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Assessment of wire arc additive manufacturing with respect to the repeatability of the process under uncertainties

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Abstract. Energy Deposition Methods (EDM) is on the rise with its capabilities to manufacture relatively big parts, and Wire-Arc Additive Manufacturing (WAAM) has been on the forefront. Developments in this technology has led to the innovation of WAAM-Cold Metal Transfer (WAAM-CMT), which is much more efficient than its predecessors. Nevertheless, it comes with its own complexities, giving rise to uncertainties, eventually causing variations in the geometry of fabricated parts. But these uncertainties can be traced back to the input parameters involved in the process. Even though, WAAM is influenced by several phenomena and parameters, only a handful of parameters are practically controlled during the process. Among these the most important parameters identified are Wire Feed Rate (V_{feed}) and Travel Speed (V_T) of the robot, which have a direct influence on the parts fabricated. To quantify the variability of these process parameters and the geometry of the bead, 140 single-layered beads are fabricated with four different set of input parameters. Quantification of the variations and the repeatability aspect of these variables, and thereby the process itself, are then studied using statistical tools like ANOVA. This gives an idea on how these vary from bead to bead. Quantifying these uncertainties and understanding the variations would help improve the process. This would enable better control of the process parameters, thus helping to make better design of the process and better predictions about the variations to expect.

Introduction

Wire Arc Additive Manufacturing (WAAM) is a process which uses the concept of adding layer upon layer, of material to build structures, contrary to Gas Metal Arc Welding (GMAW) which deposits molten material just for the purpose of joining two parts. This characteristic upgrades a simple metal joining technique into an additive manufacturing process. Or in other words, WAAM is an upgraded version of GMAW which comes from the class of Direct Energy Deposition (DED) processes [1]. Therefore, it is a direct metal feeding process which makes use of an electric arc as heat source to melt the material which is the feedstock [2,3]. Owing to its high deposition rate, ability to manufacture and/or repair structures, and manufacturing flexibility WAAM has received attention, relative to other conventional production techniques [1,4,5].

The process involves rapid heating, melting, and cooling of metal which determines the metallurgical properties and geometry of the parts. Different physical phenomena like the flow of metal in the weld pool, the influence of gravity, the rate of cooling etc. have a direct influence on the mechanical and geometric characteristics. But during the process, phenomena like distortion, squash down of metal due to gravity, surface undulations, inaccuracies with arc force etc. plays an important role and induces uncertainties in the process [2].

Several overlapping beads forms a layer and several such layers forms produces complete parts [6,7]. To reduce the various fabrication issues during the process, different WAAM methods were devised depending on the necessity. Among the various innovations, the integration of Cold Metal Transfer (CMT) with WAAM is gaining popularity which provides a controlled deposition mode through its advanced wire feed and digital control system. The higher efficiency, lower heat input and lower cost makes it more feasible relative to other WAAM processes [1,2,6,8–10].

The quality of the structure depends on the weld bead geometry and dilution, which are controlled by the process parameters like Travel Speed, Wire Feed Rate, Area of Overlap, Wire diameter, Torch Angle, Temperature etc.[11]. Therefore, studying and constructing a hierarchy of parameters of WAAM is difficult as several parameters are involved and these are inter-dependent on each other, making WAAM-CMT a complex process [1,12].

As the process is aiming higher, to be established as a standard manufacturing process, it is therefore important for the engineers to be able to predict the geometric as well as mechanical characteristics of the structure. This can only be attained through understanding the process parameters, and the related variations. This understanding of the effects of the uncertainties arising during the process and thereby optimising these parameters are necessary to obtain the desired part geometries.

The present research, therefore, characterises the variation in the process by using an observation-based approach to quantify the uncertainties present in the input parameters and output geometry of the beads. Several experiments are done fabricating simple beads, and the variations in the input parameters relative to the initially set values are recorded. The beads are then scanned using a laser scanner to study the variation in its Height and Width. This basic understanding using a simple bead can be used to create models capable of predicting parameters for much more complex parts. This work is, to the best of our knowledge, the first modelling approach of WAAM-CMT from a statistical point of view, to quantify the variations due to uncertainties. Quantifying the repeatability of these parameters (*Section: Repeatability of the Process*) is therefore the first stage in developing a model, since it would provide an insight into the input and output parameters which are assumed to be constant, if not for the influence of uncertainties.

