Limiting Travel Speed in Additive Layer Manufacturing

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Abstract

Wire and Arc Additive Manufacture (WAAM) is a new approach to modern manufacturing. This technology has been gaining the interest of the research community due to its high deposition rate and efficiency. In Wire and Arc Additive Manufacture an increase in productivity can be achieved through the use of high weld travel speeds. However, this can be overshadowed by the so called humping effect. Humping is a defect in welding which expresses itself by the formation of humps and valleys that prevent further welding deposition operation. The generation of these defects is studied by critically examining the various weld travel speeds from different weld parameters. From this study, the actual weld travel speed, in which humping starts to appear is 0.6m/min for a cold metal transfer process using mild steel wire. The effects of wire feed speed and travel speed on bead geometries are also be discussed.

Keywords

Humping, Weld travel speed, High speed welding

Introduction

Wire and Arc Additive Manufacturing is an aspect of additive manufacturing in which metallic components are built by depositing beads of weld metal in a layer by layer fashion (see Fig. 1). Standard wire based welding processes such Gas Metal Arc Welding (GMAW) and Gas Tungsten Arc Welding (GTAW) are low cost solutions employed as heat source providing high deposition rate by utilising high energy input (1). The demand for WAAM has been on the rise over the past decades (1, 3). This is because of its innovative and more popularity as this process allows the production of large custom-made metal workpiece with high deposition rate and high quality welds at much faster rate. The technology helps to realise massive savings in the form of reduction in metal waste, reduced lead time and elimination of tooling cost (1). The total avoidance of tooling in Additive Manufacturing techniques gives design freedom and the design process can now be more flexible (2).

In today’s competitive manufacturing industries, there is a constant demand to improve productivity without sacrificing the overall quality of the product. For many welds, an increase in productivity often requires use of high welding speed (3) but this is overshadowed by humps.

Weld bead humping, a high speed welding defect, is the phenomenon of formations of humps in a bead at regular intervals during welding. It can also be described as a periodic undulation of the weld bead, with a typical sequence of undulation consisting of a hump and a valley as shown in Fig.1.

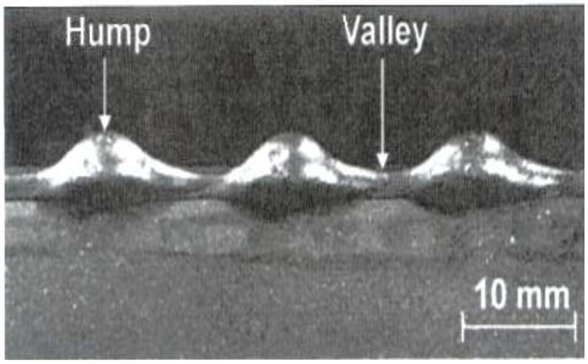


Fig. 1: Weld bead hump (3)

Based on the study conducted by Soderstorm and Mendez (4), humps occur due to the momentum of the back flow of the molten pool (Fig. 2).

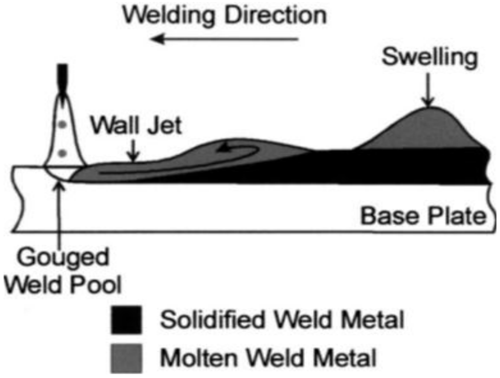
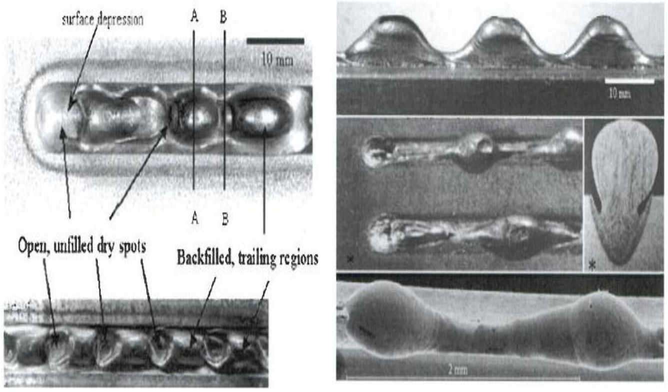


