# CHARACTERISATION OF METAL DEPOSITION DURING ADDITIVE MANUFACTURING OF Ti-6Al-4V BY ARC-WIRE METHODS

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## Abstract

This study considers the use of the gas tungsten arc (GTA) welding process in conjunction with 'cold' wire addition to give layer-wise build-up of thin walled structures, simulating those commonly found in aerospace applications, which may in the future be manufactured by additive means. Taguchi DOE and multiple regression analysis methods have been applied to quantitatively establish relationships between common process parameters including arc length, arc current, travel speed and wire feed speed and resulting weld bead geometries and actual metal deposition rates. Mathematical expressions for build-up height, thickness and surface roughness are presented and evaluated against experimental data, with observations related to physical phenomena.

## Introduction

Since their initial introduction and development, additive manufacture or solid freeform fabrication techniques have seen an ever increasing degree of interest in the field of engineering manufacturing. In general, this group of processes offers highly flexible, cost effective alternatives to conventional manufacturing methods for both large production runs and one-off prototype creations. There is particular interest for the adoption of such techniques into the aerospace sector where the increased material utilisation has the potential to deliver significant financial benefits when using costly materials such as titanium alloys [1, 2]. One such method of additive manufacture, considered in the present study, is gas tungsten arc (GTA) welding with mechanised 'cold' wire feed where weld beads are laid successively onto a substrate giving layer-wise build-up of the desired profile.

It is widely known that the parameters employed during a welding process have a great influence over the geometry of the resulting weld beads, with these geometries in turn influencing the properties of the welded structure. The importance of these weld bead geometries may be considered to be especially important during additive manufacturing procedures, such as the one considered in this study, where each bead combines to yield a final near net-shape freeform with a predefined desired profile. Any significant deviation from this desired profile may be considered as inefficiency in the process, requiring additional processing such as increased material removal and wastage or re-working, which would contribute unnecessary costs. It is clear then that a thorough understanding of the relation between process parameters and resulting weld bead geometries is crucial for the optimisation weld-based additive manufacturing procedures.

Often times welding procedures are developed by a method of trial and error where process parameters are varied until an acceptable outcome, in terms of weld bead geometry and properties, is achieved. While such methods can deliver acceptable results, they are time-consuming and rarely yield an optimised solution. In contrast, the development of mathematical models relating input parameters to output variables allows for process optimisation across a wide range of scenarios as well facilitating process automation to further increase efficiency [3, 4]. Much literature exists describing models for various aspects of the GTA welding process including weld pool and weld bead geometries [5-9], however these studies are primarily concerned with conventional joint configurations such as butt and fillet welds and are not specific to titanium alloys. As such, these models may not be well suited for predicting the geometries of multi-layer weld deposits used for additive manufacture of components from titanium alloys. For the specific case of additive manufacture with titanium alloys, the work of Charles [10] presents thermal models for prediction of microstructure evolution using GTA welding, while Sequeira Almeida and Williams [11] discuss the development of process models for modified GTA and gas metal arc (GMA) welding processes.

The aim of the present study was to establish a comprehensive understanding of the relationship between common process parameters and resulting weld deposit geometries in the additive manufacture of titanium alloys using conventional GTA welding. This was done initially through experimentation with the effect of various input parameters on deposit geometry observed and quantified. Using this data a series of mathematical models for the subsequent build-up profile were generated through analysis of variance (ANOVA) and multiple regression techniques. It is intended that such models will allow for the optimisation of process parameters during the additive manufacture of titanium alloys by GTA welding and so validate the technique as a possible low cost alternative to more conventional manufacturing methods used in the aerospace sector.

## Experimental

Samples of commercially sourced Ti-6Al-4V plate with dimensions 100mm x 16mm x 9.65mm were used to form the substrate onto which weld beads were deposited using Ti-6Al-4V wire with a diameter of 1.0mm. The nominal chemical composition of these materials (in wt%) is provided in Table 1.

