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Wire Arc Additive Manufacturing Stepover Optimization based on Varying-Ratio Flat-Top Overlapping Model

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Wire Arc Additive Manufacturing (WAAM) is a manufacturing process that deposits weld beads layer-by-layer in a planar fashion, leading to a final part. Due to the layer-by-layer nature of weld bead deposition in WAAM, the accuracy of the printed geometry is largely dependent on the knowledge of the bead profile employed, which by itself is dependent on a variety of process parameters, such as wire feed rate, torch speed, and stepover ratio. Existing models for modeling bead profiles are based on their width and height, which do not necessarily capture the geometry of the weld bead accurately. This could affect the stepover increment strategy, which dictates the geometry of the resulting overlapping multi-bead valley. In this paper, a Varying-Ratio Flat-Top Overlapping Model (VFOM), for the derivation of an optimal multi-bead stepover ratio based on a particular bead geometry is proposed. In this approach, the stepover ratios of each bead are calculated based on their input process parameters to achieve a flat-top multi-bead surface. Experiments are conducted with bronze material using our proposed model and evaluated against a variety of overlapping models found in literature based on the resulting print 'bumpiness' and height consistency. Results show that the proposed VFOM approach is better in producing a smooth surface but does not perform as well in maintaining the multi-bead height thickness for the bronze material.

1. Introduction

The deposition of overlapping weld beads in the horizontal direction, known as multi-bead, is the foundation for most Wire Arc Additive Manufacturing (WAAM) printing. Since each deposited layer acts as the substrate for the printing of the next layer, each multi-bead layer needs to be as flat as possible to facilitate printing in the vertical direction. The lack of a sufficiently flat and smooth multi-bead surface will result in irregularities and error accumulation when printing the subsequent layers. To reduce such errors, many researchers have investigated single bead modeling and optimizing multi-bead stepover ratios for WAAM.

Suryakumar et al. [1] suggested the use of Artificial Neural Network (ANN) models to predict the single bead's width and height from the input process parameters and modeled the single bead profile using a symmetrical parabolic curve. Their study employed a flat-top overlapping model (FOM) for multi-bead prints to optimize the smoothness of the layer's top surface and concluded that the ideal stepover distance equals 0.667 of the bead's width. Cao et al. [2] employs a similar FOM model and calculated an optimal stepover ratio of 0.637 when a sine curve is fitted for the weld beads. Xiong et al. [3] found that the arc model fits the bead curve better when the ratio of wire speed to torch speed is greater than 12.5, and the parabola models fit better when the ratio is less than 12.5. As such, the stepover ratio based on the FOM model varies when different bead models are used. Ding et al. [4] proposed a new multi-bead tangential overlapping model (TOM) where the overlapping region that exists between two beads will not form a flat surface, but rather one that is tangential to the second bead's curvature. This study concluded with a stepover ratio of 0.738 to create stable deposits and uniform surfaces while assuming a parabolic bead profile. Knapp et al. [5] modeled the single bead using an ellipsoidal function in 3D. Hu et al. [6] observed that multi-beads do not necessarily produce a repetition of a consistent single bead profile and assigned different stepover ratios that vary with the process parameters while assuming a parabolic profile for the initial bead. The study found that when the stepover distance exceeds a critical point, the profile of the second bead can be fitted by a different parabolic function with a rotated orientation. Otherwise, the second bead can be modeled by a circular arc function instead. Recently, Oh et al. [7] uses planar quaternion features with a non-linear neural network to model the curvature characteristics of the bead accurately.

In this paper, a Varying-Ratio Flat-Top Overlapping Model (VFOM), for the derivation of an optimal multi-bead stepover ratio based on a particular bead geometry is proposed. In this approach, the stepover ratios of each bead are calculated based on their input process parameters to achieve a flat-top multi-bead surface. An experiment consisting of the proposed VFOM, along with the original FOM and TOM that assume parabolic single bead profiles, is conducted to compare the stepover ratios between the three models. The printed multi-beads are evaluated based on their surface smoothness and overall height consistency.

2. Multi-Beads Model and Evaluation Criteria

2.1 Flat-Top Overlapping Model (FOM)

The FOM is based on the theory that the overlapping area of two single beads is equal to the area of the valley that is formed between them as shown in Fig. 1. For parabolic single beads, the optimal stepover distance is found to be $d = 0.667w$.

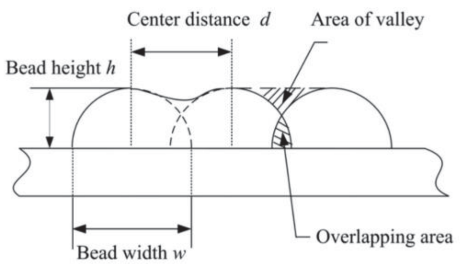

Fig. 1 Sketch of the flat-top overlapping model (FOM).

