inconel Alloy 617 (solution-strengthened alloy) and Inconel Alloy 740H (γ' -strengthened alloy), were used. Although similar in composition (both contain 20–24% Cr and significant amounts of Al and Ti), the significant differences in cobalt (Co) and molybdenum (Mo) concentrations allowed the

effects of dilution to be quantified. Deposits were made on an Inconel Alloy 617 base plate approximately 50 mm thick, 50 mm wide, and 200 mm long. The composition of these materials is shown in Table 2 in weight percent (wt-%).

The combined wire volume feed rate added to the weld pool was kept constant at 2 cm³/min (equivalent to ~ 1 kg/h. Only the relative fractions of two weld wires varied along the deposit. The measured Alloy 740H wire diameter was 0.991 mm (0.039 in.), while the measured Alloy 617 wire diameter

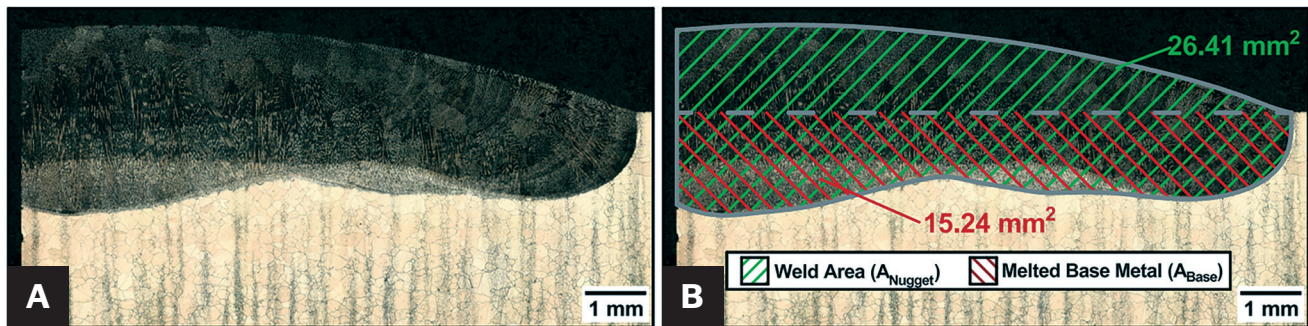


Fig. 4 – A – Transverse section of the multiwire GTA-DED deposit (25% Inconel Alloy 617 and 75% Inconel Alloy 740H, 1.95 kJ/mm); B – the image analysis data used to calculate the dilution.

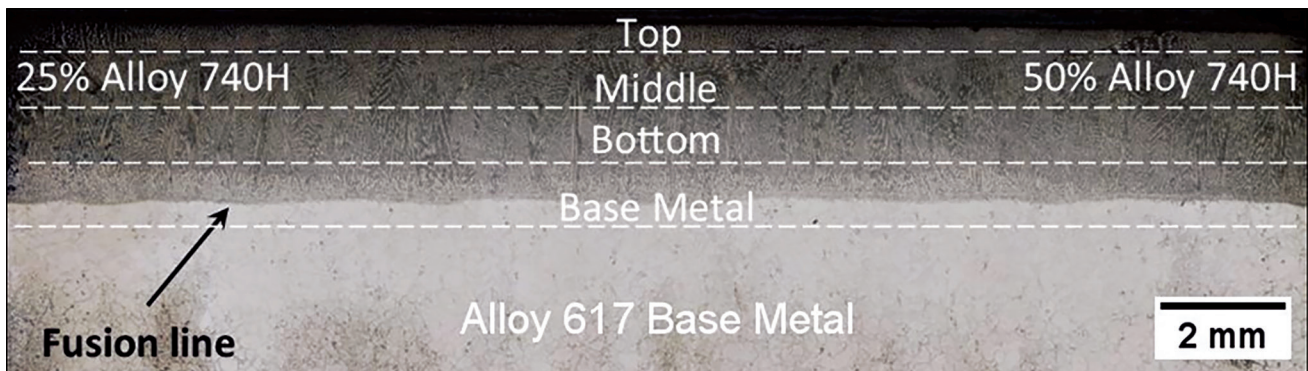


Fig. 5 – Longitudinal view of the specimen used to capture the step change in weld wire feed rates (from 25% Alloy 740H on the left to 50% Alloy 740H on the right). The dashed lines indicate the locations for EDS analysis (i.e., top, middle, bottom, and base metal).

was 1.143 mm (0.045 in.). The maximum wire feed speeds when depositing 100% of alloys 740H and 617 were 2.5 m/min (100 ipm) and 2.0 m/min (77 ipm), respectively. Both wires were fed into the leading edge of the weld pool at an approximately 30 deg angle from the plate surface.

A single weld bead was deposited (i.e., bead-on-plate) to understand the factors affecting the multiwire GTA-DED process. The fraction of each weld wire fed into the weld pool was abruptly changed at the locations indicated in Fig. 3, as shown by the longer, dashed lines, with the associated weld wire deposition information provided in Table 3.

The dilution was measured midway between the location corresponding to step changes in the wire feed rate to analyze the “steady-state” dilution (where transient composition changes due to the preceding or subsequent feed rate step change were assumed to be minimal). Dilution was determined using image analysis on optical micrographs as shown in Fig. 4, and the percent dilution was calculated using Equation 1. The dilution measurements were performed on partial, transverse sections, as opposed to the entire weld fusion zone, to also produce a centerline, longitudinal view for analyzing the composition gradient. Nearly half of the fusion zone was analyzed for dilution, and the same fraction of the fusion zone was analyzed for each location. In the 100% 617 section, a dilution measurement on a full cross section was compared to the corresponding partial cross section, which produced the same dilution value.

$$\begin{aligned} \text{Actual \% Dilution} &= \frac{A_{\text{Base}}}{A_{\text{Nugget}}} * 100\% \\ &= \frac{A_{\text{Nugget}} - A_r}{A_{\text{Nugget}}} * 100\% \end{aligned} \quad (1)$$

Where:

A_{Base} = area of weld metal within the base metal, mm²

A_{Nugget} = total area of weld metal, mm²

A_r = area of weld metal reinforcement, mm²

Specimens ~ 21 mm long were cut from the deposit to contain the location of each wire feed rate step change as shown in Fig. 3. Longitudinal views of these specimens allowed characterization of the composition profile across each step change.

Transverse and longitudinal samples were prepared by standard metallographic methods and were subjected to a final electropolishing step (ethanol-6.7% perchloric acid, 10% 2-butoxyethanol, and 10% water at 0°C and 25 V for 5–15 s). Room-temperature (20°C) electrolytic etching (using a 10% solution of oxalic acid at 2.5 V for ~ 30 s) revealed a microstructure in both the Inconel Alloy 617 base plate and the multiwire GTA-DED deposit. In some cases, structures were better revealed using a 1:1 mixture of concentrated

hydrochloric acid and 30% hydrogen peroxide, achieved by submersion for ~ 20 s (Fig. 4).

