Defect Identification in Weld Beads of Aluminium 5356 Using Liquid Penetrant Test

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Abstract. In this paper work, gas metal arc welding process was used to form weld bead. Aluminium (Al) 6082 acts as base plate and the Aluminium 5356 alloy acts as filler material. Argon (99.99%) is used as inert gas. The process parameters used in this research work were current (Ampere), stick-out distance (mm), and travel speed (mm/s). Nine beads were welded using an L9 orthogonal array. The optimal parameter was identified by using the Liquid Penetrant Test (LPT) method and also weld defects were identified. The zig-zag tool path strategy is used as it reduces thermal distortion and residual stress caused during welding which can be used for future research work. The first three samples and last two samples show the weld defect like undercut. The remaining beads exhibited with excess weld bead. The sixth bead has no defect. The process parameters value like current (120 Amp), stick-out distance (12 mm) and travel speed (3 mm/s) were chosen based on LPT and weld bead quality. Thus, it was chosen as the ideal bead in this current study. These parameter values can be used to produce multiwall-layered structure using WAAM, for Al 5356 alloy. A multiwall-layered structure can be built using WAAM (wire arc additive manufacturing) technique as it has acquired more recognition because of its increase in efficiency and ability to weld big components in a lesser time.

Keywords: Gas metal arc welding, Aluminium 5356 alloy, L9 orthogonal array, Liquid penetrant test.

1. Introduction

Gas metal arc welding is known for its high welding speeds and deposition rates which make it suitable for industrial applications where there is a demand for high productivity. The efficiency can also be increased with the help of automation which can be done in GMAW; thus, labor cost can also be reduced. With the help of GMAW non-ferrous materials can be additively manufactured which makes it versatile. The continuous wire feeding system in GMAW ensures a consistent arc and minimizes the need for frequent starts and stops, contributing to a smooth and uniform weld. GMAW can be used in various welding positions. This flexibility allows for welding in different orientations, making it adaptable to diverse project requirements. The process typically produces clean and slag-free welds, reducing the need for extensive post-weld cleanup. This is especially beneficial in applications where the appearance of the weld is important. Theo et al. [1] explore the effectiveness of additive manufacturing, specifically for Aluminium alloys to create intricate geometries and repairing parts. In this research paper, they have used Aluminium 4943 and 6061 for welding. Samples were built and cut in transverse and longitudinal directions for testing. From the results, mechanical properties for aluminum 6082 were better when compared with 4943. Kumar et al.

ICAMDMS 2024, February 23-24, Coimbatore, India
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DOI 10.4108/eai.23-2-2024.2347024