Process Parameters

The number of parameters influencing the process is numerous and could pose difficulties while trying to optimize the process, because of the influence of one parameter on the other. The principal parameters which influence the WAAM-CMT includes[8,9,13]: -

a) Wire Feed Rate (V_{feed}), which is the speed at which the wire is pulled from the bobbin.
b) Travel Speed (V_T), which is the speed at which the torch is displaced by the robot.
c) Torch Angle (T_a), which the inclination of the welding torch with respect to the surface of the substrate
d) Stick-Out Distance (SoD), which is the length of the wire, protruding from the tip of the torch.
e) Wire Diameter (d_w), which is the diameter of the wire used for the fabrication.

Other factors like the material used, shielding gas and its proportion (82% Argon + 18% Carbon Dioxide, for the current experiments), temperature of the surface to which the bead is going to be laid, Flatness of the surface of the substrate used etc. could also have passive influence on the fabrication.

Nevertheless, in the current scope of experiments T_a & d_w stays constant at 90° and 1.2 mm respectively. SoD is set to 13 mm but modified and controlled by the robot during the experiments to maintain a stabilised arc. Therefore, SoD continuously varies and is uncontrollable during fabrication. The welding wire used is steel with welding standards ER100.

This leave V_{feed} & V_T as the only two variables which can be controlled during the scope of present research. These two parameters play the most important role in determining the shape and size of the beads. The experiments done showed that a faster V_T combined with a low V_{feed} would yield in a bead which is thin and short, whereas a slow V_T with high V_{feed} would result in a bulkier bead. Thus, any combination of these parameters would result in a bead which is different in its geometric characteristics. Since the form of beads is primarily influenced by V_{feed} & V_T, the uncertainties in these parameters could also have a direct influence on the form of the bead.

Experiments

The robot and welding generator used, permits to layup the beads with a wide range of initial values, but these does not always result in a good quality of beads with good structural integrity. A study on the quality of the beads as a function of V_{feed} & V_T , was carried out in [14], in which an acceptable domain of the functionality of the process was recommended. Four combinations of V_{feed} & V_T were chosen from this domain at its boundaries, thus being able to capture the variations at the limits of the process (Table 1). The parameters in Table 1 are the initial input values for the fabrication, but their true values, and variations remains uncertain (*Section: Data Analysis*).

Table 1: Set of Input Parameters used for the Experiments.

Set No.	V_{feed} (m/min)	V_T (mm/s)
P1	9	13.3
P2	7.5	18.3
P3	10	8.3
P4	10	18.3

The number of beads to be fabricated per set of parameters was determined based on the central limit theorem. According to the probability theorem, it states that the distribution of the means of a random sample could follow a normal distribution as the sample size reaches 30. This becomes relevant for the statistical analysis and hypothesis test discussed on later sections.

Therefore, a total of 35 beads of length 150 mm were fabricated per set of parameters. This was to avoid any misdone fabrication process, which could arise due to any other issues, including human errors, that could disrupt the statistical analysis. Thus, a total of 140 beads were fabricated.

The fabrication process was guided using an ABB IRB 8700, a 6 axes Robot, and the welding was controlled by a Fronius TP-180i generator. The commands for the Robot and the Post were programmed using the software RobotStudio, in which the axis of the substrate and the dimensions of the substrate was specified. The substrate onto which the beads were to be laid was cut from a steel plate of thickness 20mm.

Fabrication. The sand-blasted, smooth, and clean surface of the substrate is clamped onto the workbench. The experiments are done in such an order that the set of parameters for each bead were chosen at random. This avoids any uncertainty which arise because of the repeated fabrication using the same set of parameters.