The composition profile at the top, middle, bottom, and within the base metal of the longitudinal sections, as shown in Fig. 5, were determined using standardless energy dispersive spectroscopy (EDS) analysis in the scanning electron microscope (SEM - FEI Quanta FEG 650, EDAX® Octane Elect Plus silicon drift detector (SDD) with EDS data analysis performed in TEAM™ software version 4.5.1). EDS analysis points were collected along lines at the top, middle, and bottom of the deposit, as well as along a line in the base metal for each field of view. The SEM was set to an accelerating voltage of 20 kV, a spot size of 3.0 μm , and a working distance of 10 mm to achieve an x-ray count rate of approximately 100,000 counts/s. A 30-s dwell time was used to collect x-ray data at each analysis point.

Since the longitudinal specimens were on the order of 21 mm long, numerous fields of view in the SEM along the length of the specimen were analyzed. These views were manually stitched together to determine the location of each EDS point, measured from the left edge of the specimen, and allowed the composition as a function of distance from the left edge of each specimen to be plotted.

Results

Dilution

Dilution, determined according to Equation 1, as a function of the fraction of Inconel Alloy 740H wire added to the deposit, is shown in Fig. 6A. For comparison, the measured weld penetration and weld toe widths are also shown in Figs. 6B and C. Dilution is lowest in the segment where only Alloy 617 weld wire was deposited (i.e., 0% Alloy 740H in Fig. 6A). Dilution is greater in all segments where Alloy 740H wire was added to the weld pool. The dilution at the high heat input condition is greater than the low heat input condition using the same wire feed speeds, since more energy is available to melt the substrate. In general, dilution for both heat inputs does not vary extensively from one step change to the next since the weld wires and substrate materials only differ in the amounts and types of minor alloying additions.

Composition Profiles

Since solidification occurred under non-equilibrium conditions and post-deposit heat treatment was not performed, considerable microsegregation is present, as shown in Fig. 7. Figure 8A shows a plot of the Co concentration around the step change in weld wire feed rates from 25% Alloy 740H to 50% Alloy 740H at the low heat input level. No evidence for enrichment or depletion of Co in the top versus the bottom of the deposit was observed. This observation implies the weld pool/deposit was well mixed, and the compositions at the top, middle, and bottom for a given location could be averaged to obtain a more accurate representation of the bulk composition.

Therefore, EDS points within 1000 μm intervals (vertical, gray dotted lines in Fig. 8B) are averaged and plotted as a

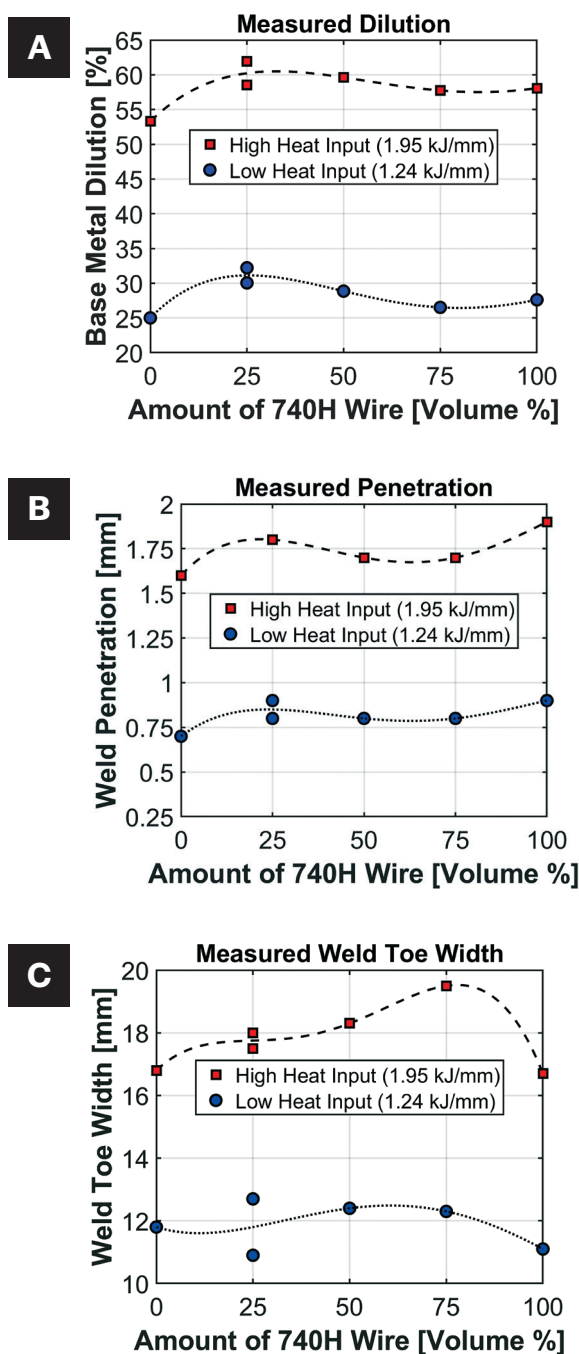


Fig. 6 — Plot of the measured dilution: A — Penetration; B — weld width; C — versus the volume fraction of Alloy 740H wire added to the deposit for the high and low heat inputs.

function of distance, i.e., the filled black circles in Fig. 8B. The average elemental concentration for an interval included a minimum of three, and as many as ten EDS points within the interval. Similarly, the average position within the interval was determined by averaging the locations of the EDS points within the interval. Using this averaging approach, the concentration of Co and Mo around each step change was plotted for the high heat input (Figs. 9 and 10) and low heat input conditions (Figs. 11 and 12). Because an average