Fig. 2: Weld bead humping formation phenomenon (3)

The occurrence of humping limits the range of usable welding speeds in most fusion welding process and prevent further increase in productivity in a welding operation. At present the physical mechanisms responsible for humping are not well understood. Thus it is difficult to know how to suppress humping in order to achieve higher welding speeds (3). Humping can be classified into two types namely: Gouging Region Morphology and Beaded Cylinder Morphology. These are shown in Fig. 3 (a) and (b) respectively.



(a) (b)

Fig. 3: (a) Gouging Region Morphology, (b) Beaded Cylinder Morphology (4)

Gouging Region Morphology (GRM) is characterised by open, unfilled dry spots in between the humped beads. Besides, the fronts of the weld pool exhibit a very large depression known as the gouging region. The bulk of the molten metal, which is called trailing region, reside in the back of the weld pool. In some cases, two small channels appear at the walls of the gouging region. Other defects that share similarity with this humping mechanism are tunnel porosities, in which the gouging region extends beyond the surface of the weld and the split bead weld (4). In GRM, gouging is caused by arc forces which push the molten pool to the rear of the arc. This type of humping is more common in Gas Tungsten Arc Welding (GTAW) where the arc pressure is high. In order to minimize this type of humping, a hollow electrode tip can be used to reduce the arc pressure. Moreover, welding position and shielding gas mixture have shown their impacts. By using downhill welding, the humping can be reduced. This is because the back flow momentum of the molten pool can be reduced by using gravitational force. It is seen that reactive shielding gases produce significantly less humping as compare to inert gases. This is because to avoid humping, it is desirable to have a wider weld pool for the same deposition which is obtained by reactive gas mixtures (4).

Beaded Cylinder Morphology (BCM) is another type of humping defects. However, this type of humping is noticeably different from GRM not only the characteristic dry spots are missing but also the welds show no evident of depressions below the workpiece; the weld bead in this case has a continuous undulating aspect. The driving force is reduction of the surface energy by having sphered shaped intermittent welds instead of continuous cylindrical beads. To minimize this type of humping, steps similar to GRM can be applied. Additionally, it is has been found that the increase in thermal conductivity increases the travel speed required to cause humping. This is because preheating decreases the molten metal tail, hence reducing welding (4). Cho and Farson (5) demonstrated that there are two conditions responsible for humping. First is the motion induced by surface tension pinching force and secondly the premature solidification of the molten pool which separates the molten pool in front and rear portions.

The humping phenomenon has been the focus of many research papers published in the past 35 years. It has been reported in several different welding processes. Bradstreet (6) is credited with publishing the first paper to directly recognise humping during GMAW. Since then, humping has been observed in Gas Metal Arc Welding (GMAW), Submerged Arc Welding (SAW), Laser Welding, Electron Beam Welding and it is even evident in other fields such as digital micro fabrication using wax (4).

The first explorative study of the humping effects in automatic gas metal arc welding by Bradstreet (6) reported a dependence on the arc current, voltage, travel speed shielding gas and electrode conditions. In the parameter range he investigated, humping was always associated with undercut. The degree of undercut was found to be fairly constant along the weld length and almost unaffected by the presence of a hump. Savage (7) examines in details the dependence of humping on these parameters in GTAW of a sample of hardened steel of 19mm thickness. The essential feature is that for a fixed value of the arc current, there exists a critical travel speed above which the humping phenomenon commences. Some observation of the high speed welding defects has been made from different authors through different experimentation. Many other researchers have all reported humping as it occurs during GTAW. Albright (10) also reported this effect happening during laser welding. Even during electron beam welding, humping has been noted. Humping also occurs in the Additive Manufacturing but throughout all these studies, none has reported any study using the WAAM technique.

