Experimental investigations of TIG welding based additive manufacturing process for improved geometrical and mechanical properties

Gokhale Nitish P.1*, Prateek Kala2, Varun Sharma3

1Birla Institute of Technology and Science, Pilani, Rajasthan, India -333031,
2Birla Institute of Technology and Science, Pilani, Rajasthan, India -333031,
3India Indian Institute of Technology, Roorkee, Uttrakhand, India-247667.

*nitish_gokhale@yahoo.com

Abstract: The welding based additive manufacturing process has a potential for producing functional 3D metallic component in a cost effective manner. Out of many welding based alternatives available TIG (Tungsten Inert Gas) based additive manufacturing process is one of the efficient processes. This article aims at developing TIG welding based additive manufacturing process for producing metallic parts with improved geometrical and mechanical properties. In this work authors have identified a process parameter condition by which components with good geometrical properties can be produced. The work reports least bead width deposited, for 1.2 mm filler wire, using wire arc based additive manufacturing system. The study performed on residual stress analysis of the deposited material showed compressive residual stresses throughout the sample. Usually welding process produces tensile stresses in the specimen which may reduce the product life. The compressive stresses reported in this study are considered good as they tend to increase product life. Authors have also addressed the reason for this unusual but favourable behaviour. This work would also help to develop automated TIG welding based metal deposition system to produce thin walled structures with improved mechanical and geometrical properties.

Keywords: TIG (Tungsten Inert Gas) welding based Additive manufacturing, Additive manufacturing, Residual stress, Geometrical properties.

1. Introduction:

The utilization of the additive manufacturing for producing relatively denser parts is increasing day by day across the globe. The additive manufacturing systems with simplified design, low initial investment costs, and high precision are needed for applications like aerospace and biomedical implants. The welding based metal deposition processes [1][2] are capable of producing relatively denser components with lower operational cost[3]. The manufacturing of parts with complex geometry by using machining process require more number of machines and it consumes more energy [4][5]. Among the different types of welding based metal deposition systems MIG welding based metal deposition system has been mostly used due to its higher deposition rate and good controllability over filler material. Few of the authors have also used TIG welding based metal deposition process rather than MIG welding based metal deposition due to the less spattering defects and high precision[6]. However, the inspiration of this work is to design a TIG welding based metal deposition system which can utilize welding for producing arc instead of using expensive heat sources like laser.
source and Electron Beam Melting. The metal deposition with Wire as a filler material is critical process to control in case of TIG welding based Additive manufacturing [7]. Researchers who have used TIG welding source for additive manufacturing of prototype parts mostly with filler wire of 1.2 mm diameter and current ranges from 110A-180A which resulted in wall thickness of 3.5 mm to 8 mm in the produced parts [4][6][7][8]. The aim of this work is to develop a TIG welding based additive manufacturing process which is capable of producing thin-walled structures with improved geometrical and mechanical properties. Many of the researchers studied the mechanical properties of the parts produced by welding based additive manufacturing process. The tensile strength, hardness, surface form properties and microstructure study have been discussed by them in elaborative manner [9]. Wang J. et. al. [10] have manufactured samples of Inconel 625 using Welding based additive manufacturing process. The mechanical properties and microstructure of deposited samples have been tested at different locations. The hardness and surface morphologies have also been investigated by many of the authors[11][12]. The study of the residual stress induced in the parts was done by only few of the authors in TIG welding based additive manufacturing process. Most of the authors studied residual stress induced on the surface of the deposited material and they found tensile residual stress in the components. The tensile residual stress reduces the fatigue life of the material. However, compressive residual stress increases the life span of the material [13]. Szost et. al. performed residual stress and microstructural analysis of parts produced by welding based additive manufacturing process. The metal undergoes though the heating and cooling cycles. Therefore the formation and relaxation of stress in the deposited material happened in simultaneous steps of deposition [14]. In another work authors measured the residual stresses through the thickness of the deposited weld beads in the thick steel sections. They have found different residual stress at different region in the deposited material [15]. Peddea S. et al. [16] investigated the residual stress induced along the surface of the thick welded steel section before and after heat treatment. This work focuses on study of residual stress induced in the deposited parts along its cross section. The geometrical accuracy has also been verified by measuring variation in the wall height and wall width.