[2] investigate the effects of various AC waveforms on wall properties in additive manufacturing, finding that the triangular waveform, with its highest height-to-width ratio. The study reveals distinct grain structures and shows that the hardness and wear properties of walls are influenced by the cooling rates associated with each waveform. Jay et al. [3] studied about the gas metal arc welding based additive manufacturing. From the results it was seen that appropriate bond was formed between layers. There was complete fusion between the layers without any oxidation and it was free from defects. The GMAW based welding showed good mechanical properties. Also, the structure built using GMAW matches the standards for applications in industries. Mukti et al. [4] provide a comprehensive review of the evolution and focus on its application to non-ferrous materials. The analysis covers key aspects such as applications, methods, process parameter control, optimization strategies, and limitations, with an emphasis on understanding the mechanical and metallurgical behavior of materials. Tawfik et al. [5] explore wire + arc additive manufacturing for depositing Al-Mg aluminum alloy thin-wall components, varying heat input through different travel speeds. Alloys deposited at 500 mm/min exhibit improved microstructure, reduced defects, and enhanced mechanical properties. It also says that metal transfer has four modes: globular, spray, short-circuiting and pulsed-spray. Each metal transfer mode has unique features which is the power supply, the type of electrode used and welding equipment. Ajeet et al. [6] studied the non-destructive (NDT) testing methods to evaluate the defects of the weld beads. Defects that are six mm from the surface are tested using liquid penetrant test (LPT). The time taken for liquid penetrant test (LPT) is less when compared to other tests. Tawfik et al. [7] address challenges in applying Wire Arc Additive Manufacturing to aluminum alloys, aiming to guide future research in overcoming limitations. They comprehensively review relevant studies to highlight diverse strategies for improving the mechanical properties of aluminum components, emphasizing the efficacy of various techniques in tailoring microstructural features and enhancing mechanical performance. Shukla et al. [8] investigate welding arc behavior utilizing a cold metal transfer power source to build a ten-layer wall. Real-time data, including welding current, voltage, thermal cycles, and synchronized high-speed arc images, indicates a gradual increase in peak temperature up to the fifth layer, followed by a decrease, with the welding arc intensity highest during the boost phase of the cold metal transfer cycle, impacting the consistency of the deposited bead profile. Bintao et al. [9] reviews the emerging techniques, metallic feedstock materials, metallurgical properties, and common defects in additive manufactured components, concluding that while advancements have been made, challenges persist, necessitating material-specific approaches to achieve defect-free and structurally sound deposited parts in operational systems. They also framed a quality-based framework where the process selection for GMAW and optimization of process parameters has been specified. Mariacira et al. [10] explore optimal process parameters for producing metal parts. The study varies feed rate and heat input during weld bead deposition. Also, parts which were deposited using GMAW almost showed no defects like spatter cracks and very low amount of porosity were identified. These are the common defects that usually arise when Aluminim alloys are welded. Despite varied parameters, minimal differences are observed, revealing a microstructure evolution from pearlitic-ferritic grains to bainitic lamellae along the vertical direction in the samples. The bead width gradually increases from the first to the fourth layer and remains consistent from the fifth to the tenth layer. Thus, there is a significant need for the study of Aluminium 5356 alloys fabricated using Zig-zag type tool path strategy in wire arc additive manufacturing. The objectives of this work are to use the three parameters like current (ampere), stick-out distance (mm) and travel speed (mm/s) for DOE. Using L9 taguchi method, nine beads are welded. The beads are to be tested with liquid penetrant test (LPT) to check for defects and the optimum

process parameters can be used for building a multi-wall structure.

2. Experimental Setup

2.1.Selection of workpiece material

The selection of workpiece material directly influences the properties and application of the fabricated component. It acts as a base metal where an electric arc is passed and wire is melted layer-by-layer to deposit the workpiece, thereby building a three-dimensional object. The workpiece should be weldable and capable of forming a strong bond between the substrate and filler wire. For this paper, Aluminium 6082 is selected as the substrate. The dimensions of the Aluminium 6082 substrate are 30mm x 150mm x 15mm. The nominal composition of the workpiece material meets the ASTM E-1251 standard, as reported in Table.1.

Table.1 Chemical composition analysis of the base plate Aluminium 6082 alloy

Composition	Si	Fe	Cu	Mn	Mg	Zn	Cr	Ti	Others	Al
Percentage (%)	0.72	0.21	0.27	0.08	0.95	0.001	0.1	0.03	0.1	97.55

2.2. Selection of welding process

Primary selection in welding depends on the type of weld. There are three types of welds depending on the heat generation. They are GMAW (gas metal arc welding), GTAW (gas tungsten arc welding), and PAW (plasma arc welding). GTAW does not consume electrodes for deposition of the material; it requires a filler rod whereas in GMAW electrode becomes the filler rod and is used for deposition. The type of welding process selected for this paper is Gas metal arc welding. GMAW has higher deposition rates in a short amount of time, allowing faster welding speeds. The type of inert gas used in this research work is 99.9% pure argon (99.99%) [2]. The deposition rate for GMAW is 3-4 kg/hr [4]. This results in increased productivity, increased efficiency, and faster completion of welding tasks and makes it suitable for high-volume production.