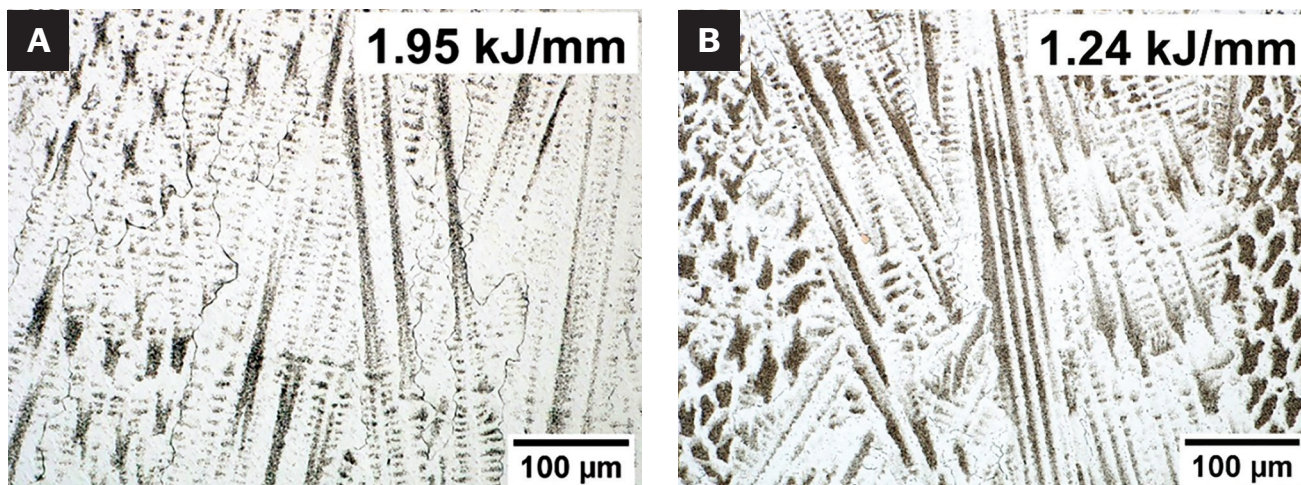


Fig. 7 — Optical micrographs of 50% Alloy 617–50% Alloy 740H. A — High heat input condition; B — low heat input condition.

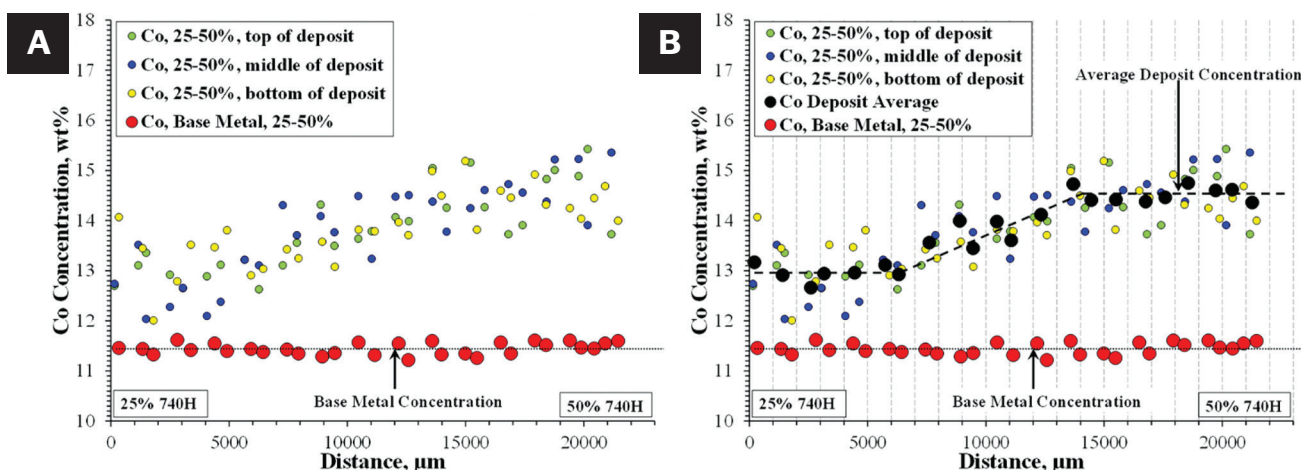


Fig. 8 — A — Plot of the Co concentration at the top, middle, and bottom of the deposit for the 25% 740H to the 50% 740H step change in filler wires at the low heat input condition; B — EDS points within 1000 μm intervals (grey dashed lines) were averaged and included on the plot (solid black circles).

of numerous measurements was used to obtain chemical composition information, the effects of a small SEM spot size for measuring interdendritic segregation or elemental depletion in a dendrite core should have been minimized to yield a representative average composition within the 1000 μm interval. Additionally, error bars representing the 95% confidence interval have been added to each data point. Microsegregation in the as-solidified weld material contributed to the relatively large error bars in these plots.

Comparison of plots shown in Figs. 9–12 show that the high heat input condition resulted in less compositional changes that are spread out over longer distances – the Co and Mo concentration changes by about 1 wt-% across each step change for the high heat input condition compared to concentration changes on the order of 1.5 wt-% at low heat input. Furthermore, more than $\sim 20,000$ μm was required to approach steady state Co and Mo concentrations under the high heat input condition compared to only $\sim 15,000$ μm for the low heat input. A steady state composition or condi-

tion results once there is sufficient time or distance for the weld pool composition to equal the relative proportions of base metal and both filler metals being introduced into the pool. This is a direct consequence of greater dilution and an increase in weld pool size as heat input increased.

Based on the Co and Mo concentration, profiles reaching a theoretical dilution value for each wire feed rate, Figs. 11 and 12, indicate that a steady state composition was achieved for the low heat input. The high heat input condition required more than 21,000 μm from the step change, and thus, the “start” of the first three step changes was not captured in the metallographic specimen, as shown in Figs. 9 and 10. Since the weld pool for the high heat condition was on the order of 23 mm in length, the metallographic sectioning kerf width was on the order of 3 mm, and step changes were made every 25 mm, slight errors in positioning during sectioning could have prevented the start of the transition associated with the step change from being captured within the metallographic mount for the high heat input condition. The change

in weld pool length was assumed to be negligible for each step change condition, but the pool size was not imaged during the process. Tables 4 and 5 present the results of averaging the concentrations for each element within the first 4000 μm of each longitudinal section. This average equated to approximately the first four points in each plot in Figs. 9–12, which were considered to be unaffected by the subsequent step change in wire feed rates, except for the first three step changes in Figs. 9 and 10. Carbon concentration was not reported due to the inaccuracies associated with EDS detection.

Discussion

Deposition of filler metals of different compositions results in the ability to selectively change the weld metal composition. Ultimately, the deposit composition is dependent on:

1. Composition and rate of the weld wire(s) being fed into the weld pool
2. Composition of the melted surface/base metal
3. Thermophysical properties of the weld wires and base metal, e.g., heat capacity, heat of melting/fusion, thermal diffusivity of the substrate
4. The volume of molten weld pool:
 - a. GTAW torch current
 - b. GTAW torch travel speed
 - c. Volumetric feed rate of the weld wire(s)

The melt pool volume (fourth parameter) relates to the energy deposition per unit length, i.e., the heat input. Higher heat input (e.g., slower travel speed and/or higher torch current) results in increased melting of the substrate, which increasingly dilutes the weld deposit, assuming a constant wire feed speed. Practical arc voltage ranges with GTAW have less influence on the heat input calculation, and voltage has been reported to minimally influence the weld area or fusion zone size (Ref. 22).

