A STUDY OF HARDNESS AND MICROSTRUCTURE OF A ROBOT DEPOSITED WAAM COMPONENT WITH VARYING WIRE FEED RATE IN THE BUILD DIRECTION

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Abstract

Wire Arc Additive Manufacturing an arc based metal additive manufacturing creates 3D components with layer by layer weld depositions has a lot of advantages over powder based techniques and has the capability of fabricating medium to large components. The present work focussed on the study of the microstructure and hardness for wall structure fabricated by weld depositions based on Wire Arc Additive Manufacturing technique with different wire feed rates utilized from bottom to top in the build direction. Component fabricated is with 3 slabs with different wire feed rate in each slab and these slabs are deposited with multiple beads and multiple layers by using ABB 6 – AXIS Industrial Robot 1520ID. It is observed that internal matrix irrespective of slabs has insignificant variations in the hardness of the material in the build direction. The microstructure characterization exposes typically a homogenous polygonal ferrite with perlite. In general the overall process looks to be stable with negligible hardness variation. The core idea of this paper is to understand the microstructure and hardness of as-built WAAM components with varying feed rates.

Keywords: Hardness, Microstructure, Wire Arc Additive Manufacturing.

I. Introduction

Additive manufacturing is an innovative process through which 3D objects are manufactured by layer by layer deposition. Additive manufacturing even though started as a tool for prototyping and modeling has expanded tremendously in other domains like Medical, Aerospace etc.

Metal additive manufacturing is rapidly emerging due to its capability of producing components at reduced cost with low buy-to-ratio. A saving of 78% in raw material proved in WAAM fabrication of air craft landing gears ribs [X].

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Metal Additive manufacturing processes are majorly categorized in to two types based on the feed stock powder bed based and wire feed based. Powder based specifically suited to smaller components and surface finish and the dimensional accuracy is very high in the powder based, however for large to medium structures powder based AM is definitely not viable, also studies indicates the powder based has an inbuilt porosity issues [I], on the contrary the wire based AM process is ideal choice for medium to heavy components / structures due to its high rate of metal deposition, and practically there is no limitation to the dimensions of fabricated component. Depending on the energy source wire feed AM is categorized in to three processes like Arc based, Lased based and Electron beam based and among all of these, Wire Arc based is energy efficient [I, VII] and economical. Depending on the heat source utilized WAAM technique is categorized in to three and they are Gas Tungsten Arc based welding (GTAW), Gas Metal based Arc Welding (GMAW), and Plasma Arc based welding. Metal deposition rate is 2-3 times more in GMAW when compared with GTAW or PAW [III]. Wire Arc Additive Manufacturing (WAAM) is basically an additive manufacturing technique where in arc is the source of heat and it uses wire as feed stock and deposits molten metal on to the substrate through layer by layer [IV]. Metal Additive manufacturing has a tremendous potential in transforming the design and fabrication of metallic components. WAAM technique combined with Robotic operation can provide the capability to manipulate the deposition parameters like current, voltage and wire feed rate to get desired properties at desired locations of the component [VIII].

Mechanical properties of components fabricated through weld metal deposition via HLM (hybrid layer manufacturing) were studied by Surya Kumar [IX] for investigating the hardness and tensile strength of WAAM fabricated components. Majority of the studies indicated the advantages of metal Additive manufacturing however Metal AM process still has certain limitations like anisotropy and heterogeneity in microstructure and mechanical properties [XI]. Anisotropy represents wide variability in properties owing to orientation specific dependent features; however heterogeneity is a measure of evenness on its features. Evolvement of anisotropic and heterogeneous microstructure significantly influences the mechanical properties and this in turn attracting extensive research activity scope in this area. Major reason for the inbuilt anisotropy and heterogeneity of metal AM components is due to the complex recurring thermal history involving of repeated melting and rapid solidification which is not the case in conventional techniques.

Recent research articles indicated that metal AM components exhibits anisotropy and also heterogeneity in microstructures and mechanical properties. In general basic requirement of any engineering application component needs better and consistent mechanical properties. The weld deposition current plays a significant role in varying the weld pool characteristics and the heat affected zones and this in turn has a substantial influence on resulting mechanical and microstructural properties of AM fabricated components. This study is to analyze properties of fabricated component through Gas Metal Arc weld deposition strategy.
In GMAW current depends on wire feed rate, as the wire feed rate increases the current also increases, so basically the variations in wire feed rate reflects in the variations of current [VI].