2.2 Tangent Overlapping Model (TOM)

The TOM assumes that the valley of two single beads does not form a flat, horizontal surface, but instead forms a line that is tangential to the second bead as shown in Fig. 2. For parabolic single beads, the optimal stepover distance is found to be $d = 0.738w$.

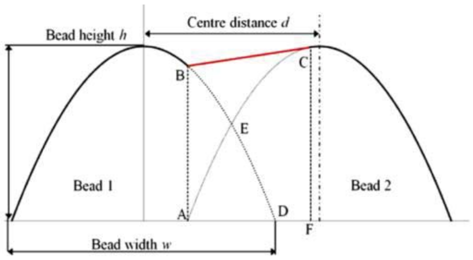

Fig. 2 Sketch of the tangent overlapping model (TOM).

2.3 Evaluation Criteria

2.3.1 Sinuosity Index

The sinuosity index measures the 'bumpiness' of the bead profile's section. It is calculated by dividing the total distance L of the multi-bead curve surface by the straight-line distance between the two endpoints of the multi-bead's middle section as shown in Fig 3.

$$SI = \frac{L}{\sqrt{(x_m - x_1)^2 + (z_m - z_1)^2}}$$

For an ideal straight line, which is a perfectly flat top, the sinuosity index is 1.

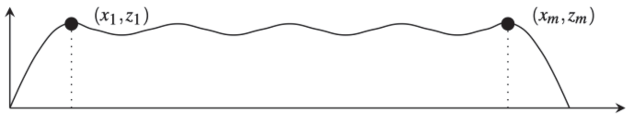

Fig. 3 Illustration of a multi-bead's middle section.

2.3.1 Gradient

The gradient G is a measure of the general trend of multi-bead material accumulation. To measure a multi-bead gradient, the height consistency at every point between its two endpoints (x_1, z_1) and (x_m, z_m) is fitted to a straight-line using MATLAB's polyfit function. The function produces coefficients a and b for a straight line with a general equation $z = ax + b$. We take the obtained value a to be the gradient G. For an ideal flat surface, the gradient G is zero.

3. Varying-Ratio Flat-Top Overlapping Model (VFOM)

Here we proposed a Varying-Ratio Flat-Top Overlapping Model (VFOM) to obtain the optimal stepover ratio based on a particular set of process parameters. The approach uses a best-fitted polynomial curve to model each single bead profile and subsequently used it to derive its optimal stepover ratio. Depending on the material used, the degree of the polynomial used may also vary. For instance, we found that the 8th-degree (n=8) polynomial fits the bronze well.

To see how we can derive the optimal stepover ratio, consider a curve ABC which represents the initial bead, and curve DFG which represents the second bead as shown in Fig. 4. The stepover distance between them is denoted as d^*. The center of overlap is at point E, which is at a distance d away from the center of the first bead. Variables h and w represent the height and width of the single bead respectively.

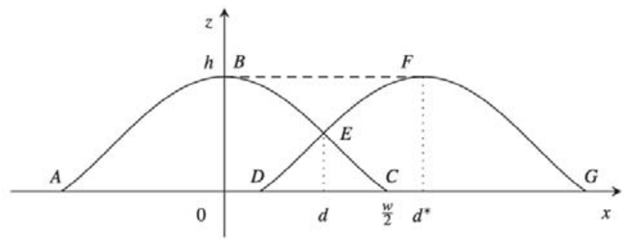

Fig. 4 The coordinate system used to represent the cross-sectional of multi-bead profile

Equating the areas DEC and BEF and assuming that the overlapping area DEC and valley area BEF are both vertically symmetrical, the optimal stepover distance d^* can be thus obtained,

$$d^* = \frac{2h}{\sum_{i=1}^{n+1} \frac{p_i}{(n+2-i)} (\frac{w}{2})^{n+2-i}}$$

Now, the stepover ratio r^* can be calculated using,

$$r^* = \frac{d^*}{w}$$

4. Experimental Setup and Results

The experiment aims to study and compare the quality of multi-beads printed using different overlapping models. They are printed using the Hybrid-WAAM work cell developed by the Singapore University of Technology and Design (SUTD) as shown in Fig. 5. The system consists of a robot manipulator (ABB IRB 1660ID), a welding power source (Fronius TPS 400i) equipped with a welding torch (Fronius WF 25i Robacta Drive), a milling cartesian coordinate robot made up of three linear rails (PMI KM4510) powered by three servos (SmartMotor SM34165DT), and a 2D laser scanner (Micro-Epsilon scanCONTROL 2910-100). The gantry system is controlled to move the line laser scanner in 3D space to obtain 3D point clouds of the printed layer's surface.