Dilution

Dilution is directly related to the magnitude of the heat input, as a higher heat input has more energy available to melt the substrate, even after accounting for energy losses, such as radiative, conductive, and convective heat transfer. The arc energy also goes into heating and melting the two weld wires, with the remaining energy being used to heat and melt the substrate. Two weld wires, differing in composition, exhibit different thermophysical properties (e.g., density, heat capacity, enthalpy of melting, etc.), and, therefore, the amount of energy available to melt the substrate varies with the relative fractions of the wires added to the weld pool. Thus, varying wire feed rates will influence weld metal dilution. Figure 6A shows that the lowest dilution for each heat input occurs when only Alloy 617 filler wire is added to the weld pool (i.e., 0% 740H wire). At the beginning of the deposition experiment, when only Alloy 617 wire is deposited, the substrate is at its lowest temperature. Therefore, more arc energy is required to heat the substrate, and the amount of energy available to melt the substrate is reduced, ultimately,

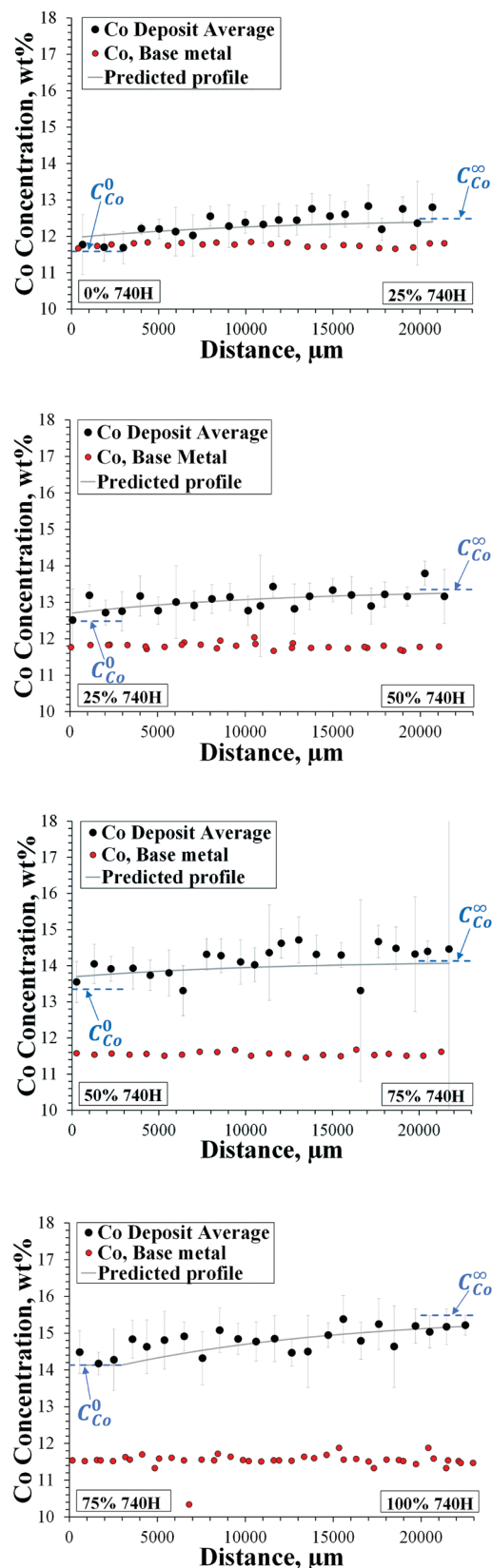


Fig. 9 — Composition profile for Co near each step change in welding wire feed rates when deposited with the high heat input condition. Solid curves show the predicted composition profile. Error bars correspond to a 95% confidence interval.

Table 4 — Chemical Compositions for the High Heat Input (1.95 kJ/mm) Deposit

Relative Weld Wire Feed Rates	High Heat Input Element Concentrations, wt-%									
617-25% 740H	Co	Mo	Cr	Nb	Fe	Al	Ti	Mn	Si	C
Measured – EDS*	12.79	7.29	22.15	0.15	1.56	0.76	0.68	0.55	0.23	–
Steady State – Predicted	12.48	7.88	22.29	0.14	1.48	1.12	0.48	0.11	0.09	0.06
617-50% 740H	Co	Mo	Cr	Nb	Fe	Al	Ti	Mn	Si	C
Measured – EDS*	13.86	7.11	22.09	0.25	1.28	1.2	0.63	0.34	0.18	–
Steady State - Predicted	13.35	7.03	22.54	0.28	1.33	1.15	0.58	0.13	0.1	0.05
617-75% 740H	Co	Mo	Cr	Nb	Fe	Al	Ti	Mn	Si	C
Measured – EDS*	14.44	6.63	22.56	0.39	1.21	1.1	1.02	0.56	0.06	–
Steady State – Predicted	14.13	6.26	22.77	0.41	1.19	1.18	0.68	0.15	0.11	0.04
617-100% 740H	Co	Mo	Cr	Nb	Fe	Al	Ti	Mn	Si	C
Measured – EDS	15.16	5.73	22.75	0.33	1.03	1.22	0.99	0.42	0.07	–
Steady State – Predicted	15.49	4.95	23.13	0.62	0.96	1.22	0.83	0.18	0.11	0.04

*Not captured at the steady-state condition based on the weld pool and the metallurgical section lengths

resulting in lower dilution. Conversely, as the welding torch approaches the end of the substrate, heat removal ahead of the weld pool becomes limited by convection across the end of the substrate rather than conduction through the substrate. Therefore, the substrate temperature is expected to rise, leading to greater dilution. The substrate temperature in the vicinity of the weld pool throughout the experiment must be monitored and/or modeled to gain a more accurate understanding of the dilution behavior shown in Fig. 6A.

Predicted Composition Profiles

The time-dependent composition of the weld pool (and the solidified deposit) for changes in weld wire feed rates can be analyzed using dilution analysis. The derivation of the dilution analysis for multiwire GTA-DED follows a similar approach to that for chemical mixing, based on mass conservation, as originally reported by Clark (Ref. 23). There are three compositional inputs to the weld pool: the substrate melted by the advancing weld pool (Alloy 617 Base), filler wire #1 (Alloy 617 Weld Wire), and filler wire #2 (Alloy 740H Weld Wire), while the total “flow” of composition out of the weld is the solidifying weld pool, Fig. 13. All elemental loss from spatter and vaporization were assumed to be negligible for the elements reported for each composition. For spatter only, the mass loss was assumed to be negligible due to the stable nature of GTAW. However, the mass loss due to vapor-

ization is unknown; nevertheless, less volatile elements, Co and Mo, were used for experimental comparison and were assumed to have minimal vaporization loss. The composition of the weld pool changes when the mass of element i entering the weld pool differs from that exiting the weld pool via the solidifying weld bead. The mass rate balance becomes that shown in Equation 2.