2.3. Selection of filler material

The selection of filler wire in wire arc additive manufacturing plays a crucial role. The primary role of the filler wire is to build up parts layer by layer. As the electric arc melts the material, molten metal is deposited onto the substrate and then deposited on the previous layer, thus forming a three-dimensional structure. The filler wire is chosen based on the requirements of the application of the final component. This can be particularly important in applications where strength, durability, or other mechanical characteristics are critical. The use of filler material reduces the thermal stress and minimizes distortion during additive manufacturing. The filler material selected for this paper is Aluminium 5356. The dimensions of Aluminium 5356 filler wire diameter is 1.2 mm. The nominal composition of the filler wire meets the ASTM E-1251 standard, as reported in Table 2.

Table. 2. Chemical composition of Aluminium 5356 alloy

Composition	Si	Fe	Cu	Mn	Mg	Zn	Pb	Ni	Sn	Ti	Al
Percentage (%)	0.05	0.17	0.01	0.11	4.77	0.001	0.002	0.004	0.001	0.13	94.55

3. Selection of process parameters

A 100% pure Argon gas was provided at a flow rate of 15 l/min [Ref. 9]. From iterative trials as shown in table.3, the process variables for deposition were selected. A dwell time of 120 second was considered between successive layer depositions. It is essential to know the characteristics of the material. Process parameters selected for fabrication are current which is measured in ampere, stick-out distance in mm and travel speed measured in mm/s, whereas additively deposited layer bead width and height (aspect ratio) is taken as output response. The levels of the process parameters that were used in this research paper are shown in table.3.

Table.3. Process parameters and its levels (ref.11)

S.No	Process Parameters	Units	Symbols	Levels		
				I	II	III
1	Current	Ampere	A	80	100	120
2	Stick-out distance	mm	B	10	12	14
3	Travel speed	mm/s	C	3	4	5

Taguchi Method is mainly used to improve the quality and performance of products and processes by systematically identifying the optimal settings for various factors while minimizing variability and sensitivity to external factors. Taguchi is a unique technique found by the Japanese engineer “Genichi Taguchi”. Taguchi Method often employs orthogonal arrays, which are matrices designed to sample the parameter space efficiently. In this research work L9 orthogonal array is employed which is briefed in Table 4, where ‘L’ denotes a particular category of orthogonal arrays and ‘9’ indicates the number of trial experiment in the design. These arrays allow for a systematic and organized exploration of the factor levels and their interactions. In taguchi Method, factors are the variables that can influence the output or performance of a system. Each factor is tested at different levels to understand its impact on the overall performance.

Table. 4. Doe using l9 orthogonal array (ref.11)

Sample	Current (A)	Stick-out distance (mm)	Travel speed (mm/s)
1	80	10	3
2	100	10	4
3	120	10	5
4	80	12	4
5	100	12	5
6	120	12	3
7	80	14	5
8	100	14	3
9	120	14	4

From the data gathered in the Table 4, it can be inferred that the aspect ratio is better in sixth sample when compared to other samples.

4. Experimental setup

The software tailored for the FANUC Arc Mate 100iC/12 welding robot is the R-30iB/R-30iB software. Its primary purpose is to facilitate the execution of intricate welding tasks with a high level of precision and repeatability. Illustrated in Figure 1, the FANUC Arc Mate 100iC/12 is outfitted with the Fronius TPS 400i Inverter Power Source for welding. This power source excels in delivering welds of superior quality, characterized by less spatter and good penetration. The robot's control and movement are done by the Arc Mate 100iC/12. These units control the six axes of the robot's arm, ensuring seamless and accurate motion. Consequently, the robot achieves high-speed and precise movements, leading to effective and efficient welding operations. Noteworthy accessories augment the robot's capabilities. For instance, the oscillation facility permits the execution of oscillating welds, enhancing the strength and durability of the welds. Precise and clean welds are obtained due to wire snipping feature in the robot. Moreover, the torch cleaning mechanism guarantees the pureness of the welding torch, preventing the introduction of contaminants that could compromise weld quality. The robot is also designed with the flexibility to incorporate additional sensors, facilitating integration and customization to sense the advanced technologies. Overall, these features collectively empower welding robot to deliver optimal performance in diverse welding applications.

