RESEARCH ON COMPUTATION, DESIGN, EXPERIMENTATION OF THE THIN PART MANUFACTURING PROCESS INTEGRATING 3D PRINTING AND ROLLING TECHNOLOGY

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DOI: http://doi.org/10.57001/huih5804.2024.170

ABSTRACT

In recent years, 3D printing technology has been rapidly developing and application in fabricating metal components. This technology has become increasingly prevalent. The research introduces a 3D printing device (AM) with an integrated material rolling mechanism, specifically designed for producing thin metal parts, and developed a manufacturing process of thin parts. The aim of this study is to enhance the quality of thin parts produced by using 3D printing technology. The authors primarily employed two research methods: theoretical analysis (covering 3D printing technology, material rolling, quality control measures, and production optimization) and experimental investigation (printing process of thin parts to evaluate and compare the quality). The research results have identified the most suitable 3D printing parameters for the best altitude. Furthermore, it has demonstrated a significant improvement in the quality of thin parts to conventional 3D printing methods.

Keywords: *AM; DED; 3D printing; Inventor 2023; Material rolling technology; Minitab16; WAAM.*

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Received: 22/8/2023
Revised: 17/10/2023
Accepted: 25/5/2024

SYMBOLS

I: Input current (A)

U: Input voltage (V)

S: The feed rate of the 3D printer nozzle (mm/s)

1. INTRODUCTION

Global competitiveness requires addressing a wide range of problems such as performance, cost, and environmental impact issues to create a viable product in the market. New processing methods or materials handling can open up novel product development opportunities for research leading to next-generation machines that improve product performance and costs, while minimizing environmental impact throughout the product life cycle [1].

In recent years, 3D printing technology has grown tremendously and become popular in the production of metal parts. In comparison with traditional methods, 3D printing technology features many outstanding advantages such as reducing production time, optimizing processe, and decreasing production costs. In particular, 3D printing technology also reduces waste materials that contributes to protecting our living environment.

However, there are still many challenges to apply the 3D printing technology to fabricating thin-walled parts, especially metal parts. The accuracy and durability of 3D printed parts can be affected in case of the manufacturing process is improper. Therefore, it crucially require a metal 3D printer that can be integrated with the rolling mechanism and the machining process optimization to enhance the quality of the final product.

It is described that the high-pressure rolling can also induce plastic deformation necessary to reduce residual stresses in welds. However, it is done with a continuous force rather than an sporadic force. When performed after welding, this method completely changed the residual stress distribution, and at the same time created a large compressive stress in the weld [2].

The main advantage of the rolling method is that it can cause plastic deformation over the entire cross-section of the weld, rather than just the surface. This more effectively counteracts welding-induced residual stress, reducing deformation of the welded part [3]. Studies on metal additive manufacturing found that large residual stresses exist deep within the deposition layers [4]. Therefore, rolling is a suitable method to change the stress in the WAAM component.

This paper focuses on the research and development of metal 3D printers with integrated rolling mechanism. The results hope that the development of 3D printing technology will be spead and applicated in variety of product especially in the production of thin-walled parts by metal materials.

2. RESEARCH METHOD

2.1. Theoretical research

2.1.1. Metal 3D printing technology

Metal 3D printing technology has many different types, but the general rule is to use a 3D printer to create metal parts by accreting metal layers in a pre-programmed manner.

One of the popular methods of metal 3D printing technology is Direct Energy Deposition (DED) [4], in which a metal material (wire or metal powder) is brought into a specific position by using a robot or a 3D printer. Then, an energy source such as an electric arc, laser, plasma, or electron beam will be used to melt the metal material. Next, the melt material will be accreted on the programmed positions. This process is repeated to create a thicker metal layer for the part [5].