It is observed that a very little work is done in fabricating the single matrix component with varying wire feed rates while depositing. The proposed work is to fabricate a wall structure with three slabs with pre-determined slab heights in the build direction and each slab is deposited with varying wire feed rate.

Individual slabs are deposited with multiple weld bead depositions through multi layers approach by using 6-axis ABB Robot 1520 ID to achieve desired slab height.

This paper is to study the Hardness and the microstructure of a WAAM fabricated component with varying wire feed rate in the build direction by using Robot. The filler wire used is a copper-coated mild steel filler wire, ER 70S - 6, of diameter of 1.2 mm.

II. Experiment Procedure

The experiments were conducted using ABB 6-Axis IRB 1520 MIG Welding Robot as shown in the Fig1. The welding process is locally protected using welding-graded (99.995%) argon to prevent oxidation of the deposited material. The feed wire used in this experiment is of ESAB ER70S-6 with 1.2 mm diameter. Typical ESAB weld wire composition is indicated in the Table 1.

| Typical AWS A5.18; ER70S-6 Weld wire composition in % |
|-----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| P               | Mn             | Cu             | Mo             | S              | Si             | Cr             | Ni             |
| 0.03            | 1.80           | 0.35           | 0.15           | 0.03           | 0.12           | 0.03           | 1.15           | 0.15           |

**Fig. 1:** ABB Robot 1520 ID
A wall structure of 75 mm in length and 20 mm width and with a height of 70 mm deposited on the mild steel substrate plate of thickness 10 mm (dimensions 140 mm X 120 mm), as per Fig 2. The fabricated wall structure is built in three slabs and the dimensions of the slabs are as shown in Fig 3.

**Fig. 2:** Fabricated components dimensions (A) Height of Component (B) Length of component (C) Width of component

**Fig. 3:** Individual slab dimensions

Each slab is deposited with different wire feed rate as indicated in the Table 2, and all other parameters as shown in the Table 3, are kept constant for the entire build irrespective of the slab.
Table 2: Wire feed rate parameter details for each slab

| Slab Number | Wire feed rate in m/min |
|-------------|-------------------------|
| Slab 1      | 7                       |
| Slab 2      | 5                       |
| Slab 3      | 3                       |

Table 3: Other Parameters used for entire build – for all the slabs

| Parameter                  | Value          |
|----------------------------|----------------|
| Voltage                    | 18 volts       |
| Argon flow                 | 22 Lit/min     |
| Torch speed                | 8 mm/sec       |
| Wire diameter              | 1.2 mm         |
| Wire specifications        | ER70S-6        |
| Cooling                    | Ambient air    |
| Distance between work piece and wire | 14 mm |

In order to arrive at the average width and height of individual bead for each individual feed rate, an initial single bead deposition were done on a MS plate, and average bead width & average bead height calculated individually and the same is indicated in the Table 4.

The critical bead distance is the distance between successive beads as shown in Fig 4, that is necessary for a stable overlapping process and is equal to 0.738 times the average bead distance measured [VIII] and the same is shown in Table 4. In this experiment critical distance is maintained with single decimal precision.
Table 4: Measured average width and average height of bead distance and calculated critical bead distance

| Slab No. | Wire feed rate (mts/min) | Avg. width of bead (mm) | critical bead distance = 0.738 X average width (mm) | Critical bead distance used in experiment (mm) | Avg. Height of bead (mm) |
|----------|--------------------------|-------------------------|--------------------------------------------------|-----------------------------------------------|-------------------------|
| 1        | 7                        | 6.95                    | 5.13                                             | 5.10                                          | 2.95                    |
| 2        | 5                        | 6.30                    | 4.65                                             | 4.60                                          | 2.49                    |
| 3        | 3                        | 4.57                    | 3.37                                             | 3.30                                          | 2.15                    |

Fig. 4: Critical distance between beads in a multiple bead component [II]

In this experiment component is fabricated with dimensions as per Fig.3. In order to build individual slabs with required dimensions minimum number of beads required for each layer and minimum number of layers required for each slab is calculated based on the finalized critical bead distance and the average height of the bead measured for specific wire feed rate from Table 4. A total of 210 weld beads needed to deposit to fabricate complete component and Table 5 show the minimum number of beads and layers for each slab.