The metallic wire is pulled from the bobbin, pass through the torch, and is guided by the robot, following a predetermined trajectory and speed (V_T). The wire, as it comes into contact with the metallic surface of the substrate, completes an electrical circuit. This creates an arc at the point of contact which melts the wire, and a drop of metal is laid onto the surface of the substrate. Now as the circuit is broken, the wire is pulled back-up, and the robot moves a step ahead. This process continues until the required length of bead is laid [Fig. 1].

The robot, to maintain a stabilised and constant arc length, controls the stand-off distance by controlling the V_{feed} of the wire, which induces variations in the parameter. Even though this ensures an optimised fabrication, the change in V_{feed} affects the geometry of the bead. The Fronius Station records this real time V_{feed} during the fabrication.

Figure 1: (a) WAAM-CMT Process (Laser tracker reflector visible on the left side) (b) Laser scanner used for the capturing the bead profile

The real time coordinates of the robot were tracked using a laser tracker, using which the V_T was later computed. Once the fabrication is completed the surface of the bead was cleared-off any silicates formed [Fig. 2] due to the presence of silicon in the steel wire which reacts with Oxygen. This is important as these could became inclusions while fabricating more complex structures. Once the bead is cooled down, the profile along the length of the bead was scanned using a laser scanner Keyence LJ-V7080 [Fig. 1] which captured the bead as a point cloud using which the various geometrical aspects of the bead could be studied. Since the scan using light to capture the bead geometry, the clearing-off of the silicates becomes important, as the silicates could disrupt the precision of the scan due to refraction of the light from the scanner.

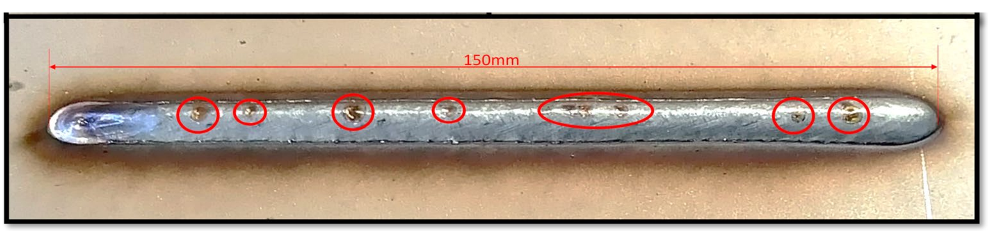

Figure 2: Welding defects: Bump, Dent and Silicates formed during the fabrication The splatter can also be seen around the bead as small dots

The process also brings with it, anomalies in the fabricated beads at the beginning and end of the bead (a bump and a dent respectively) because of the way the welding generator controls the process [Fig. 2]. These are undesirable parts of the bead and does not correspond to the bead geometry expected while using a specific set of parameters. Therefore, while studying the uncertainties linked with a given set of input parameters, these parts are removed from the analysis, which accounts to 50mm of the 150mm fabricated, i.e., 25mm from either side of the bead.

Data Analysis and Results

Wire Feed Rate. The Fronius Station records the V_{feed} with a resolution of one entry per 0.1 seconds.

The noise in the measurement, or the outliers, (not to be confused with the uncertainties during the fabrication) which are errors, are removed using the Inter-Quartile Range (IQR). The analysis following showed that: -

- All parameters take a few milliseconds to reach the specified value, but Parameter 3 takes more time than the others to get stabilised at a constant level as seen from the slope at the first two seconds [Fig. 3a].
- Even at the identical V_{feed}, P3 shows higher variation than P4, illustrating the influence of V_T on V_{feed} [Fig. 3a].
- All the actual fabrication V_{feed} falls below their set value, except for which P2 oscillates around its set value [Fig. 3a].
- The statistical analysis shows that, even though fabricated at a specified V_{feed}, practically the 35 beads are fabricated at different and fluctuating V_{feed} [Fig. 3b]. This could be very important while creating prediction models as, the beads cannot be assumed to be fabricated at the specified V_{feed}.