In the literature, nobody discussed humping in the WAAM sector of welding and the maximum travel speed limit. This establishes the purpose of this study which is to study the bead geometry within the framework of establishing the travel speed limit for a good WAAM process so as to control the process of achieving a good multi-layer part.

Materials and Methods

The material used in the experiments described in the following was mild steel consumable electrodes with very good feedability and very consistent welding performance. The diameters of the electrodes wire were 0.8mm and 1.2mm (EN 440.94 G3Sil1; AWS: A5.18 ER70S-6) and the chemical composition and mechanical properties is as shown in Table 1 and Table 2 (8).

Table 1: Chemical composition (W %) 0.8mm and 1.2mm electrodes wires

C	Mn	Si
0.08	1.55	0.85

Table 2: Mechanical properties of the 0.8mm and 1.2mm electrodes wires

Yield Strength (N/mm^2)	Tensile Strength (N/mm^2)	Elongation (%)
490	590	27

Machine setup and experimentation

The experiments were undertaken on a Holroyd Edgetek Super Abrasive Machining (SAM) machine integrated with the Fronius Cold Metal Transfer (CMT) welding machine and the shielding gas used is Argon shield CO_2 20% gas. The experimental set up is illustrated in Fig. 4.

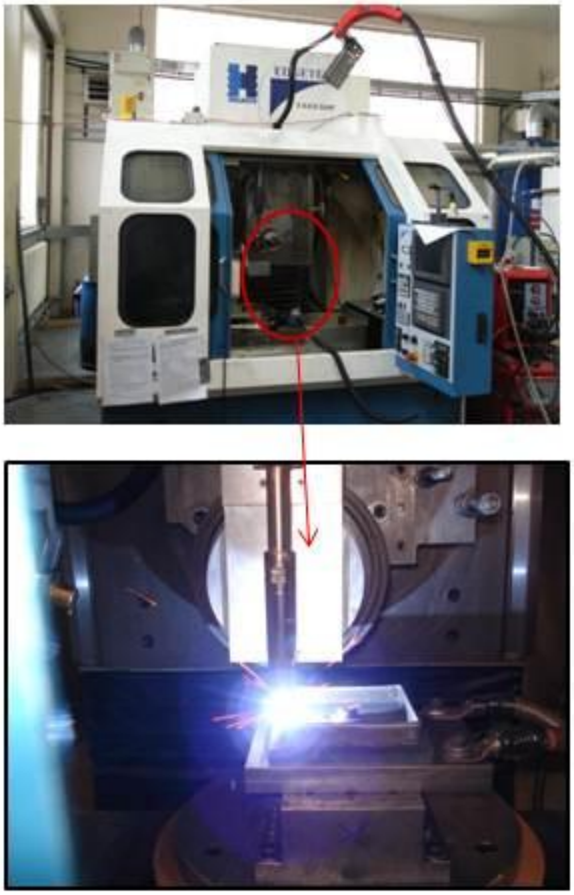


Fig. 4: Edgetek SAM machine integrated with CMT welding machine

The SAM machine was designed for high stock removal grinding to rival traditional hard turning methods. This makes it also suitable for high speed precision welding. Indeed, it has a 27KW grinding spindle, a feed speed of up to 125mm/s, and a 5 axis indexer work head. It uses Schneeberger Hi-precision linear roller bearing ways with Heidenhain linear scale on X, Y and Z axes, positioning of ±0.005mm per 30mm and repeatability of 0.005 per 300mm.