Table 5: Projected number of beads and layers in each slab

| Slab Number | Projected number of beads in the slab for a minimum width of 25 mm | Finalized distance between the beads in this slab in mm | Projected number of Layers in this Slab for a minimum of 25 mm slab height | Total No. of weld beads in this Slab |
|-------------|------------------------------------------------------------------|--------------------------------------------------------|---------------------------------------------------------------------------|-------------------------------------|
| Slab 1      | 6                                                                | 5.10                                                   | 9                                                                         | 54                                  |
| Slab 2      | 6                                                                | 4.60                                                   | 10                                                                        | 60                                  |
| Slab 3      | 8                                                                | 3.30                                                   | 12                                                                        | 96                                  |

Bead deposition pattern for each layer within each slab is indicated in Fig 5. Purposeful time delay taken between each bead and layer and is indicated in Table 6.

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III. Results and Discussion

The Brinnel hardness tester machine is used to measure the hardness, load applied is 187.5 Kg f and indenter is of 2.5 mm dia. The hardness values measured along with build direction at specified location which includes the slab1 & Slab2 interface and Slab2 & Slab3 interface regions is shown in Fig 6. Measured values of BHN at the specified locations are tabulated in Table 7.
Fig. 6: Locations on the component along the build direction where hardness is measured

Table 7: Measured BHN values at the indicated locations along the build direction

| Location          | Reading No. | A   | B   | C   | D   | E   |
|-------------------|-------------|-----|-----|-----|-----|-----|
|                   | 1           | 174 | 165 | 156 | 169 | 177 |
|                   | 2           | 169 | 166 | 162 | 169 | 177 |
|                   | 3           | 170 | 166 | 164 | 171 | 181 |
| Average           | BHN         | 171 | 165.66 | 160.66 | 169.66 | 178.33 |

Fig. 7: BHN vs. distance from bottom surface of specimen
From the Fig 7, it is observed that hardness takes a downtrend along the length of component initially, and it is noticed that hardness is highest in top layers of the component. This is due to the reason that initially the substrate will be cold and hence much of the heat generated would be passed on to the substrate predominantly through conduction so the rate of cooling for the initial layers would be high and hence the hardness in the initial layers of slab 1 is high. After considerable layers are deposited the substrate temperature gets stabilized, in parallel the heat accumulation becomes more in the structure and the convection and radiation would predominantly play a key role in the heat transfer and hence in the slab 2 heat accumulation is more and the rate of cooling is less compared to slab 1 and thus there is a decrease in hardness of slab 2. However in the slab 3 the heat input is less compared to slab 2 (since the wire feed is only 3mts/min in slab 3), and rate of heat transfer is similar to slab 2 so again there is an increase in hardness compared to slab 2. As more number layers getting deposited the specific layer distance from the most current layer increases and this increase of distance will result in reducing thermal effect on the specific layer, this is also due to the fact that temperature gradient will drop below recrystallization temperature and hence the thermal cycles will not affect the distance layer.

**Microstructure Observations:**

Fig 8, show the microstructure at six locations in the build direction from bottom of specimen sample to the top surface along with high magnification images of the same regions. The microstructure characterization reveals that most of the build consists of polygonal ferrite and bainite with small portion of pearlite. It can be seen clearly the interface region between the Slab 1 & Slab 2 and from slab 2 to slab 3 in the Fig 8.
Fig. 8: Microstructure along the build direction and magnification micrographs from different locations in the build height: (A) Bottom of the sample in slab1 (B) In the Middle of slab1 (C) In the transition between slab1 & slab2 (D) In the slab 2 (E). In the transition between slab2 & slab3 (F) In the slab 3.

In GMAW as wire feed rate increases current also increases and vice versa. So slabs with varying wire feed rate implies that slabs are deposited with varying current. Heat input to the weld deposition is proportional directly with the current and hence slabs deposited with varying current means slabs deposited with varying heat input. Heat input is calculated as

\[
\text{Weld Heat Input} = \left( \frac{\text{Voltage} \times \text{current}}{\text{weld speed in } \frac{\text{mm}}{\text{sec}}} \right) \times \eta
\]

Where \( \eta \) is the weld thermal efficiency which in general has wide range 69% - 91% for GMAW \([VI]\). The heat inputs to the slabs are indicated in Table 8.

**Table 8: Heat input in to the slabs deposited**

| Slab No. | Wire feed rate (mts/min) | Welding Voltage (volts) | Welding Current (Amps) | Welding Speed in (mm/sec) | Welding Heat input (Joule/mm) |
|----------|--------------------------|-------------------------|------------------------|--------------------------|-------------------------------|
| Slab1    | 7                        | 18                      | 251                    | 8                        | 395.33                        |
| Slab2    | 5                        | 18                      | 210                    | 8                        | 330.75                        |
| Slab3    | 3                        | 18                      | 146                    | 8                        | 229.95                        |

From the Fig 9, we can see the coarse grain HAZ volume is more in Slab1 compared to that of Slab2; this is due to the reason that heat input is more in Slab1 than Slab2 as shown in the Table 8. Similarly due to the difference in heat input of Slab2 & Slab3 the coarse grain HAZ volume differs between slab2 and slab3.
Fig. 9: Inter layer distance and HAZ Grain distribution in slabs microstructure (A) Slab1 (B) Slab2 (C) Slab3

The layer height and the layer width measured from the microscope (Fig 9) is compared with that of sample trail weld bead deposited for each individual feed rate and percentage variation is indicated in the Table 9 for each feed rate.

