Repair and Validation of Gear by using Wire Arc Additive Manufacturing

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Abstract. This paper investigates the repair of damaged gear by using wire arc additive manufacturing. This study focuses on AISI 4340 type gear which is repaired. Single track depositions were used to identify the optimized parameter. The quality of single beads are affected by wire feed rate, current and voltage. The single beads were tested visually, tensile testing and SEM analysis. The AISI 4340 gear has a strength of 900 MPa [4]. The optimized bead has 690 MPa (75% of the original gear) from the tensile testing and the bead has shown no sign of cracks and presence of Micro-void coalescence in traces. The damaged part in the gear was rebuilded in the optimized parameter. Then wire cut EDM and grinding operation were done on the rebuilded part in order to get the original geometry [5]. For validation a gear test rig was used to find the performance of gear under various loading conditions wear analysis.

Keywords: Wire Arc Additive Manufacturing; Gear; Test rig; AISI 4340

1 Introduction

A gear is a type of rotating component that is commonly used to transmit power or change the direction of motion by meshing with another toothed element. The right material choice, the right heat treatment method, the design and production quality, the working environment, and other factors all affect how long gears last. The mechanical characteristics of the equipment will be impacted by several forms of problems that arise from improper routine inspection and maintenance. When it happens, the damaged gear is often destroyed and replaced with a new one. However, it is not an economical and environmentally friendly solution [2]. Metal 3D printing, another name for additive manufacturing, has been a game-changer in the field of contemporary manufacturing. The ability of metal additive manufacturing to create highly customized, geometrically complicated items that would be difficult or impossible to fabricate is one of its main advantages through traditional methods. The layer-by-layer approach allows for precise control over the final product's geometry and enables the production of intricate structures with superior mechanical properties.

Wire Arc Additive Manufacturing is an evolving technology with the potential to revolutionize metal part production in various industries. Its cost-effectiveness, versatility and the ability to produce near-net-shape parts make it an attractive option for manufacturers seeking to

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streamline their production processes and develop innovative designs. Wire Arc Additive Manufacturing (WAAM) is an advanced 3D printing technique that employs electric arc welding to deposit metal layers systematically. By precisely melting and fusing metal wire, WAAM creates fully functional components layer by layer, allowing for complex geometries to be built with high accuracy and integrity. This process offers numerous advantages over traditional manufacturing methods, making it an ideal choice for repairing broken gears. The layer-by-layer deposition is done using 'Fanuc Robot Arc mate 100iC/12 robot (Figure 1).

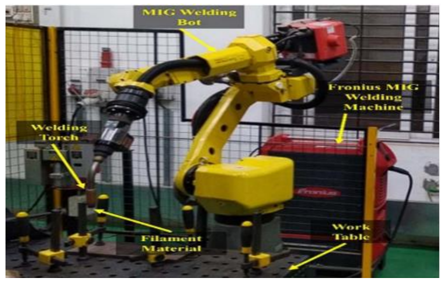

Figure 1. Fanuc Robot Arc mate 100iC/12'robot (Devendran. and Varthanan, 2021)

The machine provides the heat source for melting the wire and the robotic arm controls the movement of the deposition head. The deposition head is responsible for depositing the molten wire onto the substrate. The machine uses a fuzzy system for welding. For remanufacturing the broken gear is checked for feasibility and the best single-track deposition will be the input parameters for the remanufacturing of the gear. The single beads are affected by parameters like current, wire feed rate and voltage. Testing of the beads includes tensile testing, SEM analysis. Tensile testing can be done by cutting the specimen in the desired geometry and analyzing the UTS (Ultimate Tensile Strength) of the specimen. SEM analysis helps us to know about the microstructure of the repaired specimen. The optimal bead is the bead which has no internal cracks in it and very little Micro-void coalescence and sufficient tensile strength. Then the gear material is deposited layer by layer in the broken part of the gear.

2 Material

The damaged gear is shown in figure 2. The high strength alloy steel AISI 4340 contains carbon, nickel, chromium and molybdenum [3]. ER 70S is made into 1.2mm diameter wire and a substrate in which the single beads were deposited. The sub0strate plate is of dimension 150 x 200 x 10 mm. Nine single tracks were deposited on the substrate plate which is further used for finding the optimized parameter. The chemical composition of AISI 4340 substrate is shown in table.1.