Table 1 shows products with high precision, complex shapes, and large sizes that are created by the metal 3D printing technology. It also allows the use of different metals and increases production speed compared to traditional methods. However, the deposition rate of powder feeding technology is extremely low, usually around 10g/min, which limits its application in the production of large parts. Whereas the wire feeding method as shown in Fig. 1 has a speed of 330g/min for stainless steel and has a higher material efficiency with 100% material being fed which makes this method with more eco-friendly [6]. The coaxial wire feeding method (WAAM) will be selected in this study.

Table 1. The characteristics of some additive manufacturing methods [6]

Additive materials	Process	Layer thickness (µm)	Deposition rate (g/min)	Dimensional accuracy (mm)	Ref.
Powder	LC	N/A	1 - 30	±0.025 - ±0.069	[7]
	SLM	20 - 100	N/A	±0.04	[8, 9]
	SLS	75	~0.1	±0.05	[10]
	DLF	200	10	±0.13	[11]
Wire	WAAM	~1500	12	±0.2	[12]
	EBF	N/A	Up to 330	Low	[13]

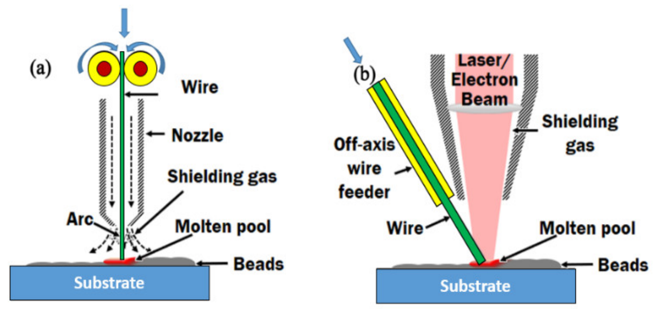

Fig. 1. The wire feeding methods of DED; (a) The coaxial wire feeding method (WAAM); (b) The off-axis wire feeding method (WLAM and WEAM) [5]

2.1.2. Materials

The metal rolling principle is the changing process of the shape of a metal material by applying a compressive force to the desired area. This process is accomplished by applying force to the material through a rolling shaft. As the material passes through the roll, its thickness decreases and its length increases.

The rolling process can be performed at various temperatures to give different properties to the metallic material. It can also be combined with other processes such as quenching or forging to produce metal products with mechanical and chemical properties that meet the required requirements.

The rolling process also creates high precision metal products and a smoother surface than other processes. Therefore, rolling technology is widely used in metal manufacturing industries such as automobile, machinery, shipbuilding, aerospace, and other applications.

2.1.3. Integration of rolling mechanism into metal 3D printer

The detail structure of the 3D printer integrated with rolling mechanism consists of components as below:

- Machine frame, protective and shielding system.
- Machine table system, jigs.
- Print head mounting system.
- Cooling system.
- Control and computer connection system.
- Rolling mechanism integrated on the machine.

Fig. 2 shows a diagram of 3D printer integrated the rolling mechanism.

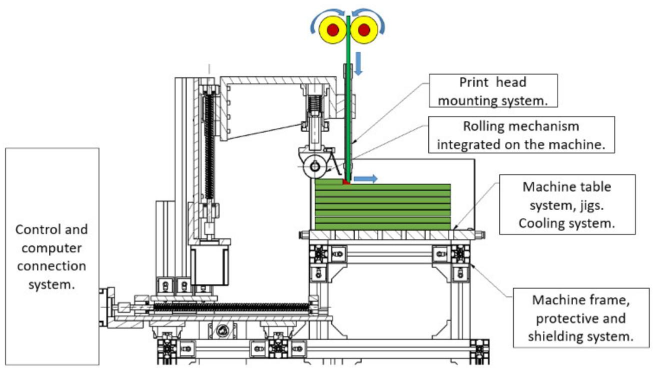

Fig. 2. The diagram of 3D printer integrated rolling mechanism [14]

2.2. Experimental research

2.2.1. Difining input variables

The material was used in the study as aluminum alloy 5052 with the size of 80 x 30 x 10mm. The printing wire is a commercial type of Pinnacle Alloy of ER5356 with the diameter of 1.2mm. Table 2 shows the chemical compositions of the Pinnacle Alloy of ER5356 [15].