The integration of both SAM and CMT machines creates a hybrid machine system capable of welding and machining operations potentially improving processes accuracy and repeatability. The electrode wire feeding rate was measured and calibrated using a tachometer after being fitted in between the wire spool and the driven rollers of the CMT welding machine.

The investigation was carried out as walls on substrates made from mild steel and measured 120mm x 120mm x 10mm. All the substrates were ground and cleaned with acetone prior to the deposition. Each wall deposited 30mm apart to minimise the thermal and mechanical interaction between the deposited walls. After the experiments, the width and the height were measured at every layer of the welding with the aid of a digital Vernier calliper.

A Systematic Experimental Approach (SEA) strategy has been used in this study. The experiments were conducted in conjunction with the parameters from CMT process model optimization chart for Structural steel (9) which gives optimum operating conditions to achieve a target good weld bead for WAAM structures. Some control variables such as Wire Feed Speed (WFS), Wire Feed Speed/Travel Speed (WFS/TS), and wire diameter were used to get the response such as bead geometry characteristics required. The experimental welding parameters used for the trials 0.8mm and 1.2mm electrode wires are shown in tables 3 and 4. The first screening trials were done with a 0.8mm (see Table 3) electrode wire.

Table 3: Experimental parameters and results with 0.8mm electrode wire

Trials	**WFS (m/min)**	**WFS/TS**	**TS (m/min)**	**Process stability**
1a	7.0	8	0.875	Unstable
2a	8.0	8	1.000	Unstable
3a	9.0	8	1.125	Unstable
4a	6.0	12	0.500	Stable
5a	7.0	12	0.583	Stable
6a	8.0	12	0.667	Unstable
7a	5.0	15	0.333	Stable
8a	6.0	15	0.400	Stable
9a	6.8	15	0.453	Stable
10a	8.0	15	0.533	Stable
11a	9.0	15	0.600	Unstable
12a	10.0	15	0.666	Unstable
13a	7.0	15	0.467	Stable
14a	7.2	12	0.600	Unstable
15a	7.5	12	0.625	Unstable
16a	4.5	8	0.563	Stable
17a	4.8	8	0.600	Unstable
18a	5.0	8	0.625	Unstable
19a	6.0	10	0.600	Stable
20a	8.4	14	0.600	Unstable
21a	10.8	18	0.600	Stable
22a	7.0	10	0.700	Unstable
23a	9.8	14	0.700	Unstable
24a	12.6	18	0.700	Stable
25a	5.0	10	0.500	Stable
26a	7.0	14	0.500	Stable
27a	9.0	18	0.500	Stable

The second screening trials (see Table 4) were done and centered on the travel speed of 0.6m/min. This was based on the earlier indication of the travel speed limit from the first screening trials. A larger electrode wire of 1.2mm was employed in order to investigate any effect of the wire diameter on the process results and stability.

Table 4: Experimental parameters and results with 1.2mm electrode wire

Trials	WFS (m/min)	WFS/TS	TS (m/min)	Process stability
1b	1.0	2	0.500	Stable
2b	1.2	2	0.600	Stable
3b	1.4	2	0.700	Stable
4b	1.6	2	0.800	Unstable
5b	2.0	4	0.500	Stable
6b	2.4	4	0.600	Stable
7b	2.8	4	0.700	Unstable
8b	3.2	4	0.800	Unstable
9b	3.0	6	0.500	Stable
10b	3.6	6	0.600	Stable
11b	4.2	6	0.700	Unstable
12b	4.8	6	0.800	Unstable
13b	4.0	8	0.500	Stable
14b	4.8	8	0.600	Stable
15b	5.2	8	0.650	Unstable
16b	5.5	8	0.690	Unstable

Results and Discussion

During the deposition of the WAAM wall samples, it was discovered that many of the wall build up experience humps as illustrated in Fig 5a and 5b.