**Table 1.** Chemical composition of Ti-6Al-4V alloy.

| Alloy | Composition (wt%) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Ti | C | Fe | H | N | O | Al | V |
| **Ti-6Al-4V** | 99.2 | 0.1 | 0.3 | 0.015 | 0.03 | 0.25 | 6.1 | 4.0 |

Welding was conducted using water cooled Conley & Kleppen (CK) machine mount torch coupled to a Kemppi MasterTIG MLS 2000 inverter power supply with independent wire feed provided through a CK WF3 dedicated cold wire feed unit. Inert gas shielding was achieved with welding grade pure argon using pre and post flow options in addition to a custom fabricated trailing shield. Shielding gas flow rates and other common process parameters are detailed in Table 2.

**Table 2.** Summary of GTA welding parameters.

| | |
|---|---|
| **Polarity** | DCEN |
| **Electrode** | 2% Ceriated, 2.4mm Ø |
| **Shielding gas** | Welding Grade Argon |
| **Flow rate – torch nozzle** | 8 L/min |
| **Flow rate – trailing shield front** | 10 L/min |
| **Flow rate – trailing shield rear** | 7 L/min |
| **Pre-flow duration** | 3 seconds |
| **Up slope duration** | 2 seconds |
| **Down slope duration** | 1 second |
| **Post flow duration** | 30 seconds |

For the present study, five common input parameters of the GTA welding process, namely arc length (L), arc current (I), travel speed (TS), wire feed speed ratio (WFSR) and interpass temperature (IT), were selected to be varied in order to characterise the geometry of deposited weld beads. Each parameter was examined at four different levels, selected based on previous experimental procedures, in order to cover a broad operating envelope. This gives 3 degrees of freedom (DOF) per parameter; totalling 15 DOF's for the five process parameters. The levels for each parameter are given in Table 3. Using the design of experiment (DOE) methods of Taguchi, a total of 16 experiments were conducted with the L'16 orthogonal array used to determine the combination of parameters for each experiment.

**Table 3.** Definition of input process parameters and levels used for GTA welding experiments.

| **Parameter** (units) | **Arc Length** (mm) | **Arc Current** (amperes) | **Wire Feed** (ratio to TS*) | **Travel Speed** (mm/min) | **Interpass Temp** (°C) |
|---|---|---|---|---|---|
| Level 1 | 3.0 | 100 | 5 | 100 | 40 |
| Level 2 | 3.5 | 120 | 7 | 150 | 90 |
| Level 3 | 4.0 | 140 | 9 | 200 | 150 |
| Level 4 | 5.0 | 80 | 11 | 250 | 200 |

*Wire feed was defined by a ratio against travel speed in order to eliminate impractical combinations of the two.

Samples were held 'on edge' in a steel clamping arrangement to simulate the beginning of a wall-like build-up, with the entire fixture attached to a linear actuator, above which the torch and wire feed were held stationary. Experiments were performed with ten successive passes conducted for each parameter set to yield a small vertical wall. This geometry was selected to mimic the type of build-up that would be required to manufacture thin walled, pocketed sections commonly found in structural aerospace applications. Arc current and voltage (V) were observed for each pass using a Triton Electronics AMV4000 weld monitor, allowing the determination of arc energies (AE) and heat inputs (HI). Temperature profiles for each pass were recorded through NI LabVIEW software using K-type thermocouples attached to each end of the sample.

## Results and Discussion

Factors of interest in terms of weld bead geometry were the build-up height per pass (H) and average wall thickness (W) as well as the apparent surface roughness of the build-up which was characterised in terms of machining layer thickness (MLT). This was defined as the maximum thickness of material required to be removed (by a machining or similar process) to bring the deposit back to a solid continuous vertical surface. This was used in preference to other measures such as Ra or standard deviations since it relates directly to the amount of tool engagement required in finishing processes and also represents potential material wastage. Height per pass was measured at the completion of each pass using a Micro-Epsilon scanCONTROL 2710-50 laser profile scanner held adjacent to the welding torch. Additionally, the sides of each sample were profiled at the completion of each experiment, with measurements used to determine wall and machining layer thicknesses. These geometry factors, illustrated in Figure 1, were used as output variables in the modelling process. Deposition rates (DR) were also determined for each experiment with knowledge of both the wire feed speed and actual mass deposited. These results are summarised in Table 4.