Table 2. The chemical compositions of Pinnacle Alloy of ER5356 (Wt%) [15]

Aluminum (Al)	Remainder
Beryllium (Be)	0.0008 max
Chromium (Cr)	0.05 - 0.20

Copper (Cu)	0.10 max
Iron (Fe)	0.40 max
Magnesium (Mg)	4.5 - 5.5
Manganese (Mn)	0.05-0.20
Silicon (Si)	0.25 max
Titanium (Ti)	0.06 - 0.20
Zinc (Zn)	0.10 max
Other elements	0.05 max each & 0.15 max total

The print samples include ten printing layers. Each layer includes two printing lines. Each printing line is 70mm. The experiments were done to monitor the quality and the hight of the deposited material. Table 3 shows the MIG welding parameters with the welding wire diameter of 1.2mm, the input current of 125 - 260A, input voltage of 20 - 29V, and the feed rate of the wire of 140 - 212mm/s. The experiments were done on the welding machine of DaiHen XD350, Japane, and protective gas of Argon.

Table 3. The MIG welding parameters (DCEP) [15]

Diameter	WFS (mm/s)	Amperage	Volts	Consumption (lb/100 ft)	Argon (cfh)
0.76mm	204-265	60-175	15-24	0.65-1.25	25-30
0.89mm	190-317	70-185	15-27	1.0-4.25	30-35
1.2mm	140-212	125-260	20-29	1.0-4.25	35-45
1.6mm	106-190	170-300	24-30	3.8-6.6	45-75

2.2.2. Design of experimental matrix

The experiments are arranged according to the Box-Behnken experiment method. I, U, and S parameters are the input current, the input voltage, and the feed rate of the welding wire. Each input parameter has three values corresponding to the levels -1, 0, 1 [16]. The values of the input parameters are selected according to the recommendations from the manufacturer as shown in Table 3 [15]. Table 4 shows the Box-Behnken experimental matrix with processing parameters used to optimize the hight of thin-walled part.

Table 4. The input parameters arranged following the Box-Behnken experiment method

Parameters	Unit	Symbol	Value of levels		
			-1	0	1
Input current	A	I	125	192.5	260
Input voltage	V	U	20	24.5	29
Feed rate	mm/s	S	140	176	212

3. RESULTS AND DISCUSIONS

3.1. The metal 3D pinter integrated rolling mechanism

Fig. 3 shows the metal 3D printer integrated rolling mechanism. The equipment has ability of printing parts with maximum length of 350mm, the maximum width of 220mm, and the maximum height of 120mm. The machine is integrated a rolling mechanism to simultaneously roll material during printing process. This rolling mechanism can be control the rolling force to improve the quality of product, especially for thin-walled parts.