Figure 2. Damaged gear

Table.1 Chemical composition of wire and substrate [3]

Ni	Mn	S	Si	Cr	P	C	Fe
1.8	0.70	0.04	0.25	0.8	0.035	0.41	Bal

2.1-Machine tool and deposition

Welding operation decides the quality of product standards in all metal work products like automobiles, aerospace vehicles, and many more. The quality of the welding process is more reliable by automating the process with robots [1]. Fanuc Robot Arc mate 100iC/12 robot is the machine tool which was used for the deposition of single beads in the substrate. Nine single beads were deposited on the substrate by varying the parameters like current, wire feed rate and voltage. Taguchi's design of experiment was used to find the combination of the nine different beads for experimentation. L9 orthogonal arrays were used for the experimental matrix. The experimental matrix is shown in table 2. Two fundamental methods were considered the zig zag track and the single bead technique (shown in Figure 3).

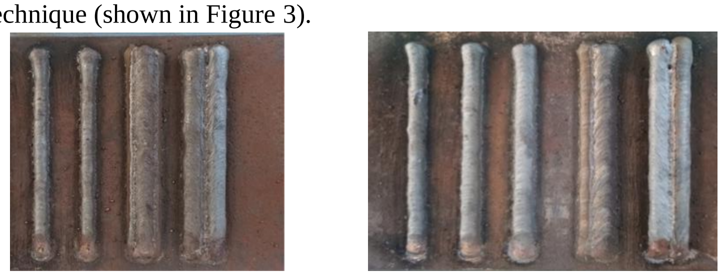

Figure 3. Single track deposition on substrate

Table 2 L9 orthogonal array for parameter optimization

Experiment No	Voltage (V)	Current (A)	Travel speed(mm/sec)	spatter	overlap	class
1	19.6	140	3	*	o	Normal
2	19.6	160	4	*	*	Bad
3	19.6	180	5	o	o	Bad
4	19.8	140	3	o	*	Normal
5	20.3	140	3	*	*	Bad
6	19.8	180	5	o	Δ	Normal
7	**19.8**	**160**	**4**	*****	**Δ**	**Good**
8	20.3	160	4	o	Δ	Normal
9	20.3	180	5	*	o	Normal
Spatter	*	No spatter				
Nospatter	o	Spatter acquired				
Overlap	*	Not overlap				
Overlap	o	Fully overlap				
Overlap	Δ	Half overlap				

While the zig zag method exhibited superior strength and efficiency, the constraints of robotic arm movements made direct application challenging. Consequently, an initial application of two layers of the single bead method was employed to begin the process of filling the missed volume on the damaged gear.

2.2 Testing and characterization of beads

The specimens were investigated for cracks, air gaps and blow holes. The beads were visually investigated for any macroscopic cracks and quality of weld by visual inspection. The visually inspected beads were tested in a tensile testing machine. For the tensile testing the beads were cut by using wire cut EDM in standard tensile testing specimen dimensions. The tensile testing cut beads are shown in figure 4.

Figure 4. Specimen beads for tensile testing

SEM analysis is used in metals to know about the composition of the alloys, fracture surface of the metal, surface cracks and dimension measurements in micrometers and even in nanometer scales. The tensile test specimens were investigated for any microstructure cracks in it. The beads were cut into10 mm horizontally and less than 40mm vertically which is desired sample size for SEM analysis. The samples were cleaned using a chemical etching process.

3 Result and discussion

3.1 Bead characteristics

The beads deposited by the zig zag track (B01 and B05) had poor quality of weld and some tracks were irregular. In single bead deposition B02 and B03 exhibit swelling in some regions and valleys in some regions, which is called humping effect. Generally humping defects are caused due to low current. A deposited bead with a humping defect becomes a periodically undiluted and irregular surface of deposited tracks [6]. Length and width of beds were affected by travel speed. The increase of the printing speed leads to the decrease of width of the deposited layer. This is because faster travel speeds enhance the cooling rate but reduce the ratio of the temperature gradient to solidification growth [7]. Beads B04 and B09 showed unevenness which is an effect of higher wire feed speed. The increase of WFS increased the unevenness of the bead surface within the framework of a constant travel speed. The deposition height increased rapidly with the increase of WFS and there was also a slight increase in deposition width. Thus, WFS with constant travel speed results in an undercut defect which is undesired for an optimal bead