(a)
(b)

Fig. 5(a): Trial sample 7a with no hump and (5b): trial sample 7b exhibiting humping defects.

The walls with the humps were identified as an unstable process because more layers could not be built on it while the one without humping were regarded as a stable process. Tables 4 and 5 show the summary of the process stability of the trials using various deposition parameters. Using the 0.8mm electrode wire, fourteen out of twenty-seven trials had successful wall build up without humping while the remaining thirteen were unstable due to humping. In the case of 1.2mm electrode wire, nine successful build up were achieved while seven were unsuccessful (see Table 3). For all the unsuccessful tests, the humps occur between the first layer and the fourth layer (see Table 4).

Effect of welding parameters on wall geometry

For a constant wire feed speed and current combination, the width of the weld bead decreases with increasing travel speed. This is caused by the reduction of the material being deposited per unit time and by less heat input from the arc to the weld pool which diminishes the weld pools temperature. The reduced temperature increases both the viscosity of the weld pool and the constricting weld pool-substrate surface energy thereby reducing the effect of the arc pressure and aerodynamic forces on the molten metal. The overall effect is a narrower weld build up which is more pronounced in the first three layers of WAAM build up (see Fig. 6a and 6b).

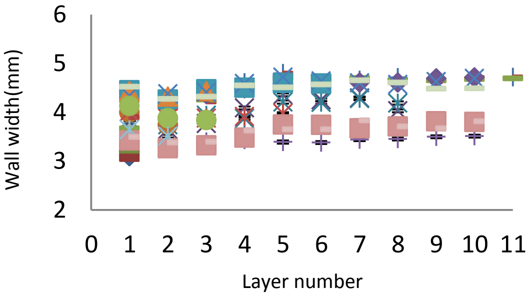


Fig. 6a: Wall width per layer for wall build up (0.8mm electrode wire)

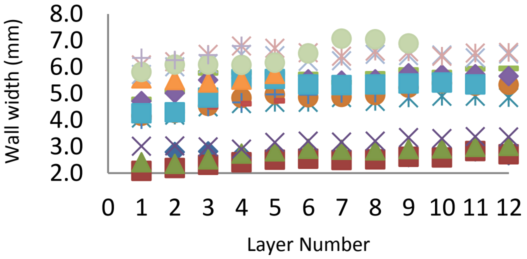


Fig. 6b: Wall width per layer for wall build up (1.2mm electrode wire)

Irrespective of the parameters, it is noticed that the width of the first three layers is smaller than the subsequent layers. It is also apparent that their heights are appreciably higher than the subsequent layers (see Fig.7a and 7b). However, it should be noticed that the number of layers is not dependent solely on the absolute wall height to be built but also on the individual weld bead dimensions.

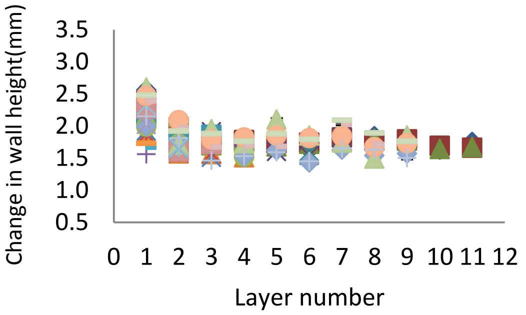


Fig. 7a: Increment per layer for wall height build up (0.8mm electrode wire)

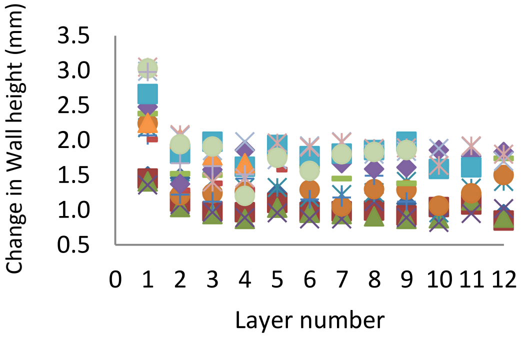


Fig. 7b: Increment per layer for wall height build up (1.2mm electrode wire)

Fig. 8a and 8b shows the dependence of the aspect ratio. This is the deposited bead height per bead width. The aspect ratio is higher (0.55) in the first layer but tend towards a constant value (0.4) as the number of layers increases.