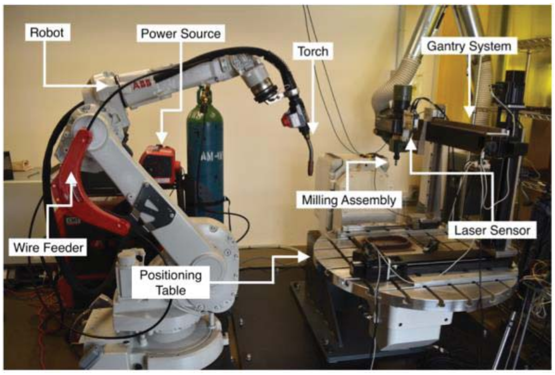

Fig. 5 Experimental setup of the SUTD H-WAAM work cell

The overlapping distances of different single beads are calculated based on the FOM, TOM and VFOM. Since the VFOM overlapping ratios depend on the single bead's cross-sectional geometry, the single bead data and MATLAB's polyfit function are used to obtain the necessary polynomial coefficients for the calculation of optimal stepover distance d^*. An eighth-degree polynomial is used for curve-fitting the bronze material and the fitted curves are as shown in Fig. 6.

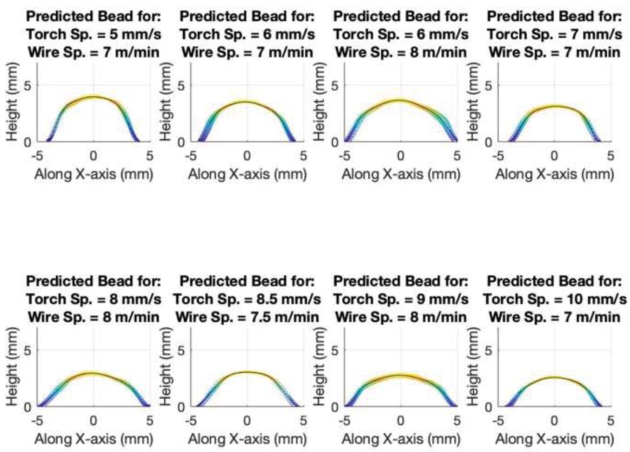

Fig. 6 Polyfitted single bead curves from the measured data

Next, eight sets of multi-bead consisting of three overlapping beads were printed for each of the FOM, TOM, and VFOM models. The torch speed and wire feed rates are selected such that they provide a variety of bead curvatures and consistent print quality for the assessment of the models across different types of bead profiles. The input process parameters, including the stepover ratio, torch speed, and feed rate, of the experiment are summarized in Table 1.

Table 1 Summary of Experimental input parameters

Models	v_t (mm/s)	v_w (m/min)	Stepover Ratio
Flat-Top Overlapping Model (FOM)	5.0	7.0	0.6667
	6.0	7.0	0.6667
	6.0	8.0	0.6667
	7.0	7.0	0.6667
	8.0	8.0	0.6667
	8.5	7.5	0.6667
	9.0	8.0	0.6667
	10.0	7.0	0.6667
Tangent Overlapping Model (TOM)	5.0	7.0	0.7380
	6.0	7.0	0.7380
	6.0	8.0	0.7380
	7.0	7.0	0.7380
	8.0	8.0	0.7380
	8.5	7.5	0.7380
	9.0	8.0	0.7380
	10.0	7.0	0.7380
Varying-Ratio Flat-Top Overlapping Model (VFOM)	5.0	7.0	0.7018
	6.0	7.0	0.6982
	6.0	8.0	0.6908
	7.0	7.0	0.7333
	8.0	8.0	0.6793
	8.5	7.5	0.6824
	9.0	8.0	0.6930
	10.0	7.0	0.7020

5. Discussion

The quality of each multi-bead print is assessed based on their 'bumpiness' and height consistency using their SI and G values. The results are summarized in Table 2.

Table 2 Summary of Experimental input parameters

No.	v_t (mm/s)	v_w (m/min)	Model	Mean *SI*	S.D. of *SI* along bead	Mean *G*	S.D. of *G* along bead
1	5.0	7.0	FOM	1.0133	0.0100	0.0731	0.0149
			TOM	1.0058	0.0013	0.0646	0.0069
			VFOM	1.0086	0.0013	0.0681	0.0081
2	6.0	7.0	FOM	1.0050	0.0023	0.0224	0.0097
			TOM	1.0047	0.0016	0.0215	0.0074
			VFOM	1.0063	0.0015	0.0293	0.0100
3	6.0	8.0	FOM	1.0139	0.0039	0.0076	0.0039
			TOM	1.0098	0.0032	0.0090	0.0078
			VFOM	1.0063	0.0025	0.0114	0.0055
4	7.0	7.0	FOM	1.0131	0.0072	0.0209	0.0118
			TOM	1.0044	0.0012	0.0155	0.0072
			VFOM	1.0058	0.0013	0.0246	0.0101
5	8.0	8.0	FOM	1.0097	0.0038	0.0301	0.0124
			TOM	1.0057	0.0028	0.0292	0.0191
			VFOM	1.0043	0.0008	0.0463	0.0103
6	8.5	7.5	FOM	1.0084	0.0038	0.0150	0.0103
			TOM	1.0069	0.0024	0.0140	0.0100
			VFOM	1.0044	0.0014	0.0120	0.0073
7	9.0	8.0	FOM	1.0083	0.0061	0.0439	0.0065
			TOM	1.0062	0.0037	0.0437	0.0099
			VFOM	1.0053	0.0040	0.0441	0.0100
8	10.0	7.0	FOM	1.0047	0.0025	0.0209	0.0095
			TOM	1.0062	0.0021	0.0087	0.0056
			VFOM	1.0041	0.0019	0.0089	0.0052