3.2 Ultimate Tensile Testing

Table 3 illustrates the tensile strength of beds tested in Instron 8801 tensile testing machine. Figure 6 illustrates the relationship between force and displacement. It was observed that sample 2 has the least tensile strength as the area covered by the bead is very less whereas sample 5 has maximum area. Thus sample 5 has highest tensile strength. Other samples had tensile strength that lies between tensile strengths of sample 2 and sample 5 (Figure5). Sample 4 had higher tensile stress at yield than sample 5 (Table 3). Figure 6 illustrates the stress vs strain relationship from sample 1 to 5. From figure 6 it is evident that sample 5 has the highest tensile strength and sample 2 has the least tensile strength. Thus, once again it is confirmed that sample 5 is the optimum bead for the repair process.

Table 3 Tensile strength of single beads

No	Tensile strength(MPa)	Maximum force (KN)	Modulus(MPa)	Tensile stress at Yield(MPa)	Tensile strain at yield(%)
1	626.20	49.97	51313.27	349.34	0.86
2	543.65	43.38	47886.21	302.79	0.81
3	598.04	47.72	49812.38	361.40	0.88
4	674.63	53.86	50496.21	387.34	0.95
5	690.25	55.08	50321.76	380.88	0.96

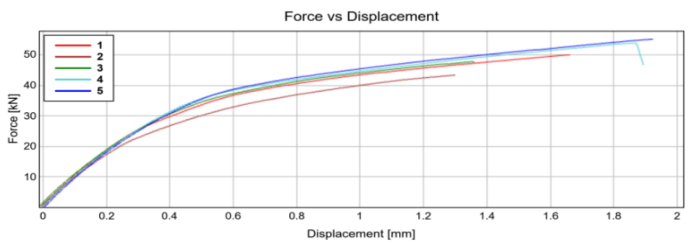

Figure 5. Force vs displacement graph

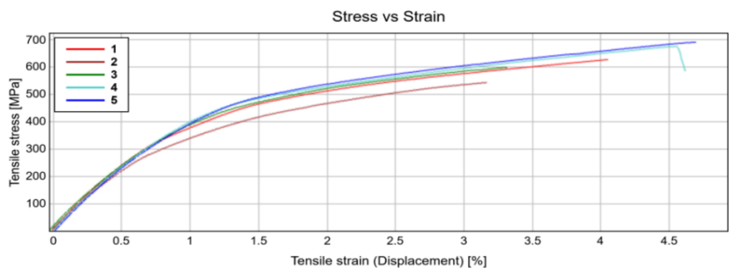

Figure 6. Stress vs Strain graph

3.3 Microstructure

Sample beads from the tensile test are tested for Micro-voids and internal cracks. Figure 7 shows the microstructure of gear in various magnifications. From figure 7 it can be depicted that the gear was subjected to cyclic loadings. But there are only a few traces of voids and cracks in the gear material.

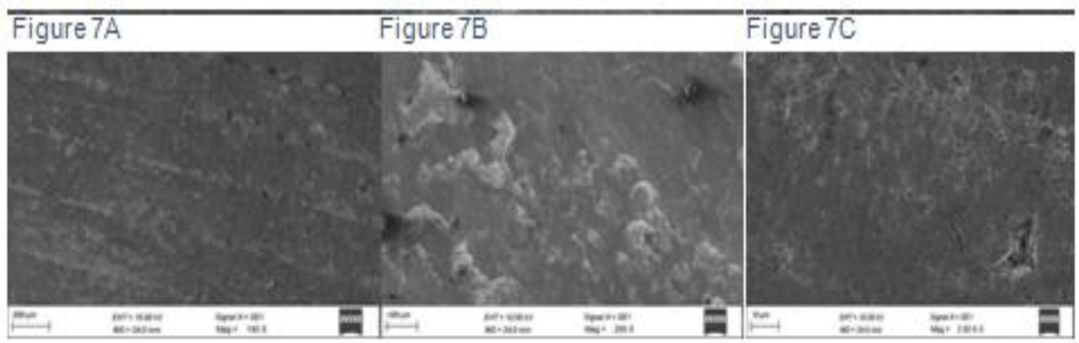

Figure 7. Microstructure of gear in A 150x, B 250x and C 2.50x magnification

From figure 8 in 40x magnification there is a crack in the bead and in 60x magnification the crack is even more evident. So, it is confirmed that there is an internal crack in bead B09 from figure 8. In 250x magnification there are voids in the microstructure of bead B09 (figure 8). Therefore, B09 is considered to be a defective bead.