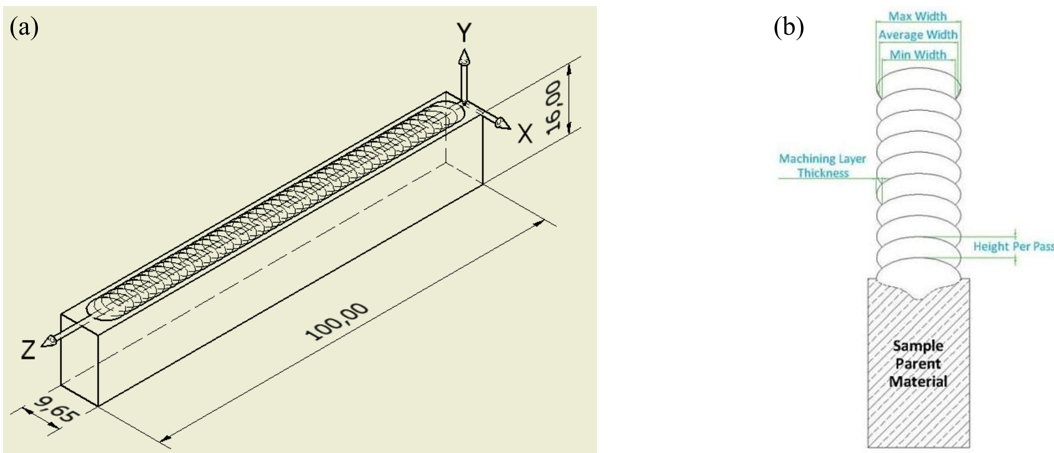


**Figure 1.** Sample geometry with (a) coordinate system and (b) geometry factors defined.

**Table 4.** Experimental results for deposition rate and weld build-up geometry.

| Experiment | DR (kg/hr) | H (mm) | W (mm) | W:H (mm/mm) | MLT (mm) |
|---|---|---|---|---|---|
| **1** | 0.107 | 0.50 | 8.63 | 17.28 | 1.13 |
| **2** | 0.216 | 0.83 | 8.62 | 10.44 | 1.43 |
| **3** | 0.359 | 0.92 | 8.58 | 9.31 | 1.54 |
| **4** | 0.371 | 1.03 | 6.07 | 5.89 | 5.86 |
| **5** | 0.295 | 1.07 | 6.25 | 5.82 | 2.34 |
| **6** | 0.269 | 0.64 | 6.59 | 10.30 | 3.17 |
| **7** | 0.232 | 0.77 | 11.00 | 14.36 | 2.38 |
| **8** | 0.285 | 1.19 | 5.84 | 4.90 | 1.16 |
| **9** | 0.463 | 1.28 | 5.23 | 4.07 | 1.83 |
| **10** | 0.453 | 1.17 | 7.19 | 6.13 | 1.80 |
| **11** | 0.145 | 0.51 | 9.89 | 19.25 | 2.24 |
| **12** | 0.154 | 0.85 | 7.74 | 9.09 | 1.68 |
| **13** | 0.349 | 1.25 | 7.09 | 5.68 | 1.34 |
| **14** | 0.201 | 0.82 | 10.47 | 12.83 | 1.07 |
| **15** | 0.355 | 0.80 | 7.18 | 8.93 | 1.09 |
| **16** | 0.209 | 0.76 | 4.80 | 6.34 | 1.94 |

Initial multi-way analysis of variance (ANOVA) showed comparatively low *F*-statistics for interpass temperature, implying that for the range of values considered in this study, the interpass temperature had negligible effects on the thickness, height and surface roughness of the multi-layer weld deposit. As such, interpass temperature was not considered as a factor in all subsequent analyses and modelling. The *F*-statistics results from 4-way analysis of variance (neglecting interpass temperature) for the weld deposit geometric outputs of interest are summarised in Table 5.