2. Experimental study:

The experimental setup consists of ESAB TIG welding machine, customized metal deposition system having facility of holding wire feeding nozzle and TIG welding torch. The 2.4mm 2% thoriated Tungsten electrode has been used in TIG torch to form arc for melting the filler material. The wire of material ER706-S having diameter 1.2 mm has been used and fed to the metal deposition with the automatic wire feeding machine from the melting pool side. The composition of alloying elements in the wire material is as shown in table 1.

| Alloying materials | C | Mn | Si | P | S | Ni | Cr | Mo | V |
|-------------------|---|----|----|---|---|----|----|----|---|
| ER706-S (In %)     | 0.15 | 1.45 | 0.8 | 0.025 | 0.035 | 0.15 | 0.15 | 0.03 | Max | Max | Max | Max | Max |

Table. 1 Composition of elements in Filler material
The mild steel plate of 4 mm thickness was used as substrate material. The metal deposition system is having movement in X, Y and Z direction (Ref. Fig.1). The substrate mounting platform is having movement in X and Y direction however, Z axis movement has been given to the torch and wire feeding nozzle holding fixture. The table movement along X-direction has been automated and controlled by programable logical controller. The start and termination of the deposition process has been synchronized with help of the inductive proximity sensors mounted near to the table at respective start and end positions.

![Fig.1 Experimental setup for TIG welding based Additive Manufacturing](image)

The experimentation has been performed to analyze the geometrical properties and residual stress induced in the structure. The novelty of the process has been studied by depositing single weld beads. The process parameter condition has been selected based on these single bead experiments for the deposition of thin walled structures having minimum thickness. After performing these single bead experiments values of TIG welding Process parameters have been identified which are as given in the table 2.

| Sr. No. | Process Parameters                      | Set Value of Process Parameters |
|---------|----------------------------------------|---------------------------------|
| 1.      | Current                                | 65A                             |
| 2.      | Torch Movement Velocity                 | 3 cm/min.                       |
| 3.      | Wire feeding speed                      | 0.8m/min.                       |
| 4.      | Voltage                                | 18V                             |
| 5.      | Arc Gap (Electrode to substrate distance)| 2 mm                            |
| 6.      | Flow rate of Shielding gas              | 7 lit/min.                      |
| 7.      | Shielding Gas                          | Argon (100%)                    |
| 8.      | Substrate plate thickness               | 4 mm                            |

Many of the researchers used the higher current range and arc gap for the metal deposition. They have used current ranges from 110A-180A and arc gap of 4mm-8mm, which resulted in wall thickness in the range of 3.5 mm – 8mm. In this study the current range and arc gap has been set to 65A and 2mm respectively to get metallic structures having thinner wall of nearly 3mm with precise geometrical properties and improved mechanical properties.
3. Results and Discussion:

3.1. Measurement of wall width and wall height for Geometrical accuracy: As discussed in previous section a heat source is generated between non-consumable tungsten electrode and the substrate with the help of ESAB TIG welding machine. The material deposited with process parameter conditions given in table. 2 have been measured for deposition height and deposition width. The Celestron digital microscope has been used with magnification of 21X after calibration. The surface form properties have also been examined visually. The surface appearance of the deposition width and deposition height is as shown in fig. 2(a) and Fig. 2(b) respectively. The average wall width of 2.947mm and average wall height of 2.767 mm has been achieved in this work.

The geometrical properties have been tested in terms of variation in the wall width and wall height throughout the deposition. The wall width and wall height has been measured throughout the length of deposition. Five set of measurements for deposition height and width have been taken for the verification of the process. The measurements have been taken at points spaced at 10 mm from each other. The variation in the Deposition width and deposition height is as shown in fig. 3 and Fig. 4 respectively.

