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ARTICLE

Influence of Process Parameters on Forming Quality of Single-Channel Multilayer by Joule Heat Fuse Additive Manufacturing

Li Suli, Fan Longfei, Chen Jichao, Gao Zhuang, Xiong Jie, Yang Laixia

College of Mechanical Engineering, Xi'an University of Science and Technology, Xi'an 710054, China

Abstract: To overcome the shortage of complex equipment, large volume, and high energy consumption in space capsule manufacturing, a novel sliding pressure Joule heat fuse additive manufacturing technique with reduced volume and low energy consumption was proposed. But the unreasonable process parameters may lead to the inferior consistency of the forming quality of single-channel multilayer in Joule heat additive manufacturing process, and it is difficult to reach the condition for forming thin-walled parts. Orthogonal experiments were designed to fabricate single-channel multilayer samples with varying numbers of layers, and their forming quality was evaluated. The influence of printing current, forming speed, and contact pressure on the forming quality of the single-channel multilayer was analyzed. The optimal process parameters were obtained and the quality characterization of the experiment results was conducted. Results show that the printing current has the most significant influence on the forming quality of the single-channel multilayer. Under the optimal process parameters, the forming section is well fused and the surface is continuously smooth. The surface roughness of a single-channel 3-layer sample is 0.16 μm, and the average Vickers hardness of cross section fusion zone is 317 HV, which lays a foundation for the subsequent use of Joule heat additive manufacturing technique to form thin-wall parts.

Key words: Joule heat; additive manufacturing; single-channel multilayer; process parameter; forming quality

1 Introduction

The exploration of space is a high-level battlefield of science and technology among great powers[1], and the development of aerospace engineering[2] is inseparable from advanced manufacturing techniques. Additive manufacturing technology, as a new manufacturing technology[3] with revolutionary breakthrough[4], has been widely used in medical application[5–6], high-end equipment[7], automobile[8], and aerospace fields[9–10]. With the further exploration of space, new space manufacturing equipment should have low power consumption, miniaturization characteristic, high precision, and other technical requirements to adapt to the complex space environment[11]. In response to the restrictions of current mainstream metal fuse additive manufacturing techniques[12], which rely on heat sources (such as lasers[13], electron beams[14], and arcs[15]) and are associated with complex equipment and high energy consumption, a straightforward and energy-efficient Joule heat fuse additive manufacturing technique has been proposed[16].

Currently, worldwide scholars have conducted preliminary research on Joule heat additive manufacturing technique. Yuan et al[17] set up an experimental system for resistance heating wire and investigated the process of melting and secondary melting mechanism involved in resistance heating wire. However, the droplet additive manufacturing method faces challenges, such as difficulty in controlling the droplets. Therefore, an experimental system of Joule heat with sliding

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Corresponding author: Li Suli, Ph. D., Professor, College of Mechanical Engineering, Xi'an University of Science and Technology, Xi'an 710054, P. R. China, E-mail: Lsl15802949318@xust.edu.cn

pressure additive manufacturing was proposed to simultaneously achieve the preheating and melting of the wire. Related studies were also conducted on single-channel and single-layer printing[18–20]. During the formation process of single-channel multilayer, it was found that the forming process of single-channel multilayer requires high thermal stability of Joule heating and it is simultaneously influenced by multiple process parameters, leading to difficult control of the forming quality. For this innovative technique, there are few studies about the influence of process parameters on the quality of multilayer forming. Liu et al[21] delved into the realm of tungsten inert gas welding arc additive manufacturing technique and reported that welding current is the primary influencer for the weld bead width, which is closely trailed by welding speed, and the wire feeding speed exerts the most significant impact on the weld bead height. Concurrently, Fan et al[22] investigated the impact of process parameters on the quality of arc additive manufacturing, found the optimal process parameters, and achieved superior quality in the resultant components. Liberini et al[23] studied the influence of heat input on the shape of arc additive manufacturing and found that the process parameters greatly influenced the shape. Feng et al[24] found that the surface quality and corrugation of stainless steel and carbon steel prepared by additive manufacturing were better with the faster deposition speed when the deposition current remained unchanged. Wang et al[25] studied the influence of process parameters, such as flow rate, deposition rate, and layer thickness, on the forming morphology.

Therefore, the influence of process parameters on the forming quality of single-channel multilayers was investigated in this research to explore the key of Joule heat fuse additive manufacturing. This study provided theoretical data and experimental support for forming thin-walled parts by Joule heat additive manufacturing technique, showing important research significance and practical value for the development of aerospace manufacturing industry.