Fig. 9a and 9b also show the dependence of the aspect ratio in terms of cumulative height to width on the layer number in which the relationship is linear, i.e. as the layer number increases the aspect ratio increases.

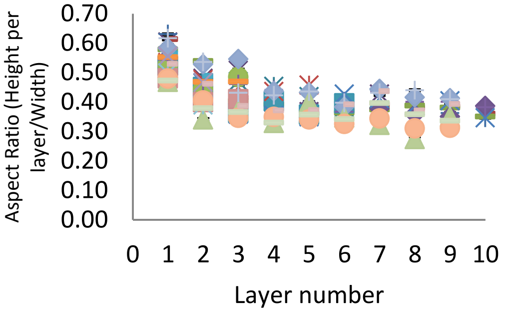


Fig. 8a: Aspect ratio per layer for 0.8mm electrode wire trials

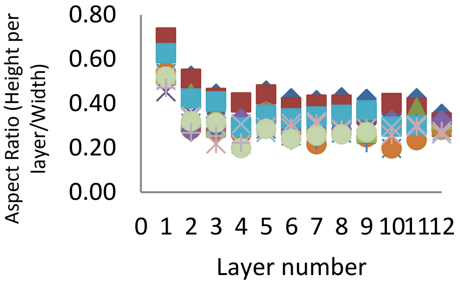


Fig. 8b: Aspect ratio per layer for 1.2mm electrode wire trials

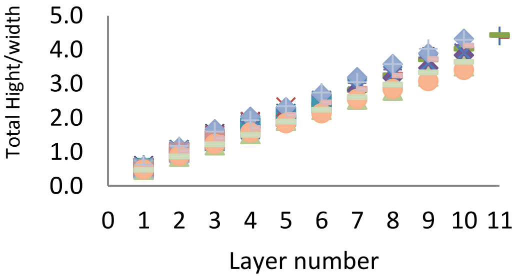


Fig. 9a: Cumulative aspect ratio for 0.8mm electrode wire trials

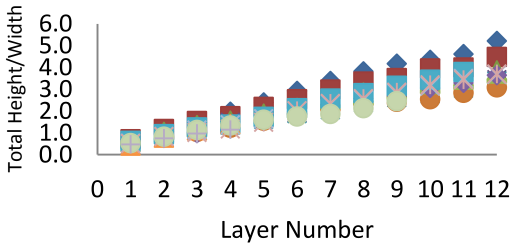


Fig. 9b: Cumulative aspect ratio for 1.2mm electrode wire trials

Effect of travel speed on weld bead humps

Theoretically, higher weld speeds can be obtained by optimizing various process variables while maintaining the same heat input per unit distance (11). This will provide the required productivity increase while retaining the same weld dimension. However despite having the same amount of heat input per unit distance continues increases in the weld travel speed are in practice limited by the deterioration of the quality of weld bead (3).

Fig. 10a and 10b show the experiment parametric plot highlighting the regions where process parameters produced good weld beads or generated humps and other welding defects. However, from those results, it was discovered that for a travel speed of 0.6m/min and below, the deposited walls show no significant variation in term of dimension or shape along their length. Such processes were classified as stable. Moreover, any attempt to go above a travel speed of 0.6m/min was hindered due to the development of humps in which wall build up could not be continue further due to exhibition of intermediate swellings that are separated by valleys and as the travel speed increases, the consistency of humps increases.