$$\begin{aligned}
 & V_{weld\ pool} * \rho_{weld\ pool} * \Delta C_i^{weld\ pool} \\
 &= (A_{Base} * S * \Delta t * \rho_{Base} * C_i^{base}) \\
 &+ (A_{wire\ 1} * v_{wire\ 1} * \Delta t * \rho_{wire\ 1} * C_i^{wire\ 1}) \\
 &+ (A_{wire\ 2} * v_{wire\ 2} * \Delta t * \rho_{wire\ 2} * C_i^{wire\ 2}) \\
 &- (A_{Nugget} * S * \Delta t * \rho_{Nugget} * C_i^{Nugget})
 \end{aligned} \tag{2}$$

Where:

A_i = Area of wire 1, wire 2, melted base metal, or weld nugget, mm²

S = welding travel speed, mm/min

v_j = linear feed rate of wire 1 or wire 2, mm/min

C_i^∞ = steady state concentration of element, i , in the weld nugget, $t = \infty$

C_i^k = weight fraction of element, i , in the weld pool, base metal, wire 1, or wire 2

$\Delta C_i^{weld\ pool}$ = change in the concentration of element, i , in the weld pool

ρ_k = density of base metal, wire 1, wire 2, or weld pool, kg/mm^3

$V_{weld\ pool}$ = volume of the weld pool, mm^3

The last term is defined by “nugget” in Equation 2.

Equation 2 is the mass rate of the element flowing out or solidifying at the back of the weld pool or nugget. Dividing by Δt and rearranging results in Equation 3.

$$\begin{aligned} & \left(V_{weld\ pool} * \rho_{weld\ pool} \frac{\Delta C_i^{weld\ pool}}{\Delta t} \right) \\ & + (A_{Nugget} * S * \rho_{Nugget} * C_i^{Nugget}) \\ & = (A_{Bulk} * S * \rho_{Bulk} * C_i^{Bulk}) \\ & + (A_{wire\ 1} * v_{wire\ 1} * \rho_{wire\ 1} * C_i^{wire\ 1}) \\ & + (A_{wire\ 2} * v_{wire\ 2} * \rho_{wire\ 2} * C_i^{wire\ 2}) \end{aligned} \quad (3)$$

The three terms on the right side of Equation 3 are constant with time (after the step change), so Equation 3 can be rewritten as Equation 4:

$$\begin{aligned} & V_{weld\ pool} * \rho_{weld\ pool} \left(\frac{\Delta C_i^{weld\ pool}}{\Delta t} \right) \\ & + (A_{Nugget} * S * \rho_{Nugget} * C_i^{Nugget}) = A'_i \end{aligned} \quad (4)$$

Where:

$$\begin{aligned} A'_i &= (A_{Bulk} * S * \rho_{Bulk} * C_i^{Bulk}) \\ &+ (A_{wire\ 1} * v_{wire\ 1} * \rho_{wire\ 1} * C_i^{wire\ 1}) \\ &+ (A_{wire\ 2} * v_{wire\ 2} * \rho_{wire\ 2} * C_i^{wire\ 2}) \end{aligned}$$

Assuming complete and instantaneous mixing in the weld pool and letting the time increment become exceedingly small, the governing differential equation can be written as shown in Equation 5.

$$\frac{d(C_i^{weld\ pool})}{dt} + B * C_i^{Nugget} = A'_i \quad (5)$$

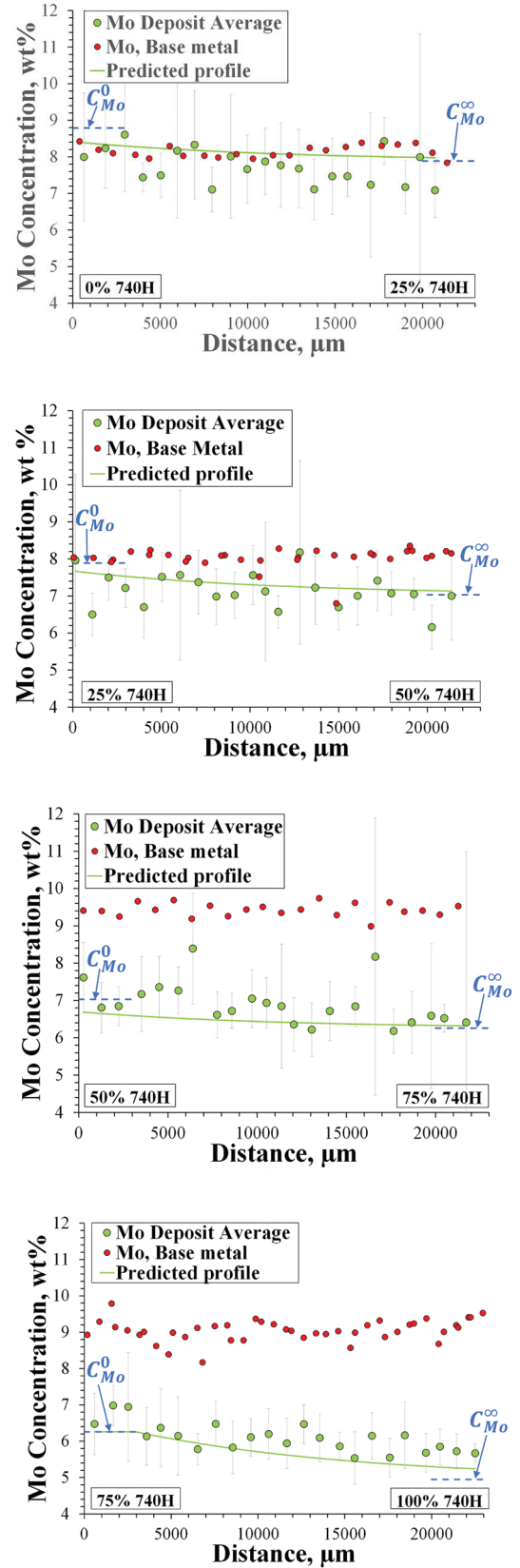


Fig. 10 – Composition profile for Mo near each step change in welding wire feed rates when deposited with the high heat input condition. Solid curves show the predicted composition profile. Error bars correspond to a 95% confidence interval.