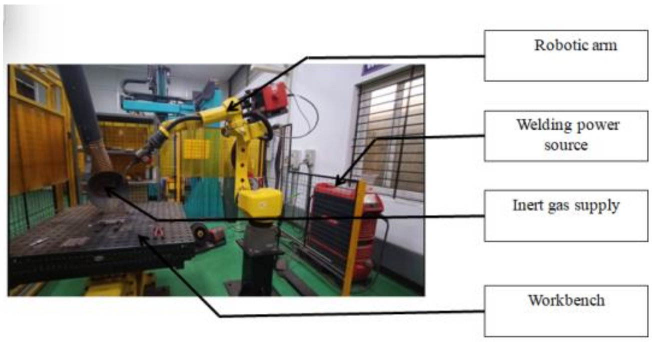


Fig. 1 FANUC - welding robot

5. Liquid penetrant test

The LPT is a nondestructive testing (NDT) method used to detect surface defects on materials, especially those that are non-porous. NDT’s analysis techniques are used to check the properties of materials without causing distruction to the sample. They have various applications in construction industries, marine industry, shipbuilding, aircraft engine parts, automotive industry and more. The utilization of a viscous fluid to examine materials characterizes liquid penetrant testing as one of the non-destructive testing (NDT) methods. The procedures outlined in the liquid penetrant test are depicted in Figure 2.

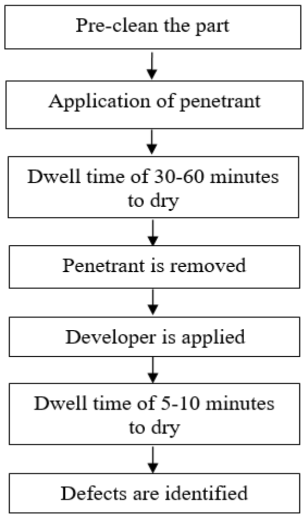


Fig. 2. Procedure followed in LPT

The liquid penetrant test was carried out using ASTM E165 standard. Using a cleaning solution, the base plate was cleaned. The cleaning was done to remove the dust particles that are present in the surface which might cause deviations in the result due to contaminants. Penetrant was put on the surface of the component which was to be tested for defects. A dwell time of 30 minutes to 60 minutes was given for the penetrant to absorb in the plate and then dry. This allows the defect to be easily identified [7]. Developer was applied to the surface after it dried. A dwell time of 5 minutes to 10 minutes was given for the surface to dry and then the defects are identified [7].

6. Results and Discussion

The material used in this research is Aluminium 5356 which has a good weldability. Thus, Aluminium 5356 was chosen as the main material which serves as of filler rod. The base metal selected for this research paper was Aluminium 6082 which has good yield strength and tensile strength. Gas metal arc welding was used in this research work as it reduces the defects caused in the weld like spatter and other defects. The parameters considered are current, stick-out distance and travel speed. The nine bead samples were built and it is shown in Figure 3.

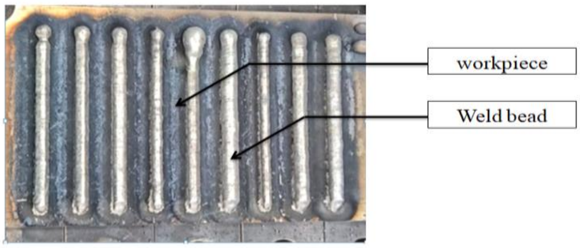
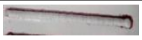


Fig. 3. Welded specimen based on L9 array

In the welded samples, it found with excess deposition and undercut as weld defects, which will cause the bead to have lack of strength and infusion when a product is build using these parameters.