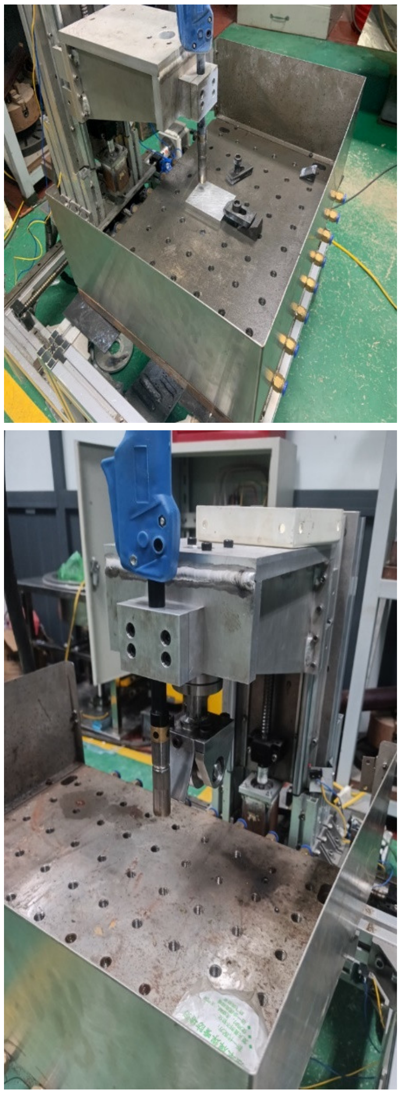

Fig. 3. The metal 3D printer integrated rolling mechanism

The calculation and analysis simulation of static strength analysis were done using computer-aided engineering (CAE) software following the requirements of the metal 3D printer integrated rolling mechanism. The material of the shaft is SKD11.

Fig. 4 show the results of static strength Von Mises analysis with the maximum bending stress of the rolling mechanism as 49.86MPa at the neck position of the shaft. The bending stress of the material is about 2706MPa for tensile strength and 2000MPa for initial yield stress [17]. The result reveals that the mechanism is completely durable.

Fig. 5 shows the results of the displacements analysis following X, Y, and Z axes. The maximum displacement of the rolling mechanism in YOX plane is 99.75µm. The displacement value in the vertical direction, from bottom to top at the contact position between the rolling end and the printing layer is quite important, it affects the error of printing layer height. According to Fig. 6 this value is equal to 1.53µm, corresponding to the height error of the printed layer after lamination.

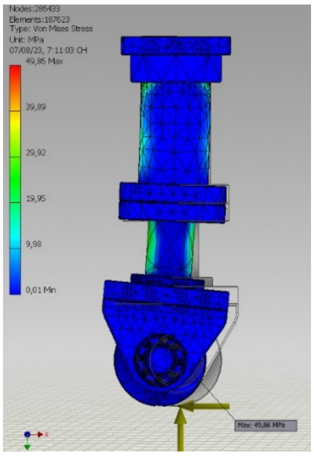

Fig. 4. The static strength Von Mises analysis

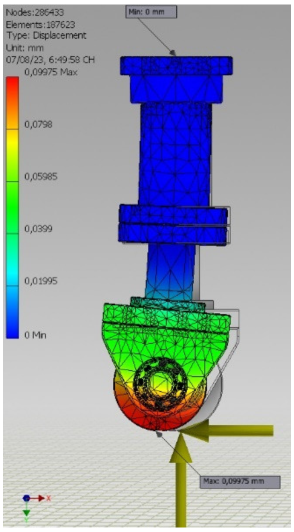

Fig. 5. The displacement analysis results

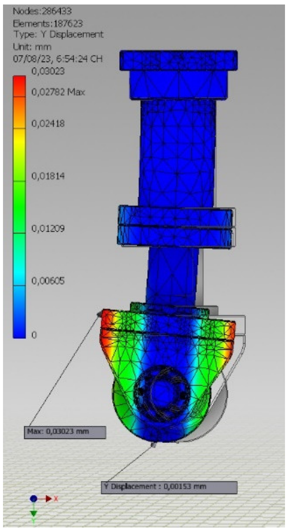

Fig. 6. Displacement value at contact position between rolling end and printing layer

3.2. The experimental assessment

Table 5 shows the Box-Behnken experimental matrix conducted with 15 experiments. The results show that the maximum hight of the samples is 40mm corresponding to the input current of 192.5A, the input voltage of 24.5V, and the feed rate of 176mm/s. The minimum hight of the printed samples is 32mm corresponding to the input current of 192.5A, the input voltage of 29V, and the feed rate of 140mm/s. The experiments are marked with x symbol in the hight column that will be ignored because of the fails of the printed samples.