Table 5 – Chemical Compositions for the Low Heat Input (1.24 kJ/mm) Deposit

Relative Weld Wire Feed Rates	Low Heat Input Element Concentrations, wt-%									
617-25% 740H	Co	Mo	Cr	Nb	Fe	Al	Ti	Mn	Si	C
Measured – EDS	12.92	7.17	20.86	0.21	1.51	0.42	0.66	0.72	0.03	–
Steady State – Predicted	13.09	7.39	22.36	0.24	1.39	1.14	0.54	0.12	0.09	0.06
617-50% 740H	Co	Mo	Cr	Nb	Fe	Al	Ti	Mn	Si	C
Measured – EDS	14.48	5.8	21.4	0.39	1.25	0.49	0.89	0.75	0.03	–
Steady State – Predicted	14.58	5.93	22.78	0.48	1.14	1.19	0.71	0.15	0.1	0.05
617-75% 740H	Co	Mo	Cr	Nb	Fe	Al	Ti	Mn	Si	C
Measured – EDS	16.05	4.25	21.77	0.46	1.05	0.52	0.96	0.79	0.03	–
Steady State – Predicted	16.1	4.44	23.21	0.72	0.88	1.24	0.89	0.19	0.11	0.04
617-100% 740H	Co	Mo	Cr	Nb	Fe	Al	Ti	Mn	Si	C
Measured – EDS	17.48	2.76	22.24	0.71	0.8	0.53	1.28	0.86	0.02	–
Steady State – Predicted	17.63	2.93	23.64	0.97	0.61	1.29	1.07	0.22	0.12	0.03

Table 6 – Measured Dimensions for Each Weld Pool Volume Approximation

Weld Pool Dimensions	High Heat Input	Low Heat Input
Surface Length, 2b (mm)	23.1	15.9
Surface Width, 2a (mm)	17.4	13.0
Weld Bead Height, 2h (mm)	3.05	2.74
Estimated Weld Pool Volume (mm ³)	642	296

Where:

(Eq. 5 continued)

$$B = \frac{A_{Nugget} * S * \rho_{Nugget}}{V_{weld pool} * \rho_{weld pool}}$$

$$A_i'' = \frac{A_i'}{V_{weld pool} * \rho_{weld pool}}$$

Finally, assuming the composition of the nugget is equal to that of the weld pool, allows for creating Equation 6.

$$\frac{d(C_i^{weld pool})}{dt} + B * C_i^{weld pool} = A_i'' \quad (6)$$

The solution to this type of differential equation is shown in Equation 7, and A_i'' is given by Equation 8.

$$C_i^{weld pool}(t) = C_i^\infty + (C_i^0 - C_i^\infty)e^{-\frac{A_i''}{C_i^\infty}t} \quad (7)$$

$$A_i'' = \left(\frac{1}{V_{weld pool} * \rho_{weld pool}} \right) * (A_{Base} * S * \rho_{Base} * C_i^{Base} + A_{wire 1} * v_{wire 1} * \rho_{wire 1} * C_i^{wire 1} + A_{wire 2} * v_{wire 2} * \rho_{wire 2} * C_i^{wire 2}) \quad (8)$$

The steady state concentration C_i^∞ of any element, i, is calculated according to Equation 9, which was derived considering that, at steady state, the mass of element, i, entering the weld pool is equal to the mass of element, i, leaving the weld pool as the weld nugget solidifies, moving

with velocity, S (i.e., Equation 2 with $\Delta C_i^{weld pool} = 0$, since the composition of the weld pool is not changing at steady state).

$$C_i^\infty = \frac{(A_{617} \cdot v_{617} \cdot \rho_{617} \cdot C_i^{617}) + (A_{740H} \cdot v_{740H} \cdot \rho_{740H} \cdot C_i^{740H}) + (A_{Base} \cdot S \cdot \rho_{Base} \cdot C_i^{Base})}{A_{Nugget} \cdot S \cdot \rho_{Nugget}} \quad (9)$$

The weld pool volume, $V_{weld pool}$, was approximated as an ellipsoid, Equation 10. The weld pool half-width, a , and half-length, b , are obtained from measurements on the solidified weld pool after immediate arc extinction upon conclusion of the experiment, Fig. 14. The height, h , of the ellipsoidal weld pool was measured from the transverse cross sections as shown in Fig. 15. The measured dimensions of the weld pool for each heat input are shown in Table 6. The weld pool volume was assumed to be constant for all wire feed rate combinations. Finally, the value of the melted base metal (A_{Base}) was also determined by image analysis for each wire feed rate combination, as shown in Fig. 15.

$$V_{weld pool} = \frac{4}{3} \pi a b h \quad (10)$$

Where:

a = half-width of weld pool, mm

b = half-length of weld pool, mm

h = half-height of weld pool, mm

Using the values from Table 2, Table 3, and Table 6 in Equation 9, the predicted steady state concentrations, C_i^∞ , for each section of the deposit, were calculated and included in Table 4 and Table 5. Generally, the predicted steady state concentrations of the elements agree with those obtained from EDS analysis (accuracy of EDS analysis is commonly accepted to be approximately $\pm 5\%$ for heavier elements and approximately $\pm 10\%$ for light elements [Ref. 24]).

Equations 7 and 8 were then used to create an elemental composition profile following the step change in wire feed speeds, with the values for C_i^∞ and A_i'' from Table 7. C_i^0 for the transition being profiled was taken as C_i^∞ from the previous transition (or, in the case of the first transition, C_i^0 was the composition of the base metal). The predicted concentration profiles have been plotted as solid lines in the plots of Figs. 9–12, and the predicted composition fit the experimental data within the limits of EDS and solidification segregation variations. The positioning of the predicted concentration profiles was accomplished by minimizing the sum of the squares of the difference between the experimental composition and the predicted composition on a point-by-point basis, as shown in Equation 11.

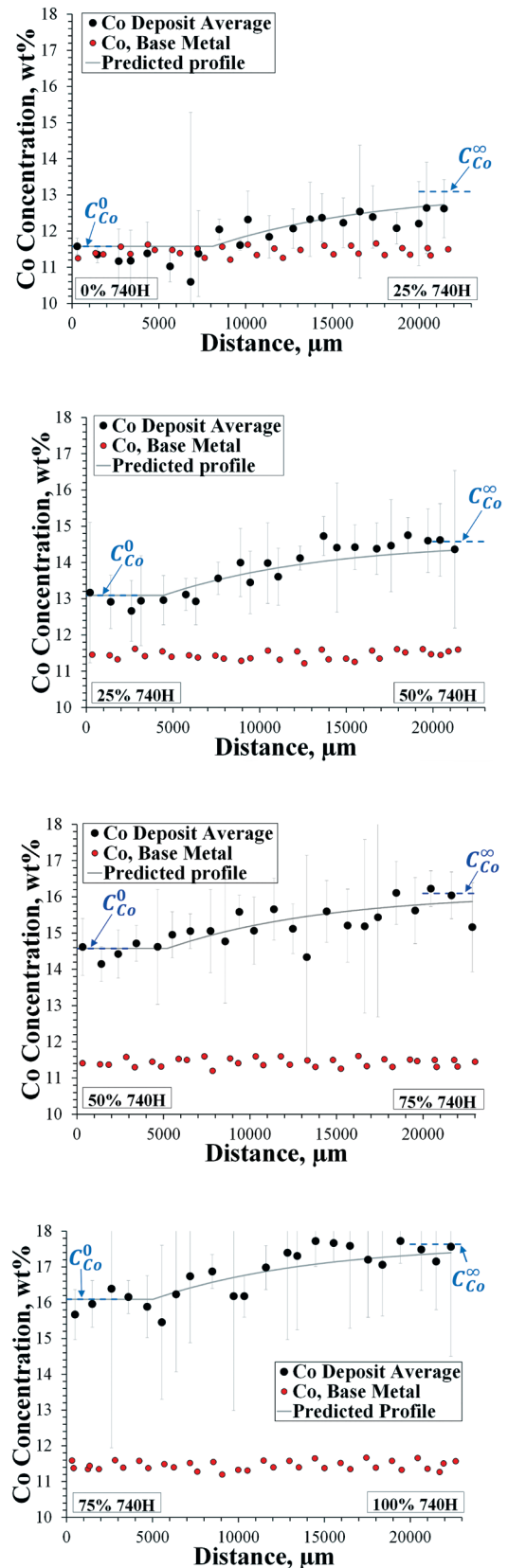


Fig. 11 — Composition profile for Co near each step change in welding wire feed rates when deposited with the low heat input condition. Solid curves show the predicted composition profile. Error bars correspond to a 95% confidence interval.