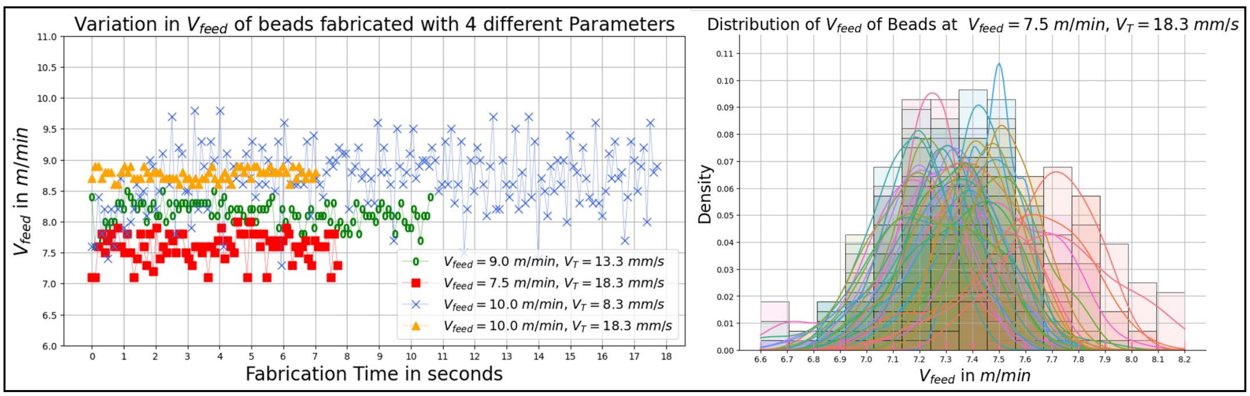

Figure 3: (a) Variation in V_{feed} for one bead fabricated with each Parameter and (b) The statistical distribution of 35 beads fabricated with Parameter 2

Travel Speed. V_T is not a direct output like the V_{feed}. The position of a tracker attached to the robot is recorded using a laser tracker, which gives its the real-time coordinates [Fig. 1a]. Each output is recorded at a frequency of acquisition of 96ms. Using the coordinates, the travel speed components are calculated since the time between two measurements are known. The coordinates are smoothed to accommodate the resolution error of ± 0.3 μm of the laser tracker.
Then with all the components, V_T is calculated as the norm of the speed components: -

$$V_T = \sqrt{v_x^2 + v_y^2 + v_z^2} \quad (1)$$

The analysis following showed that: -

- All the recorded V_T respect the set value with very small variations [Fig. 4a].
- There is not enough evidence to say that V_T is depended on V_{feed}, since P2 and P4 are superposed at the set value of 18.3 mm/s [Fig. 4a].
- The statistical analysis showed that, the beads were fabricated more or less at the set value of V_T which gives confidence on this parameter.

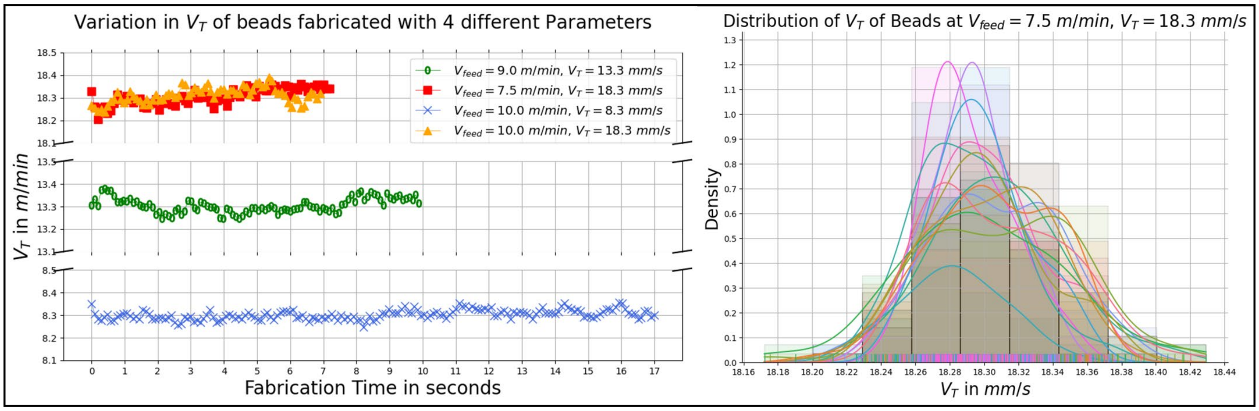

Figure 4: (a) Variation in V_T for one bead fabricated with each Parameter and (b) The statistical distribution of 13 beads fabricated with Parameter 2