It can be seen from the Fig. 3 and Fig. 4 the variation in the deposition height is more than variation in the deposition width of the manufactured thin walled structure. The variation in the height has been caused due to the flow of molten metal on the narrow region of deposition width. The variation in the deposition height lies within 0.080 mm for first four layers however, this error will goes on increasing. The variation in the deposition height has minor effect for producing structures having less number of layers. This issue should be eliminated by deploying more precise control system for controlling heat input at start and end of the deposition. The variation in the width also showing same trend at start and the end of the process but variation lies within 0.015 mm which was lower than variation in the height of deposition. The width also has small variation at the start and end of the deposition. The variation in the wall thickness lies within the DIN standard 1685(± 0.10 mm for measuring thickness less than 25mm) for the casting processes.
The cut section view of the deposited structure is as shown in fig.5. The effective area which we can actually get for functional use is also identified in the fig.5. The effective wall width of 2.947 mm will be achieved from actually deposited wall width of 3.024 mm after performing minor machining operation of 0.2 to 0.3 mm.

3.2. Study on induced Residual stresses: The residual stresses are stresses trapped inside the components. The phase transformation of the material plays important role in the formation of residual stresses in the part. The residual stress induced in the parts should be less than the elastic limit of the component. There are two types of residual stresses. It should be compressive residual stress or tensile residual stress depends on the locality in the welded specimen. The structure produced in this work has been tested for examining residual stress induced. The X-ray Diffraction method has been used for this study. The sample has been analysed by Panalytical - XRD machine at National facility of Texture and OIM, IIT Bombay, India. The samples have been verified for the residual stress through its thickness. The residual stress at two points has been evaluated. The stress developed in the single weld bead and interfacing layers may differ from each other. For verification of this circumstance the first point was selected at the interface of the two layers and another point was at the centre of the layer. The compressive residual stress has been observed along the thickness of deposited material. The compressive residual stress of -122 MPa and -133 MPa has been observed at the respective points. The residual stress at the interface of two layers was found more compressive than the point chosen at the centre of the layer. The points at which the residual stress has been analysed are as shown in fig.6.
Fig. 6 Points on the deposited material for measurement of residual stress.

The metal deposition has been performed at current of 65A with constant voltage of 20V which may be considered as low energy heat source. This type of low energy heat source results in the lower metal transformation temperature which leads to the formation of compressive residual stresses in the material deposited through welding based metal deposition process[17][18]. Another reason behind the induced compressive residual stress could be solid state phase transformation in the solidification process. The deposited metal may go through heating and cooling cycle after depositing each and every layer in the deposition. This will cause the non-uniform relaxation and redistribution of the residual stresses in the deposited surface. As per the study done by Paddea S. et al [16] the non-uniform heating cycle of solidified deposited layer and molten metal which is going to get solidified after some time leads to the thermal compression in the deposition. The partially solidified material in the previous layer has the temperature nearer to austenitic temperature. However, the molten metal has gone through Austenitizing as its surface having temperature more than austenitic phase temperature, So that material is having lower or compressive residual stress after it comes to room temperature [16][19][15]. The contraction of the thermal strains generated at the time of cooling and solidification cycle may also leads to the evolution of the compressive residual stress.

4. Conclusion:

The TIG welding based metal deposition system has been designed and developed for producing thin walled metallic structures having average wall thickness nearer to 3 mm. The wall thickness reported in this study was found smaller as compared to the similar work using filler wire of 1.2 mm for TIG welding based metal deposition. The average wall width and wall height of 2.947 mm and 2.767 mm has been achieved in this work for four layered structure. The geometrical accuracy in wall width has been achieved with minimum variation of 0.015 mm (Standard deviation=0.007) but work on controlling flow ability of the molten metal at start and end position of deposition needs to be done to avoid the variation in the deposition height which has variation lies between 0.080 mm (standard deviation=0.0299). The observed variation in the wall thickness lies within the DIN standard 1685(± 0.10 mm for measuring thickness less than 25mm) for the casting processes. The compressive residual stress was found in the deposited structures due to the change of phase in the solid state phase transformation. The tensile residual stresses lead to fatigue failure of the structures. However, this study significantly reported a compressive residual stress which is considered to increase the life of the structure.
References:

[1] Spencer DJ, Dickens PM W C 1998 Rapid prototyping of metal parts by three dimensional welding *Mech. E. J. Eng. Manuf.* 212 175–82

[2] Silva R J, Barbosa G F and Carvalho J 2015 Additive manufacturing of metal parts by welding *IFAC-PapersOnLine* 28 2318–22

[3] Cunningham C R, Wikshåland S, Xu F, Kemakolam N, Shokrani A, Dhokia V and Newman S T 2017 Cost Modelling and Sensitivity Analysis of Wire and Arc Additive Manufacturing *Procedia Manuf.* 11 650–7

[4] Zhang Y M, Li P, Chen Y and Male A T 2002 Automated system for welding-based rapid prototyping *Mechatronics* 12 37–53

[5] Zhang Y M, Chen Y, Li P and Male a. T 2003 Weld deposition based rapid prototyping: a preliminary study *J. Mater. Process. Technol.* 135 347–357

[6] Wang H, Jiang W, Ouyang J and Kovacevic R 2004 Rapid prototyping of 4043 Al-alloy parts by VP-GTAW *J. Mater. Process. Technol.* 148 93–102

[7] Bonaccorso F, Cantelli L and Muscato G 2011 Arc welding control for Shaped Metal Deposition process *IFAC Proc. Vol.* 18 11636–41

[8] Olivares E A G and Díaz V M V 2018 Study of the hot-wire TIG process with AISI-316L filler material, analysing the effect of magnetic arc blow on the dilution of the weld bead *Weld. Int.* 32 139–48

[9] Yang D, He C and Zhang G 2016 Forming characteristics of thin-wall steel parts by double electrode GMAW based additive manufacturing *J. Mater. Process. Technol.* 227 153–60

[10] Wang J F, Sun Q J, Wang H, Liu J P and Feng J C 2016 Effect of location on microstructural and mechanical properties of additive layer manufactured Inconel 625 using gas tungsten arc welding *Mater. Sci. Eng. A* 676 395–405

[11] Lu X, Zhou Y F, Xing X L, Shao L Y, Yang Q X and Gao S Y 2017 Open-source wire and arc additive manufacturing system: formability, microstructures, and mechanical properties *Int. J. Adv. Manuf. Technol.* 93 2145–54

[12] Suryakumar S, Karunakaran K P, Chandrasekhar U and Somashekara M A 2013 A study of the mechanical properties of objects built through weld-deposition *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.* 227 1138–47

[13] Morikage Y, Igi S, Oi K, Jo Y, Murakami K and Gotoh K 2015 Effect of Compressive Residual Stress on Fatigue Crack Propagation *Proceedia Eng.* 130 1057–65

[14] Szost B A, Martina F, Boisselier D, Pryptuliac A, Pirling T, Hofmann M, Jarvis D J, Terzi S, Martina F, Boisselier D, Pryptuliac A, Pirling T, Hofmann M and Jarvis D J 2016 A comparative study of additive manufacturing techniques: Residual stress and microstructural analysis of CLAD and WAAM printed Ti – 6Al – 4V components *Mater. Des.* 89 559–67

[15] Smith D J, Bouchard P J and George D 2000 Measurement and prediction of residual stresses in thick-section steel welds *J. Strain Anal. Eng. Des.* 35 287–305

[16] Paddea S, Francis J A, Paradowska A M, Bouchard P J and Shibli I A 2012 Residual stress distributions in a P91 steel-pipe girth weld before and after post weld heat treatment *Mater. Sci. Eng. A* 534 663–72

[17] Kannengiesser T, Komizo Y I, Babu S S and Ramirez A J 2010 In-situ studies with photons, neutrons and electrons scattering *In-situ Stud. with Photons, Neutrons Electrons Scatt.* 1–204

[18] Reynolds A P, Tang W, Gnaupel-Herold T and Prask H 2003 Structure, properties, and residual stress of 304L stainless steel friction stir welds *Scr. Mater.* 48 1289–94

[19] Nasir N S M, Razab M K A A, Mamat S and Ahmad M I 2016 Review on Welding Residual Stress *ARPN J. Eng. Appl. Sci.* 11 6166–75