From the results, it is found that the original FOM that assumes parabolic single bead cross-section did not perform well in the 'bumpiness' test when compared to the other models. The mean SI of 1.0095 for the FOM multi-beads is much higher than that of the TOM and VFOM. TOM appears to produce less bumpy multi-bead with a mean SI of 1.0062, but is subjected to fluctuations across different printing process parameters. The proposed VFOM is observed to produce consistently low mean SI values, averaging to be 1.0056 with a standard deviation of 0.0018 across multiple process parameters.

In regard to consistency, the TOM seems to produce the most height-consistent multi-beads with a mean gradient of 0.0258, which aligns with previous experimental observations where larger stepover distances tend to create more space for adjacent beads as they overlap, reducing material and therefore height accumulation. The VFOM and FOM multi-beads tend to lead to an increase in height with a mean gradient of 0.0292 and 0.0306 respectively.

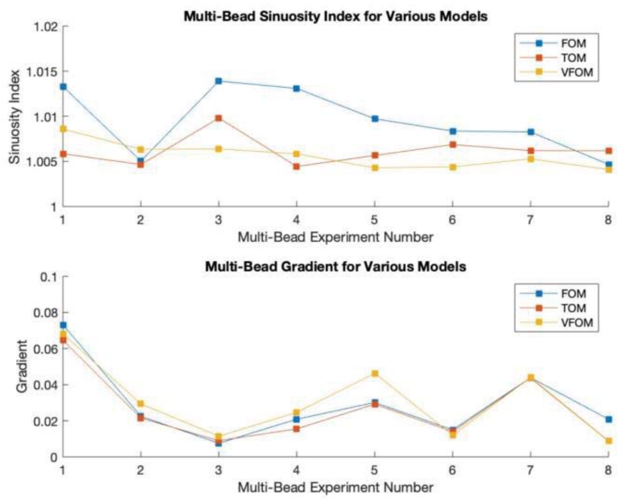

Fig. 7 Plot of overall SI and G of various multi-beads

Overall, using the stepover ratio for the TOM resulted in the most height-consistent multi-bead, while the proposed VFOM produced the least bumpy multi-bead. From Fig. 7, it can be observed that while the gradients of each multi-bead model fluctuate similarly with little deviation from one another, the sinuosity index of the three models behaves differently across the multi-bead experiments with varying input torch speeds and wire feed rates. Of the three models, the VFOM has the most consistent sinuosity index, maintaining below an SI of 1.0090, while the SI values of the FOM and TOM are more volatile. This may indicate that the VFOM has more potential of minimizing bead bumpiness when different input process parameters are used and is thus a preferred model for printing multi-beads with more consistent layer quality.

It should be noted that using bronze for the experiment was advantageous in reducing multi-bead surface 'bumpiness', as the material is observed to be less viscous than other materials, such as stainless steel. Given another material, it is possible that other models, such as the TOM, may perform better in reducing the 'bumpiness' of multi-beads. This is because the material may be more resistant to flow into the valley between adjacent beads. Therefore, the optimal model and stepover ratios determined are greatly dependent on the properties of the material used.

5. Conclusions

In this paper, a Varying-Ratio Flat-Top Overlapping Model (VFOM), for the derivation of an optimal multi-bead stepover ratio based on a particular bead geometry is proposed. From the experimental results, it is observed that the multi-beads obtained using the proposed VFOM produced the smoothest surface most consistently across various process directions of adjacent bead deposition. However, it is observed that all three models (FOM, TOM, VTOM) behave similarly in height accumulation with little deviation. On the other hand, the respective models contribute to vastly different behaviors in the 'bumpiness' of the multi-beads. Hence, the VFOM holds an advantage over the other two models in producing the most consistent multi-bead quality across different input process parameters. This demonstrates the effectiveness of the new proposed model given that the single bead's cross-sectional profile may not necessarily follow the parabola function.

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