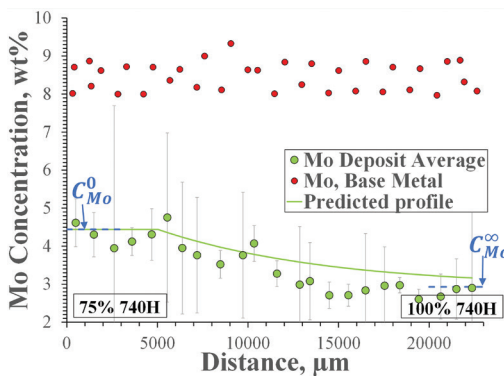
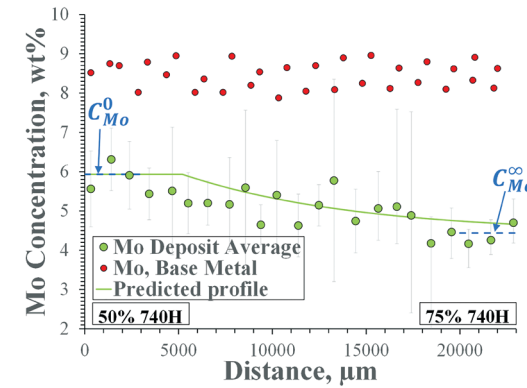
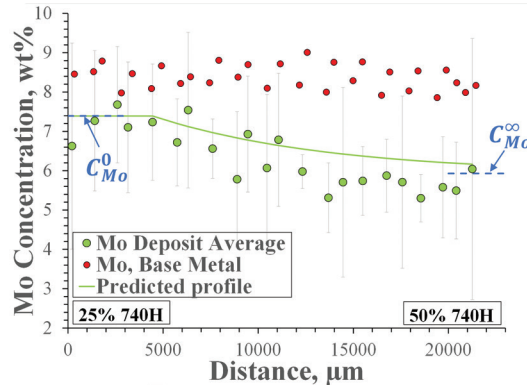
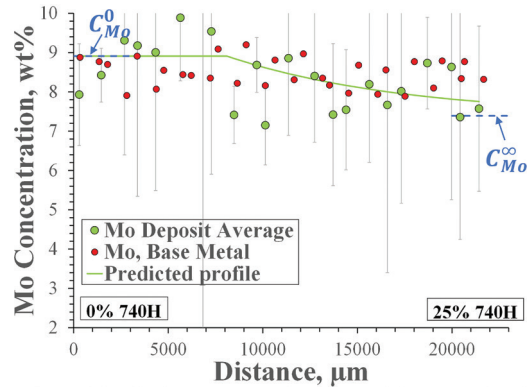


Fig. 12 — Composition profile for Mo near each step change in welding wire feed rates when deposited with the low heat input condition. Solid curves show the predicted composition profile. Error bars correspond to a 95% confidence interval.

$$R = \sum (C_i^{Experimental} - C_i^{Predicted})^2 \quad (11)$$

Where:

R = sum of squares

$C_i^{Experimental}$ = composition of element i from experimental measurements

$C_i^{Predicted}$ = composition of element i from the prediction

Finally, Equation 7 contains an exponentially decaying term that controls the shape of the composition profile. The time constant is defined as the time for the exponential term to equal e^{-1} . Thus, for Equation 7, τ is given by Equation 12.

$$\tau = \frac{C_i^{\infty}}{A_i''} \quad (12)$$

Where:

τ = time constant, min

A_i'' = length constant, min⁻¹

At one time constant, the second term on the right side of Equation 7 becomes $(C_i^0 - C_i^{\infty}) \times e^{-1}$, or $(C_i^0 - C_i^{\infty}) \times 0.368$, and the concentration transition is approximately 63% complete. After two time constants, the transition is about 86% complete (i.e., $e^{-2} = 0.14$) and the composition changes slowly, thereafter. If the time constant is multiplied by the experimental travel speed, $S = 101.6$ mm/min, a length constant, κ , can be calculated and compared to the composition profiles in Figs. 9–12. Tabulated values for τ , κ , and 2κ for each transition have been included in Table 7. This table shows that the time constant is independent of the element used to calculate it. Also, a high heat input condition results in a longer length constant, $\kappa = 11.3$ – 13.0 mm, than that at low heat input conditions, $\kappa = 9.2$ – 9.3 mm, with only small variations of κ for a given heat input. Finally, the distance associated with 2κ at high heat, ~ 24 mm, exceeds the length of the metallographic mounts, ~ 21 mm, and, therefore, only a portion of the transition is contained within the plots of Figs. 9 and 10. Interestingly, the distance of 2κ is very close to the length of the weld pool reported in Table 6 and, therefore, simply measuring the weld pool length may provide a reasonable estimate of κ . Ultimately, this dilution analysis shows that a step change in weld wire feed rates will only gradually change the composition of the weld pool over time/distance. Larger composition changes over smaller distances are favored at lower heat inputs due to a smaller weld pool.

Summary and Conclusions

Multiple weld wires were fed into the GTAW weld pool, demonstrating multiwire GTA-DED as a viable fabrication method for functionally graded materials. Furthermore, various multiwire GTA-DED parameters, particularly heat input, have a profound effect on the composition gradi-

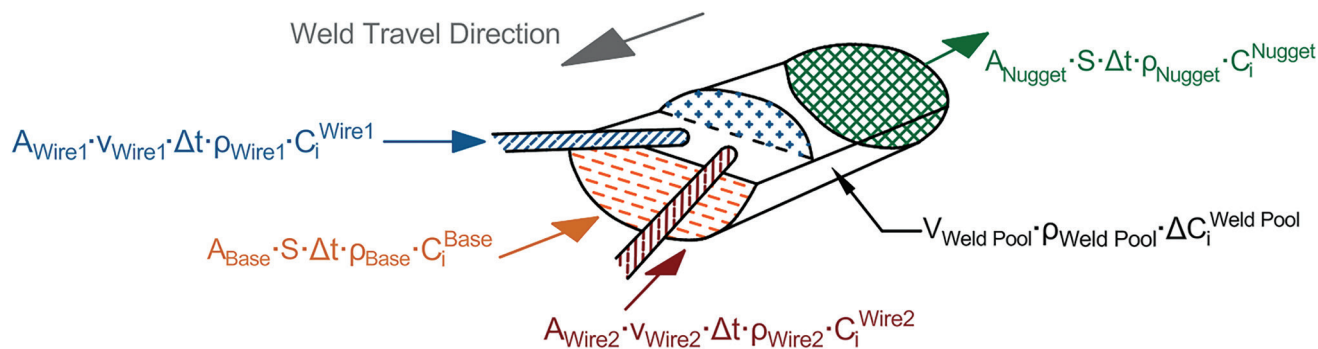


Fig. 13 – Schematic depicting the masses of material flowing into the weld pool with composition $C_i^{weld pool}$ and mass of material flowing out of the weld with composition C_i^{Nugget} .