Table 5. The Box-Behnken experimental matrix and results

STT	Std Order	Run Order	Pt Type	Blocks	Input current I(A)	Input voltage U (V)	Feed rate S (mm/s)	Hight (mm)
1	6	1	2	1	260	24,5	140	36
2	12	2	2	1	192.5	29	212	36
3	14	3	0	1	192.5	24,5	176	40
4	15	4	0	1	192.5	24,5	176	40
5	1	5	2	1	125	20	176	35
6	7	6	2	1	125	24,5	212	x
7	11	7	2	1	192.5	20	212	x
8	10	8	2	1	192.5	29	140	32
9	3	9	2	1	125	29	176	34
10	4	10	2	1	260	29	176	34
11	5	11	2	1	125	24,5	140	34
12	2	12	2	1	260	20	176	36
13	13	13	0	1	192.5	24,5	176	39
14	8	14	2	1	260	24,5	212	36
15	9	15	2	1	192.5	20	140	39

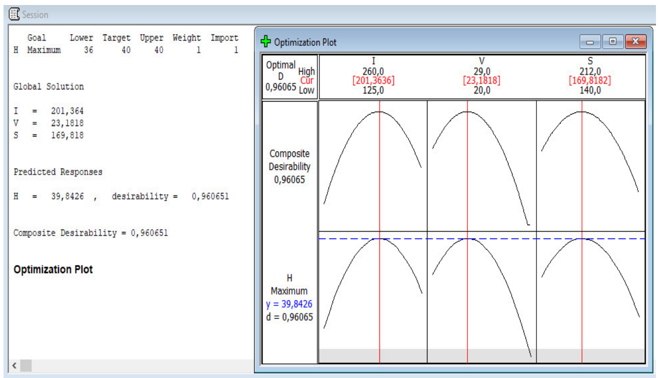

Fig. 7. The optimization analysis result

Fig. 7 shows the optimization plot conducted by using the Box-Behnken analysis tool in the Minitab 16 software. The results show that the maximum height of the printed samples is 39.84mm with the reliability of 96.1% corresponding to the input current of 201.4A, input voltage of 23.2V, and feed rate of 169.8mm/s.

Fig. 8 shows the metal 3D printing samples as printing with the optimal parameters of 201.4A, input voltage of

23.2V, and feed rate of 169.8mm/s. Fig. 8(a) shows the metal 3D printing by using the optimal parameters without rolling mechanism. Fig. 8(a) shows the metal 3D printing by using the optimal parameters with the rolling mechanism.

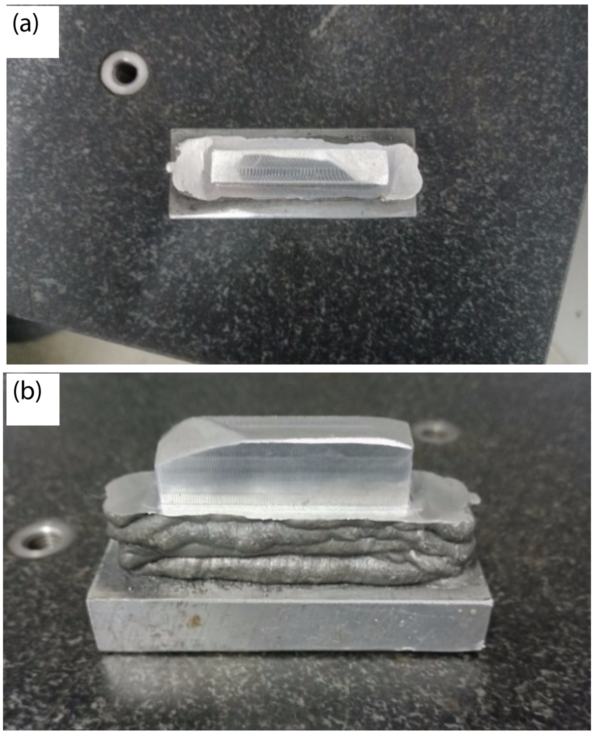

Fig. 8. The metal 3D printing samples as printing with the optimal parameters; (a) The metal 3D printing by using the optimal parameters without rolling mechanism; (b) the metal 3D printing by using the optimal parameters with the rolling mechanism