Table. 5. Weld defects identified in weld bead for (L_9) array

Sample	Current (Ampere)	Stick out distance (mm)	Travel speed (mm/s)	Samples	Weld Defect identified in each weld bead
1	80	10	3		Undercut
2	100	10	4		Undercut
3	120	10	5		Undercut
4	80	12	4		Excess deposition
5	100	12	5		Excess deposition
6	120	12	3		No defect
7	80	14	5		Excess weld bead
8	100	14	3		Undercut
9	120	14	4		Undercut

Using these parameters nine beads was welded. Using L9 Taguchi, the nine beads were built on a base plate which was then subjected to penetrant test. The LPT was used for testing of defects like over deposition, undercut and surface lack of fusion in the weld beads. First the surface of the welded base plate was cleaned using a cleaning agent. The base plate is cleaned to avoid the dust particles which might affect the results. A penetrant is sprayed on the base plate after cleaning. This is done so that the penetrant can seep through the holes and cracks present on the surface. The penetrant is allowed to dry. The penetrant will dry in about 20 min depending on the surrounding temperature. [ref 7] Then the developer is applied on the base plate after removing the penetrant. The developer is allowed to dry. The developer will dry after 40 min from the application time. The developer is applied so that the defects can be seen to the naked eye. As shown in Fig 4. LPT test was done for the nine weld beads. The first sample showed undercut as the current and travel speed is very less, also excess deposition can be seen in the weld bead. The second sample also exhibits undercut. The third sample exhibits undercut where the current and travel speed is more. The fourth and fifth sample exhibits over deposition due to less current, increased stick-out distance with increased travel speed. The eighth and ninth sample exhibits undercut as the current supplied is more. The seventh sample shows over deposition as the stick-out distance and travel seed are more. The sixth sample has no defect as the current is more and travel speed is less. The current and travel speed is indirectly proportional to each other. Hence no defect is found in the sixth sample where the weld bead has good aspect ratio.

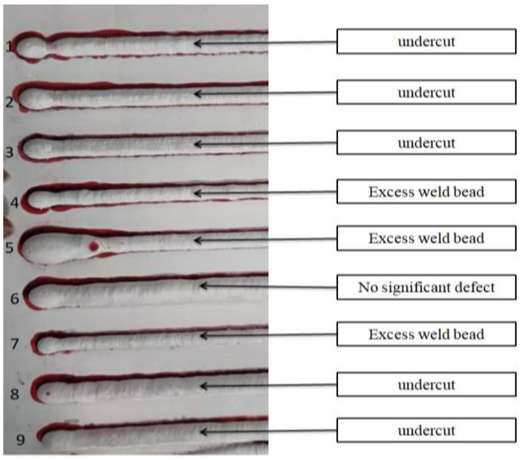


Fig. 4. Identified weld defectives of nine beads using LPT

7. Conclusion

From this research work, it is concluded from the liquid penetrant test that defects like undercut, lack of fusion, and excess deposition identified. The following research findings were also identified.

- From the experimental results, it is observed that the first, second, and third weld beads had undercut defects.
- The fourth, fifth, and seventh weld beads had excess deposition in the weld bead, and so their levels and factors also cannot be used as optimum parameters.
- The eighth and ninth weld beads showed undercut defects; thus, these parameters and their levels cannot be used as optimum. Also, these weld beads do not exhibit a good aspect ratio, which is necessary for a good weld bead.
- A weld bead with a good aspect ratio can have controlled heat input. Thus, the properties of the material to be welded can be altered by controlling the heat input according to the applications needed. By welding a bead with a better aspect ratio, the distortion in the weld bead can be reduced. Thus, the fusion between the layers of each weld bead can be better without any lack of fusion.
- The sixth weld bead showed no significant defect in the bead, which makes it suitable to choose as the optimal parameter. This weld bead had no defects like undercut, over deposition, or lack of fusion.
- Thus, the sixth sample's levels and their parameters were chosen with the optimum weld parameters values.
- The zig-zag tool path strategy can be used to build samples with a good aspect ratio. Thus, zig-zag tool path strategy which leads to good weld bead can be recommended to use these parameter and conditions for building multiwall layered structure using WAAM.

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