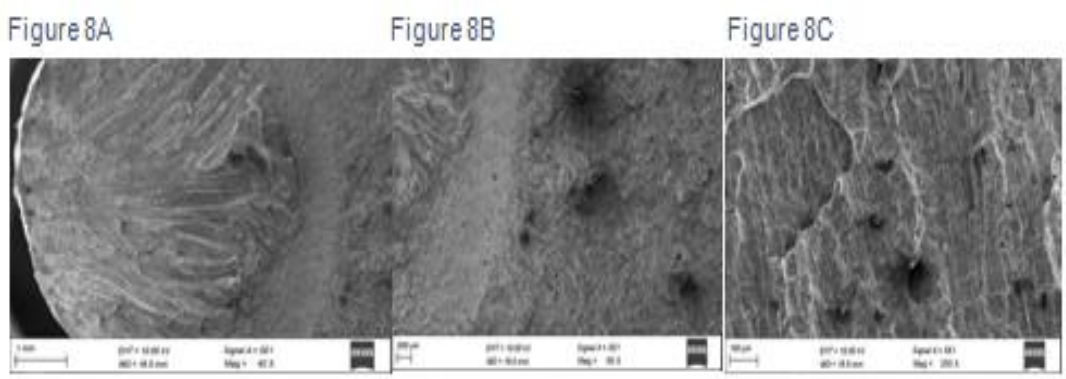

Figure 8. Microstructure of B09 in A. 40x, B. 60x and C 250x magnification

Figure 9 illustrates the microstructure of B08 in 60x, 100x and 250x magnifications. In 60x magnification (figure 9) there are many Micro-void coalescences and in 100x magnification the voids are even more evident. Micro-void coalescence is due to the ductile fracture of the material. But in 250x magnification (figure 9) there is an internal crack into the bead B08. B08 is also a defective bead.

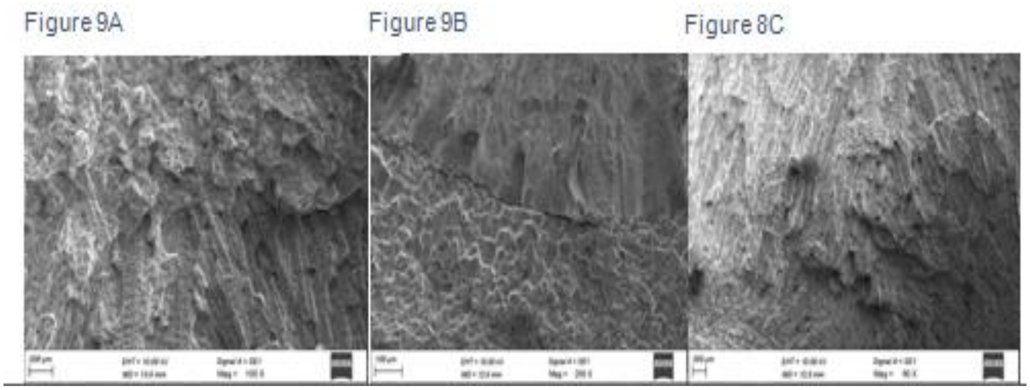

Figure 9. Microstructure of B08 in A 60x, B 100x and C 250x magnification

Figure 10 shows the microstructure of B07 in 50x, 100x and 250x magnifications. In 50x magnification there is no clear evidence of cracks in B07. Also, Micro-void coalescence presence is also very less which was better than the other beads. In 250x magnification there is no evidence any dimple structure formed due to the Micro-void coalescence. Hence B07 is considered to be the optimum bead as it doesn't have any internal cracks and its Micro-void coalescence does not affect the quality of the bead.