**Table 5.** F-statistic values from 4-way ANOVA.

| Input Parameters | Output Variables | | |
|---|---|---|---|
| | **H** | **W** | **MLT** |
| **L** | 4.32 | 0.43 | 0.57 |
| **I** | 18.53 | 10.88 | 0.47 |
| **WFSR** | 59.01 | 0.19 | 0.94 |
| **TS** | 16.45 | 11.72 | 1.09 |

Considering firstly the average wall thickness, W, it can be seen from the comparatively large *F*-statistics values for arc current and travel speed that these two input parameters appear to have the greatest influence over the thickness of the weld deposit. This may be readily explained as both arc current and travel speed, when combined with arc voltage, relate directly to arc energy and so heat input. As heat input is a measure of the amount of thermal energy delivered to the weldment, it can be clearly understood that for a given heat input, a molten pool of a given size will be created (assuming other factors such as the thermal properties of the weldment are consistent, as in the present study). The width of the molten pool then acts as to limit the width of the deposited bead, and so the thickness of the wall type build-up that forms the basis of this additive manufacturing technique. This finding is consistent with the models for weld bead width during conventional GTA butt weld developed by of Esme et.al. [7] and Tarng and Yang [9].

In contrast, the ANOVA results for build-up height per pass show a strong dependence on wire feed speed, with arc current and travel speed having a lesser influence. This observation is self-evident as wire feed speed is directly related to the material deposition rate during the welding process. Given that the width of the deposit is effectively controlled by heat input, conservation of volume infers that the addition of filler material will yield a proportional build-up in terms of height per pass. It is this independence of wire feed from heat input that gives GTA welding a considerable advantage over GMA and other arc-wire based welding processes, offering precise control over bead geometry and surface quality, and so making it well suited to additive manufacture methods [11].

While not quantified, results of this study indicate that there exists a physical limit to the deposition rate possible for a given heat input while maintaining acceptable weld quality. This was particularly evident in experiment four where the combined low heat input and high wire feed speed produced the ‘stubbing’ of the wire on the solid-liquid interface within the molten pool, as seen in Figure 2 by the deposition of ‘folded’ sections of unmelted filler material. By comparison, the sidewall profile of experiment eight, which was deposited using a more realistic parameter set, is significantly more desirable. Despite such qualitative observations, the results of ANOVA presented in Table 5 show no clear correlation between the chosen measure of surface roughness and the input parameters considered. It is considered that the MLT may be a function of the thickness-to-height ratio as well as heat input and deposition rate however further investigation is required to test these hypotheses.

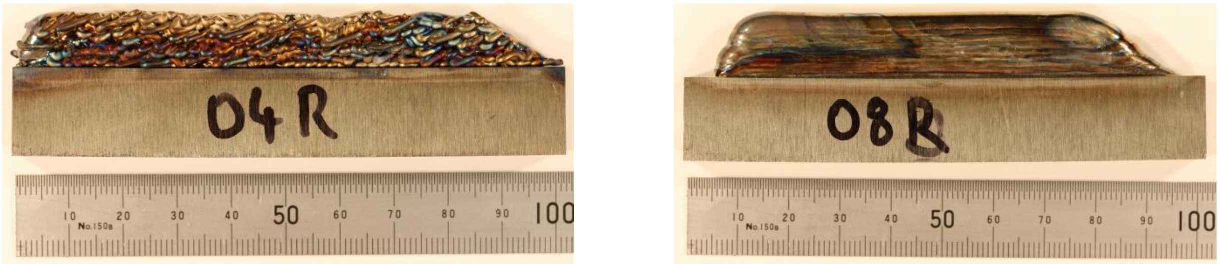


**Figure 2.** Samples from experiments four and eight showing variation in sidewall surface profiles.

Using the experimental results obtained, mathematical models relating input parameters and output variables were developed using empirical curvilinear equations [12]. Here, geometrical output variables, represented by the response parameter *Y*, are related to the four key input parameters under the assumption of linear relationships for close ranges. This yielded equations of the form:

$$Y = kX_1{}^aX_2{}^bX_3{}^cX_4{}^d \tag{1}$$

where: *Y* is any output variable such as H, W or MLT
$X_1$-$X_4$ are the input parameters of L, I, WFSR and TS respectively
*a*, *b*, *c*, *d* and *k* are modelling constants

Values of modelling constants for each geometrical output were determined using multiple regression techniques, with these results presented in the following equations. Within these models, the relative influence of each input parameter may be determined by consideration of the power to which it is raised.