Table 9: Comparison of measured layer height between trail sample bead deposited and the bead and layer height calculated from microscope.

| Slab No. | Wire feed rate for slab in mts/min | calculated layer height in mm for the single deposited trail bead | Layer height observed from Microscope in mm | Percentage variation in layer height from calculated to Microscope observed |
|----------|-----------------------------------|---------------------------------------------------------------|------------------------------------------|---------------------------------------------------------------|
| Slab 1   | 7                                 | 2.95                                                          | 2.67                                     | 9.47                                                          |
| Slab 2   | 5                                 | 2.49                                                          | 2.38                                     | 4.42                                                          |
| Slab 3   | 3                                 | 2.15                                                          | 2.10                                     | 2.14                                                          |

IV. Conclusions

1) It is noticed that hardness variation along the build direction is not significant; however there is a slight variation in hardness numbers of three slabs, Hardness variation is due to the variation in rate of cooling in three slabs.

2) The microstructure characterization reveals that most of the build consisted of polygonal ferrite and bainite with small portion of pearlite.

3) The more the wire feed rate, the more would amperage and accordingly more would be the heat input and this reflects in more coarse grain HAZ volume. As the wire feed rates are in descending order from slab1 to slab3 (in the build direction) and accordingly coarse grain HAZ volume is in the descending order from slab1 to Slab3.
References

I Apparao and M. V. J. Raju, International Conference on Emerging Trends in Engineering (ICETE), vol. 2, no. 1. Springer International Publishing, 2020.

II Cong, Z. Qi, B. Qi, H. Sun, G. Zhao, and J. Ding, “A comparative study of additively manufactured thin wall and block structure with Al-6.3%Cu alloy using cold metal transfer process,” Appl. Sci., vol. 7, no. 3, 2017.

III J. Ding et al., “Thermo-mechanical analysis of Wire and Arc Additive Layer Manufacturing process on large multi-layer parts,” Comput. Mater. Sci., vol. 50, no. 12, pp. 3315–3322, 2011.

IV L. Quintino, O. Liskevich, L. Vilarinho, and A. Scotti, “Heat input in full penetration welds in gas metal arc welding (GMAW),” Int. J. Adv. Manuf. Technol., vol. 68, no. 9–12, pp. 2833–2840, 2013.

V P. M. Sequeira Almeida and S. Williams, “Innovative process model of Ti-6Al-4V additive layer manufacturing using cold metal transfer (CMT),” 21st Annu. Int. Solid Free. Fabr. Symp. - An Addit. Manuf. Conf. SFF 2010, pp. 25–36, 2010.

VI S. Suryakumar and M. A. Somashekara, Manufacturing of functionally gradient materials by using weld-deposition. Woodhead Publishing Limited, 2013.

VII S. Suryakumar, K. P. Karunakaran, U. Chandrasekhar, and M. A. Somashekara, “A study of the mechanical properties of objects built through weld-deposition,” Proc. Inst. Mech. Eng. Part B J. Eng. Manuf., vol. 227, no. 8, pp. 1138–1147, 2013.

VIII S. W. Williams, F. Martina, A. C. Addison, J. Ding, G. Pardal, and P. Colegrove, “Wire + Arc additive manufacturing,” Mater. Sci. Technol. (United Kingdom), vol. 32, no. 7, pp. 641–647, 2016.

IX Sola and A. Nouri, “Microstructural porosity in additive manufacturing: The formation and detection of pores in metal parts fabricated by powder bed fusion,” J. Adv. Manuf. Process., vol. 1, no. 3, pp. 1–21, 2019.

X Wu et al., “A review of the wire arc additive manufacturing of metals: properties, defects and quality improvement,” J. Manuf. Process., vol. 35, no. February, pp. 127–139, 2018.

XI Y. Kok et al., “Anisotropy and heterogeneity of microstructure and mechanical properties in metal additive manufacturing: A critical review,” Mater. Des., vol. 139, pp. 565–586, 2018.