Table 7 – Calculated Values for C_i^∞ , A_i'' , Time Constant, and Length Constant

Transition	i	C_i^∞	A_i''	Time Constant, τ , Minutes	Length Constant, κ , mm	Two Length Constant, 2κ , mm
High Heat Input						
25% 740H	Co	12.48	106.3	0.117	11.9	23.8
	Mo	7.88	67.2	0.117		
50% 740H	Co	13.35	115.6	0.116	11.7	23.4
	Mo	7.03	60.8	0.116		
75% 740H	Co	14.13	127.3	0.111	11.3	22.6
	Mo	6.26	56.4	0.111		
100% 740H	Co	15.49	121.3	0.128	13.0	26.0
	Mo	4.95	38.8	0.128		
Low Heat Input						
25% 740H	Co	13.09	143.0	0.092	9.3	18.6
	Mo	7.39	80.7	0.092		
50% 740H	Co	14.58	160.8	0.091	9.2	18.4
	Mo	5.93	65.4	0.091		
75% 740H	Co	16.10	176.8	0.091	9.3	18.6
	Mo	4.44	48.8	0.091		
100% 740H	Co	17.63	192.6	0.092	9.3	18.6
	Mo	2.93	32.0	0.092		

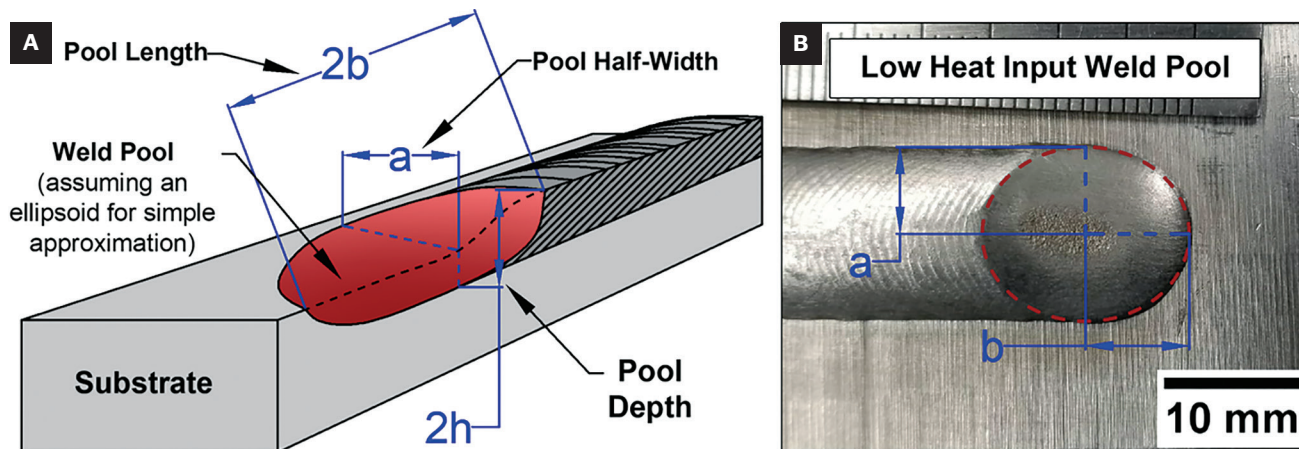


Fig. 14 – A – Schematic of the weld pool width, length, and height used to estimate the weld pool volume; B – photograph of a weld pool and the respective measurements.

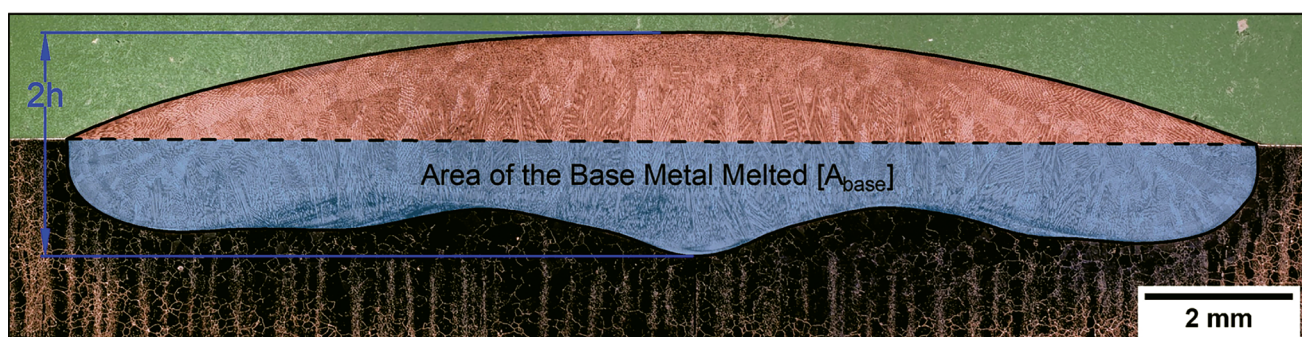


Fig. 15 – Macrograph of a high heat input weld section for estimating the weld pool depth, $2h$, and the area of base metal melted, A_{base} .

ent, offering considerable flexibility in producing desired composition profiles. Step changes in welding wire feed rates at a lower heat input resulted in greater compositional change over shorter distances (up to ~ 1.5 wt-% for the Co and Mo concentrations over 15 mm at 1.24 kJ/mm) compared to higher heat input (up to ~ 1 wt-% for the Mo and Co concentrations over 20+ mm at 1.95 kJ/mm). A simple dilution model predicted composition profiles based on weld wire compositions, substrate composition, and heat input/dilution, to allow for further design of multiwire GTA-DED builds for tailored composition.

Although this work focused on producing functionally graded deposits along the length of the deposit, similar issues, arguments, and conclusions apply to gradients in the vertical direction made by changing deposit compositions on a layer-by-layer basis. Therefore, gradient analysis and composition prediction are possible in three dimensions.

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