Theoritically, higher welding speed can be obtained by optimizing various process variables while maintaining the same heat input per unit distance. This will produce the required productivity increase while retaining the same weld dimensions; however, despite having the same amount of heat input per unit distance, a continued increase of the welding speed is in practice limited by deterioration of the quality of weld bead profile as shown in Fig.10a and 10b.

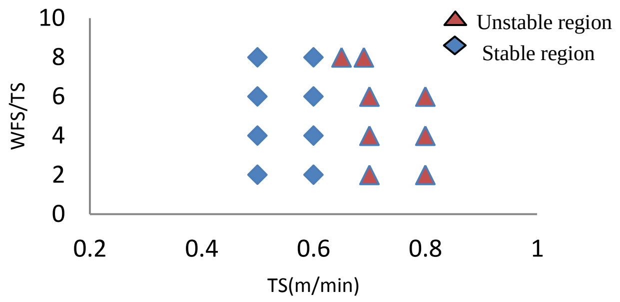


Fig. 10a: Parametric plot showing the travel speed limit (0.8mm electrode wire)

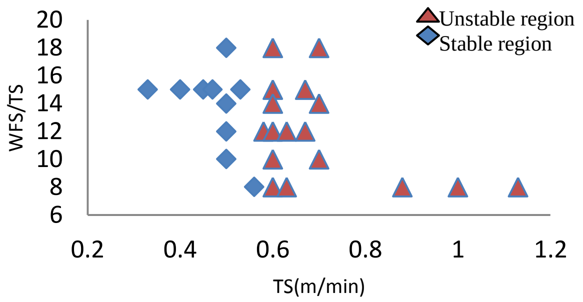


Fig. 10b: Parametric plot showing the travel speed limit (1.2 mm electrode wire)

The occurrence of humps can clearly be identified by the significant variations in the weld beads deposit dimension and shapes that occur along the length of the hump and valley. Cho and Farson, (5) attributed the cause of this hump to the arc forces which push the molten pool to the rear of the arc and the premature solidification of the molten pool which separates the molten pool in front and rear portions.

To confirm the establishment of the travel speed limit, the number of wall layers deposit attained with various travel speed were plotted (Fig. 11). This clearly highlights that 0.6m/min is the limiting speed in which walls with ten or more layers can be achieved without humps. Above this travel speed, the highest number of walls layers attained was six layers whereas below this travel speed, wall build up is continued until the trials were stopped after ten and twelve layers for 0.8mm and 1.2mm electrode wires respectively.

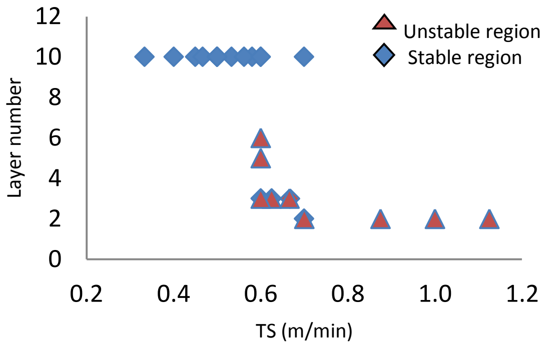


Fig. 11: Travel speed limit with respect to the number of layers attained

Effect of wire feed speed on weld bead geometry

The height and the width of the weld bead increase with higher wire feed speed even if the travel speed is kept constant. Generally, an augmentation of wire feed speed also results in an increase of the deposition rate and the weld bead dimensions. This can be explained as higher wire feed speeds lead to an increase in the volume of metal melted at the same heat input. This signifies a reduction in temperature of the weld pool therefore both its viscosity and the surface energy of the substrate-weld pool interface increase. The weld pool abilities to flow, spread out and increase in width are diminished (5).