Bead Geometry. The bead geometry is characterized by a set of cross-sections obtained by the laser scanner. For each cross-section, elementary shape parameters can be defined, such as height, the position of the cross-section's feet and its apex along the width etc [Fig.5]. The results shown in Figure 6 & 7 illustrates the variation in the principal geometric variables, height, and width of the bead.

The Laser scanner used for scanning the bead had a good resolution of 0.05mm, which would give around 2000 sections of useful sections per bead (100 mm), after filtering off the defects. Each of these sections contains 800 points corresponding to 40mm of cross-section of bead. The section of the bead profile is later extracted from the point cloud excluding the substrate [Fig. 5].

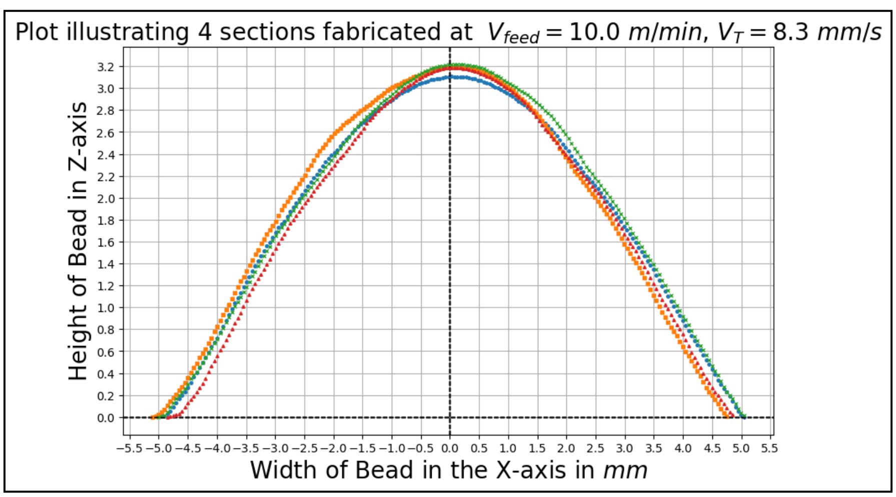

Figure 5: Plot showing four sections of an extracted bead, clearly showing the variations in its form along its length. Both the height and width can be seen to be fluctuating

As expected, beads fabricated at lower V_T and higher V_{feed} have bigger profiles compared to the ones which had faster V_T and lower V_{feed}.

It can also be noted that the variation in Parameter 3 is more prominent than the others, possibly because of the bigger drop size, higher volume of melt pool, higher cool down time etc. This variation could have an adverse effect on the profile of the bead, with change in geometry from section to section [Fig. 6 & Fig. 7].