Build-up height per pass: $$H = 0.301 \cdot X_1{}^{0.198}X_2{}^{-0.455}X_3{}^{0.730}X_4{}^{0.282} \tag{2}$$

Average wall thickness: $$W = 2.613 \cdot X_1{}^{-0.171}X_2{}^{0.751}X_3{}^{0.055}X_4{}^{-0.462} \tag{3}$$

Thickness-to-height ratio: $$WH = 8.837 \cdot X_1{}^{-0.369}X_2{}^{1.206}X_3{}^{-0.675}X_4{}^{-0.744} \tag{4}$$

Machining layer thickness: $$MLT = 1.618 \cdot X_1{}^{-0.826}X_2{}^{-0.364}X_3{}^{0.085}X_4{}^{0.547} \tag{5}$$

As a means of comparison, values for each geometric output were calculated using the mathematical models derived and then plotted against the corresponding experimental data as shown in the scatter plots of Figure 3.

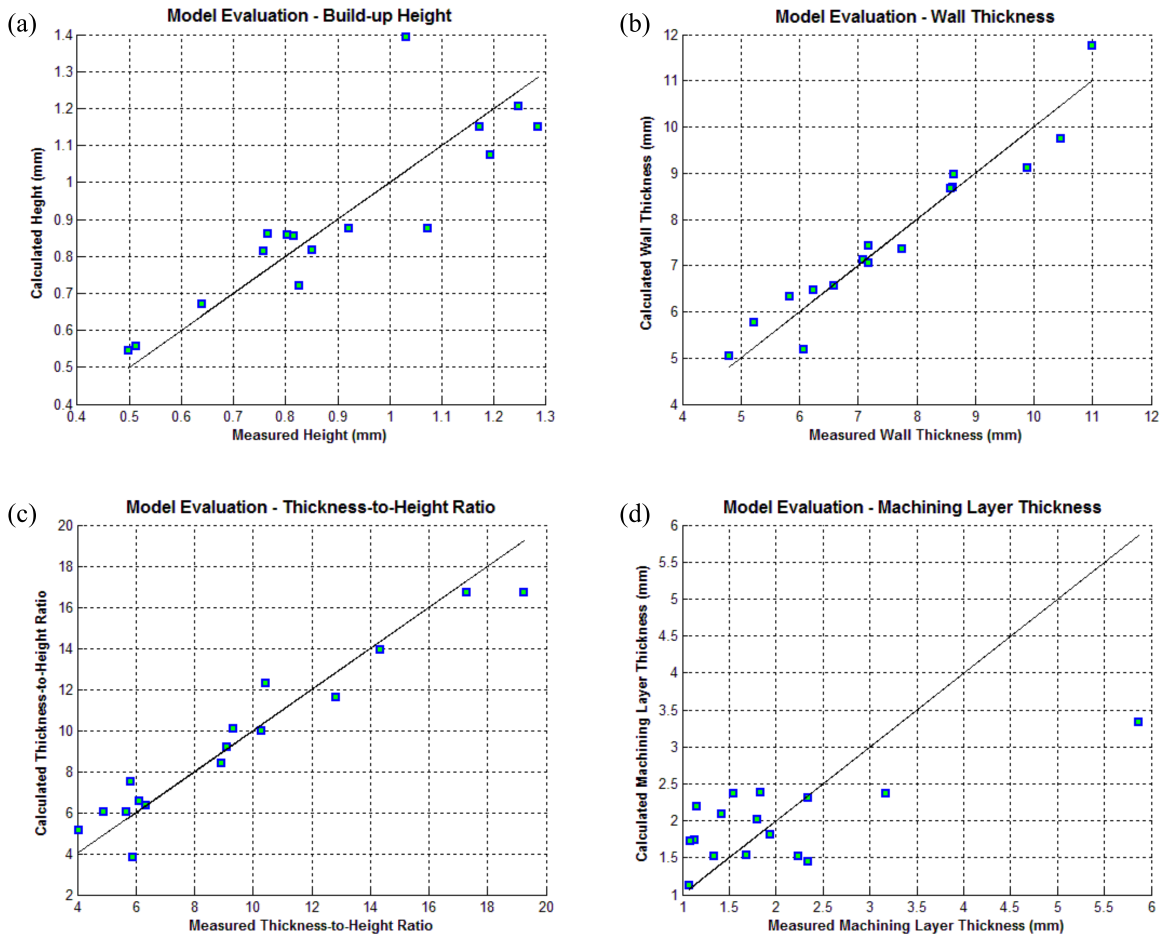


**Figure 3.** Comparison of measured and calculated values for (a) build-up height per pass, (b) average wall thickness, (c) thickness-to-height ratio and (d) machining layer thickness.