A similar result was obtained by Shimanda (12) in plasma arc welding process. A higher wire feed speed increases the deposited cross sectional area and the contact angle. This results in the reduction of the weld pool temperature thereby increasing its viscosity and reducing its flow rate thus augmenting its height and contact angle. Generally, the process becomes unstable at high wire feed speeds as undercut and lack of fusion may result. As the heat input rises, the wire feed speed window also increases before the process becomes unstable. The wire feed speed has a large effect on the weld bead height and on the weld width. The higher the wire feed speed, the higher the weld bead height and the weld bead width are. However, the variation in the first three layers, having narrower width and higher height, compared to the subsequent layers is still valid.

Conclusions

Humping phenomenon in Wire and Arc Additive Manufacture has been investigated from the point of understanding the appropriate working travel speed limit using a Cold Metal Transfer welding machine. It is shown from the study that there exists a limiting speed of 0.6m/min at which humping starts to take place. As the travel speed increases above this limit, the formation of this discontinous weld bead defect start to get worse as the travel speed increases until the process cannot be continued. The backflow of molten metal inside the weld pool is responsible for the initial formation (which starts at the travel speed of 0.6m/min) and growth of the hump which themselves are promoted by high surface tension of the molten weld metal. The strong momentum of the backward flow of the molten matal inside the wall jet prevents backfilling of the front portion of the weld pool, which leads to the elongation and ultimately solidification of the wall jet to form valley in a humped weld bead.

For a constant Wire Feed Speed and Travel Speed, there is a big difference in the first layer of the entire wall built up when comparing with the subsequent ones. This first layer is constantly narrower in width but higher in height. The ratio of height/width is very significant unlike the other layers which tend towards a constant.

References

(1.) Ding, J., *et al.*, "Thermo-mechanical analysis of Wire and Arc Additive Layer Manufacturing process on large multi-layer parts", *Computational Materials Science*, Vol. 50, No. 12 (2011), pp. 3315-3322.

(2.) Karunakaran, K. P. *et al*., "Low cost integration of additive and subtractive processes for hybrid layered manufacturing", *Robotics and Computer-Integrated Manufacturing*, Vol.26, No 5 (2010), pp. 490-499.

(3.) Nguyen, T. C. *et al*., "The humping phenomenon during high speed gas metal arc welding", *Science and Technology of Welding and Joining*, Vol. 10, No. 4 (2005), pp. 447-459.

(4.) Soderstrom, E. and Mendez, P., "Humping mechanisms present in high speed welding", *Science and Technology of Welding and Joining*, Vol. 11, No. 5 (2006), pp. 572-579.

(5.) Cho, M. H and Farson, D. F., "Understanding bead hump formation in gas metal arc welding using a numerical simulation", *Metallurgical and Materials Transactions B: Process metallurgical and material processing science*, Vol. 38, No. 2 (2007), pp. 305-319.

(6.) Bradstreet B. J., "Effects of surface tension and metal flow on bead formation", *Welding Journal*, Vol. 47, No. 7 (1968), pp. 314s-322s.

(7.) Savage, W. F. *et al.*, "Effect of arc force on defect formation in GTA welding." *Welding Journal*, Vol. 59, No. 7 (1979), pp. 212s-224s.

(8.) Lincoln Electric. www.lincolnelectric.eu.

(9.) Almeida, P. M. and Williams, S., “Innovative Process Model of Ti-6Al-4V Additive Manufacturing Using Cold Metal Transfer”, Proceedings International Solid Freeform Fabrication Symposium, Austin, Texas August, 2010.

(10.) Albright C. E and Chiang S., “High speed laser welding discontinuity” *J. Laser Appl.*, Vol. 18, No. 2 (1988), pp. 18-24

(11.) Carry, B.: Modern welding technology, 5th edition, (Toronto 2002), Prentice Hall Canada Inc. pp. 477

(12.) Shimada, W. and Hoshinouchi, S., "A study on bead formation by low pressure TIG arc and prevention of undercut bead” *Journal of Japan Welding Soc.*, Vol. 51, No. 3(1982), pp. 280-286.