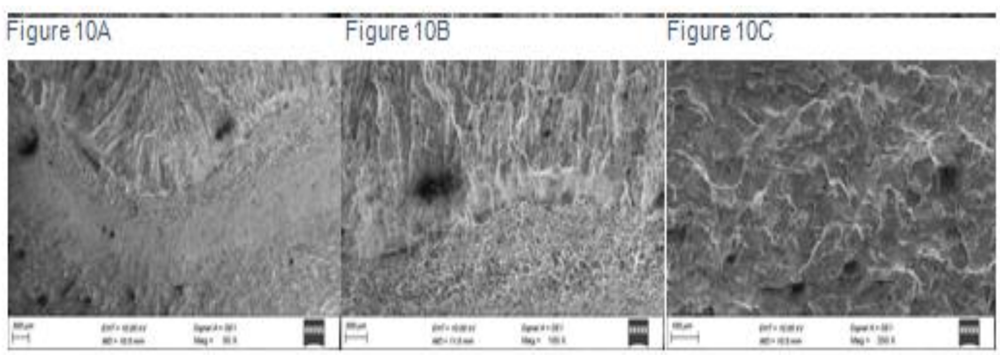

Figure 10. Microstructure of B07 in A 60x, B 100x and C 250x magnification

4 Repair, Post Processing and Validation

From the beads tested, bead B07 is the optimal bead as it has no cracks and only traces of Micro-void coalescence also have the maximum tensile strength. The optimal bead has parameters as **Current -180 I; Voltage -19.6V; travel speed-4 mm/sec.** The damaged gear is repaired [10] by the parameters of bead B07. The repaired gear is shown in figure 11. Wire EDM is used for post processing of the repaired gear as it has a significant position among production technologies mainly due to its capacity of machining hard materials and intricate shapes [9]. The repaired gear is validated by using a gear test rig.

Figure 11. Repaired gear by Wire arc additive manufacturing with B07 as desired parameter

The equipment is tested and put through its paces. The brake drum adds resistance as the motor spins it around, simulating the circumstances it will encounter in real operation. This aids in determining whether the equipment is robust enough to support the load without experiencing any issues. We closely monitor the equipment's performance, looking for any indications of problems or malfunctions. When everything works as it should and there are no problems, we may conclude that the gear was successfully repaired and is now fit for use. If the gear passes the functioning test with flying colours, we may exhale with relief. It indicates that the extensive efforts put into fixing it have been fruitful, and we can be confident that it will function dependably once it is operational again. Considering that it saves time and money instead of needing to replace the gear totally, this is a huge victory. Additionally, since we're not tossing away perfectly excellent gear and creating new ones from start, it's beneficial for the environment.

All things considered; the functionality test is an essential part of the gear repair procedure. The knowledge that the equipment is in good condition and prepared for use again provides us with piece of mind. We can also be certain that the equipment will function just as it did when it was brand-new because of the meticulous testing and attention to detail. Therefore, we can rely on any gearbig or smallto do its function without any problems, whether it's in a factory or a machine.as shown in figure 12 running of gear test rig.

Figure 12. Running of gear test rig

5 Conclusion

This article investigates the study on optimization of parameters for Wire Arc Additive Manufacturing of AISI 4340 gear and efforts to push WAAM as a repair technique for remanufacturing of damaged gears that are used in high volume applications such as aerospace, industry and automotive applications. The quality of beads is mainly affected by current, voltage and wire feed rate. An increased wire feed speed 5mm/sec resulted in humping effect and the 3mm/sec bead had very less head input. The beads with 4mm/sec had much lesser defects. Width of the beads in the deposition layer was reduced due to increased travel speed. Microstructure study revealed that Micro-void coalescence presence affects the internal structure of the beads. Micro-void coalescence is a characteristic which is responsible for ductile fracture of the bead. The bead with **Current -180 I; Voltage -19.6V; travel speed-4 mm/sec** is considered as optimum bead as it had almost 75% (690 MPa) of tensile strength of the AISI 4340 gear. The hardness of the repaired gear is 53HRC. The gear was repaired by using the parameter and Wire EDM and the grinding processes were done as post processing in order to get the original geometry of the gear. Hence it can be considered as a promising technology for the repair of damaged gears. The gear test rig is used for the functionality test. This study also leaves a scope for research as efforts to reduce air gaps during the process of layer-by-layer addition.

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