The relative error, *e*, associated with each calculation from mathematical models was determined using:

$$e = \left|\frac{m-c}{m}\right| \times 100\% \qquad (6)$$

where: *m* is the measured value for the geometrical factor of interest, and *c* is the calculated value for the same geometrical factor.

The errors accompanying each of the mathematical models are summarised in the histogram presented in Figure 5. This illustrates that models used to relate build-up height and wall thickness to the selected input parameters are in close agreement with experimental data with an average accuracy of 91% and 95% respectively. The model generated to predict thickness-to-height ratios of build-up deposits still shows good agreement with experimental data with an average accuracy of 88%. In contrast the model for machining layer thickness has poor correlation to the experimental data with an average accuracy of 68%. This low level of accuracy is to be expected given the apparent lack of influence of the selected input parameters. As such, further work in this area is required in this area, be it the investigation of relations to dependent variables such as heat input, deposition rate and thickness-to-height ration, or the definition of a new measure for sidewall surface roughness.

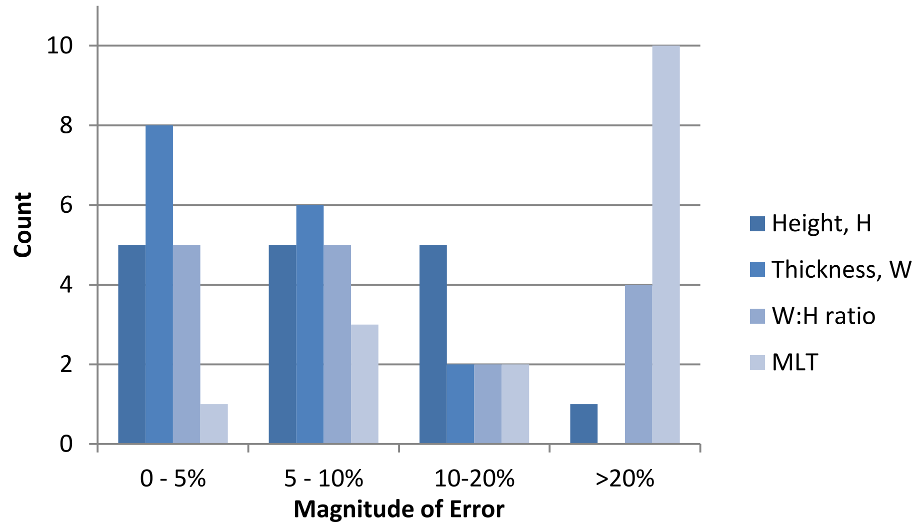


**Figure 4.** Accuracy analysis of models showing errors between measured and calculated values.

It is hoped that empirical relations, such as those developed in the present study, may be used to optimise the GTA welding process for additive manufacture and so allow the process to be competitive on a cost basis with more conventional manufacturing methods, particularly for high cost components such as those fabricated from titanium alloys for use in the aerospace sector. Escobar-Palafox et.al. [13] have also shown that process models can be used to generate control regimes allowing for more flexible automation of the GTA-wire based additive manufacturing process.

## Conclusions

Gas tungsten arc welding has been used in conjunction with 'cold' wire feed to successfully generate additively manufactured profiles in Ti-6Al-4V. Using Taguchi DOE techniques, experiments were conducted to investigate the influence of common welding process parameters on the geometry of the resulting multi-layer deposit. Results show that the average thickness of the wall type deposit is primarily a function of arc current and travel speed while build-up height is chiefly related to wire feed speed, and hence deposition rate. Empirical curvilinear models relating the process parameters considered to the geometrical factors of interest were generated using multiple regression techniques, with models for wall thickness and build-up height showing good agreement with experimental data. Conversely, machining layer thickness, used to characterise sidewall surface roughness, showed very little dependence on any of the welding process parameters considered, with this being reflected in the relatively poor accuracy of the mathematical model. The mathematical models developed show considerable promise for both process optimisation and control of process automation.

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