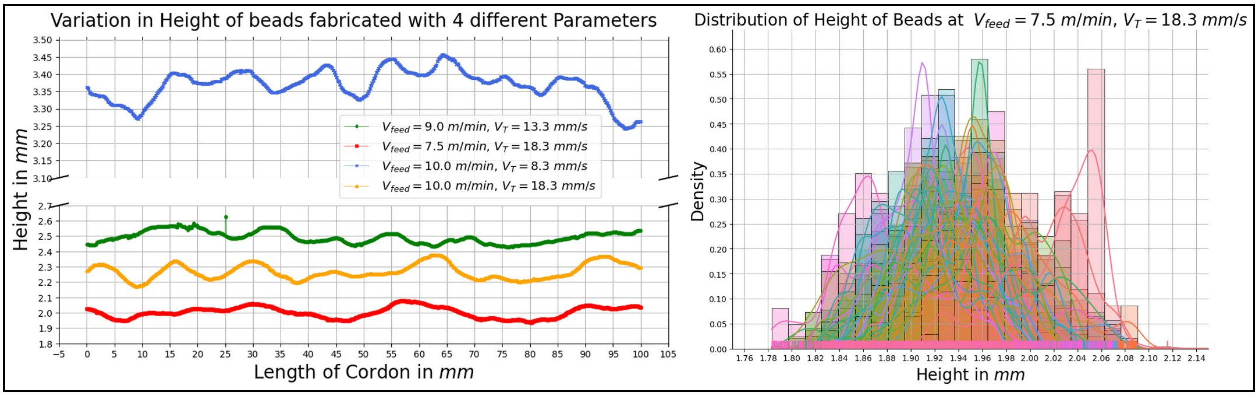

Figure 6: (a) Variation in Height for one bead fabricated with each Parameter and (b) The statistical distribution of Height of 35 beads fabricated with Parameter 2

The statistical analysis of Height and Width shows that there is no evident relation between the distributions of beads fabricated with the same set of parameters [Fig. 6b & 7b]. Rather the distributions are widespread showing that no two beads could be reproduced with a given set of parameters.

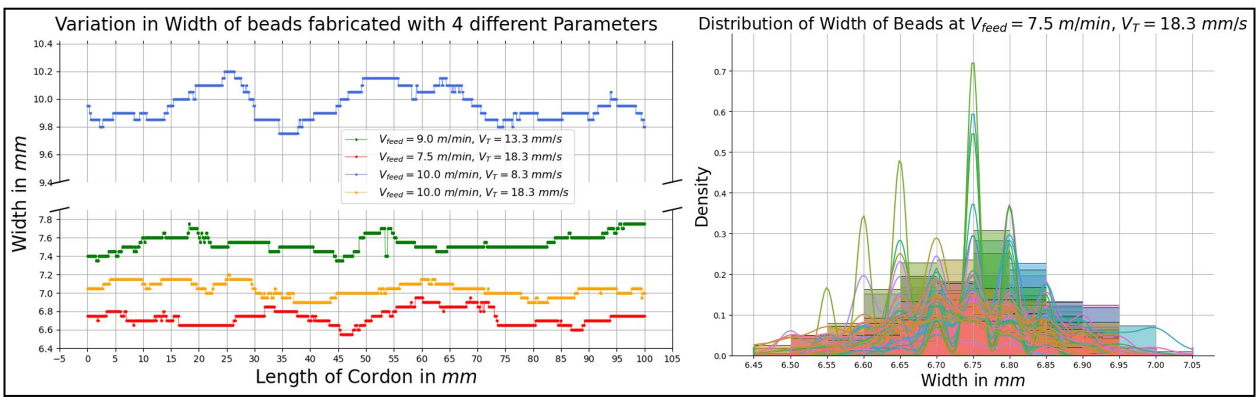

Figure 7: (a) Variation in Width for one bead fabricated with each Parameter and (b) The statistical distribution of Width of 35 beads fabricated with Parameter 2

Repeatability of the Process. The general statistical inferences made are rather qualitative and it is essential to prove quantitatively if the difference between the statistical distributions of two parameters are significant or not .The Joint Committee for Guides in Metrology (JCGM) defines repeatability as ”The closeness of the agreement between the results of successive measurements of the same measured carried out under the same conditions of measurement” [15].

Mathematically, it can be quantified as the standard deviation of a mean result under the repeatability conditions [16]. In the present study it can be used to identify if the difference between the distributions of several beads, fabricated using a set of parameters are considerable or not. Thus, it can be quantified if the parameters and thereby the process itself can be repeated.