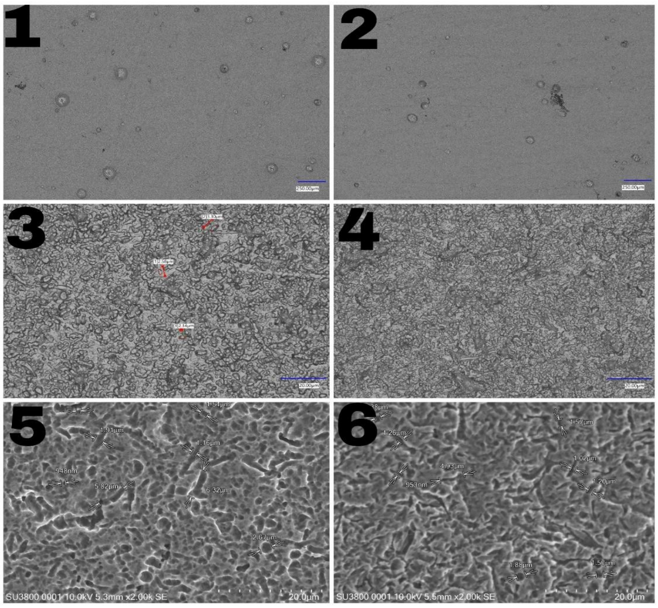

Fig. 9. 1) scale of 1K of the optimal sample without rolling mechanism; 2) scale of 1K of the optimal sample with rolling mechanism; 3) scale of 2K of the optimal sample with out rolling mechanism; 4) scale of 2K of the optimal sample with rolling mechanism; 5) scale of 2K of the optimal sample without rolling mechanism with etching; 6) scale of 2K of the optimal sample with rolling mechanism with etching

Fig. 9 shows the SEM images of the optimal samples after printed by using optimization parameters of 201.4A, input voltage of 23.2V, and feed rate of 169.8mm/s. Fig. 9(1) shows the SEM image with the scale of 1K of the optimal sample without rolling mechanism. Fig. 9(2) show the SEM image with the scale of 1K of the optimal sample with rolling mechanism. Fig. 9(3) shows the SEM photo with the scale of 2K of the optimal sample without rolling mechanism. These particles have the width of 1.16 - 1.91µm and the length of 5.82 - 6.32µm. Fig. 9(4) shows the SEM photo with the scale of 2K of the optimal sample with rolling mechanism. The particles have the width of 1.02 - 1.20µm and the length of 4.58 - 4.93µm. Fig. 9(5) shows the SEM photo with the scale of 2K of the optimal sample without rolling mechanism with etching. Fig. 9(6) shows the SEM photo with the scale of 2K of the optimal sample without rolling mechanism with etching.

The results that the crystal structure of the printed optimization samples with rolling mechanism are smaller than that of the crystals structure of the printed optimization samples without rolling mechanism as shown in the scanning electron microscope (SEM). The SEM images of the printed samples show that the samples with rolling mechanism are more constant than that of the samples without the rolling mechanism.

4. CONCLUSIONS

The paper figures out the optimal parameters of the metal 3D printing method for the thin-walled parts by using the welded wire ER5356 with the diameter of 1.2mm on the 3D printing system of Daihen XD350 and the metal 3D printing equipment. The maximum hight of the printed sample is 39.84mm with 10 printing layers and the reliability of 96.07%. The results show that the quality of the printed layer is improved by using the rolling mechanism during the printing process. The optimal metal 3D printing parameters are input current of 201.4A, input voltage of 23.2V, and feed rate of 169.8mm/s. The results hope that it will be contributed on the fabricating the metal parts with high mechanical properties and using for its applications such as thin-walled parts and workpiece with high quality.

ACKNOWLEDGEMENTS

This work was sponsored by Hanoi University of Industry, 298 Caudien Street, Hanoi 10000, Vietnam.

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