The standard test used for this is the Analysis of Variance (ANOVA) Test, which numerically precise if the difference between two distributions is significant or not. The test computes the ratio between the mean square of variability of two group means (here means of two beads for the parameter under consideration), with the variation of the distribution itself. This is called F-Statistic which is compared with a Critical F-statistic obtained from the F-distribution table at a significance level of 5%.

$$F_{statistic} = f(group\ means, overall\ mean, number\ of\ groups, number\ of\ observations\ per\ group) = \frac{MS\ between\ the\ group}{MS\ within\ the\ group} \quad (2)$$

Table 2. ANOVA test results of Input Parameters

Parameter No.	V_{feed} (m/min)	V_T (mm/s)	F-Statistic V_{feed}	F-Critical V_{feed}	F-Statistic V_T	F-Critical V_T
P1	9	13.3	79.90	2.32	1.83	1.59
P2	7.5	18.3	53.24	3.26	1.88	1.72
P3	10	8.3	20.63	3.24	1.81	1.51
P4	10	18.3	65.35	1.47	0.19	1.72

Table 3. ANOVA test results of Output Variables

Parameter No.	V_{feed} (m/min)	V_T (mm/s)	F-Statistic Height	F-Statistic Width	F-Critical
P1	9	13.3	1072.1	234.31	1,43
P2	7.5	18.3	1287.6	107.92	1.43
P3	10	8.3	947.1	133.40	1.44
P4	10	18.3	522.5	78.74	1,45

The ANOVA test returned expected results with very high values of F-Statistic for V_{feed}, Height and Width, implying that these have a high numerator of F-Statistic [Table 2 & 3]. Therefore, the variation from one bead to another is much more significant than the variation within a bead making these variables non-repeatable. On the other hand, V_T showed promising results even though it failed ANOVA test since the ratio of numerator to the denominator of F-Statistic is very small [Table 2].

A further investigation into this data, involving bead to bead comparisons, proved that around 90% of the beads fabricated were repeatable. Only a couple of beads were going beyond the acceptable variation for V_T, the reason for which the ANOVA test failed. Nevertheless, it can be ascertained that the process is not repeatable, with drastic variations in geometry found even on a single bead.

Conclusion

WAAM-CMT despite being an advanced manufacturing process used for fabrication of big structures, comes with its own defects. Today, a non-standardised factor of safety is used during the fabrication to accommodate for the bad repeatability of the process depending on the in-situ research. The present study has been able to analyse the principal process parameters and basic geometry of the bead to quantify the variation in these parameters. Important variations in the Wire Feed Rate are found in the recorded measurements, which have a direct influence on the fabricated parts. Nevertheless, the variations found in the Travel Speed of the robot were rather small. The bead profiles, and thereby, the height and the width were different from one another even on a single bead analysed.

The ANOVA test confirms the inferences that neither the input parameters nor the output geometry is repeatable. It also shows the extend of this aspect, which indicate that the Travel Speed is close to being identifiable as repeatable, with only a couple of beads going beyond the acceptable variations. Nevertheless, the Wire Feed Rate is much further from being repeatable, which could be a characteristic of this fabrication technique and more difficult to optimise to reduce the variations. As a result, the process becomes non-repeatable even for the single beads fabricated. Therefore, more complex geometries involving overlapped and layered beads is certain to be non-repeatable since the physics of the fabrications are much more complex.

It is also worth pointing out that the uncertainties cannot be attributed only to these two inputs parameters and could be a result of several other thermo-chemical-mechanical phenomena. Even the unaccounted-for principal parameters like Torch Angle, and wire diameter could introduce small uncertainties into the process, because of their tolerances.

The present study throw light into the repeatability aspect of the process. But further research is required, to take into account additional uncertainties that take place while fabricating more complex geometries than just a bead. Nevertheless, these understanding of variations, with further research on the profile of the bead would enable to model the process better. The study could help future research avoid the hypothesis of constant geometric characteristics for WAAM beads while developing models. Further research on the additional bead profile characteristics like skewness, the overlapping and layered fabrication could be modelled to predict the geometry using statistical tools. Thus, understanding more of the variations in the input parameters and output geometry have the potential to optimize the errors in the modelling arising due to the uncertainties and aid the user to have more stable results.

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