2 Experiment

The substrate and wire materials used in the experiment were 316L stainless steel. The diameter of the wire was 0.4 mm, the size of the substrate was 100 mm×100 mm×3 mm, and the surface roughness was 0.8 μm. 316L stainless steel has high resistivity and low heat transfer rate, so it is ideal for Joule heat fuse additive manufacturing technique. The primary chemical composition of 316L stainless steel is detailed in Table 1[26]. Before the experiment, thorough cleaning of both the substrate and wire surfaces was imperative. The samples were cleaned by industrial alcohol followed by a wipe-down using an oil-free dust cloth and finally dried. The cleanliness of the substrate and wire was important because it might affect the quality of experimental forming. Electron backscattered diffraction (EBSD) analysis was used to investigate the sample microstructure.

The equipment used in the experiment is shown in Fig. 1, which mainly includes the vacuum system, the motion system, the programmable power supply, and the computer. The vacuum system includes an empty tank, TRIVAC D60T (LEYBOLD, Cologne, Germany) mechanical pump, TURBOVAC 90i (LEYBOLD, Cologne, Germany) semi-magnetic suspension molecular pump, and ZDF-III-LED composite vacuum gauge. IT-M3910D-10-1020 programmable power supply was used as heat source to melt wire (working energy consumption within 400 W). Improved CNC/M-micro CNC milling machine was used as the motion system (only 50 kg).

Orthogonal experiments were used to study the factors influencing the forming quality of single-channel multilayer by Joule heat fuse additive manufacturing. To prevent surface oxidation, the vacuum degree of the experimental environment was set to 9×10^{-2} Pa. The substrate was fixed horizontally to the moving platform base by a fixture to prevent movement or deflection during the forming process. Analysis was conducted to explore the change rule regarding the influence of three process parameters, namely printing current, forming

Table 1 Chemical composition of 316L stainless steel[26]

Cr	Mn	Mo	Ni	Si	C	P	Cu
18.74	1.55	2.67	11.82	0.56	0.014	0.03	0.17

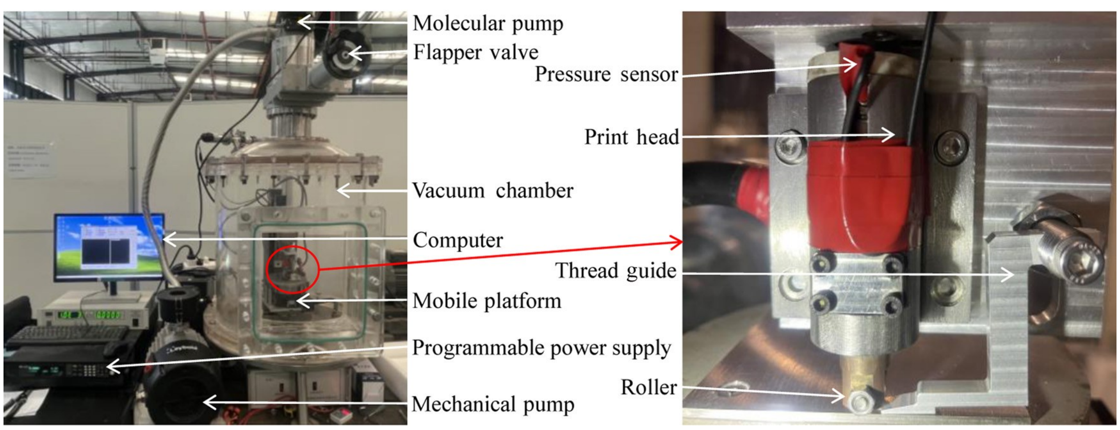


Fig.1 Experiment equipment for Joule heat additive manufacturing

speed, and contact pressure, on the quality of single-channel multilayer forming. The orthogonal experimental design comprised 3 levels and 3 factors, resulting in the formation of single-channel multilayer samples with three different layer heights: single-channel 2-layer, single-channel 3-layer, and single-channel 4-layer. A total of 27 experimental sets were obtained, as listed in Table 2.

Other less influential process parameters were fixed as roller cross-section width of 0.8 mm; guide nozzle angle of 25°; silk dry elongation of 5 mm. The forming principle and process parameters are shown in Fig.2.

3 Results and Discussion

3.1 Effect of different process parameters on quality of single-channel multilayer forming

The quality of single-channel multilayers by Joule heat melt wire additive manufacturing was quantified by analyzing macroscopic morphology. The forming quality scores of samples with different process parameters have a total score of 10 points and the higher the score, the better the forming quality. The scoring criteria are shown in Fig. 3. The samples whose actual and ideal layers are inconsistent with each other are scored as 0 point (Fig. 3a). The samples that are discontinuous or have bumps and depressions are scored as 1 – 5 points (Fig. 3b). Specifically, the samples that are broken are scored as 1 point, the samples that are completely melted at the top are scored as 2 points, the samples that are partially raised or depressed as a whole are scored as 3 – 4 points, and the samples with uneven surfaces at the top are scored as 5 points. Samples without obvious defects and have roughly the same number of layers are scored as 6–9 points (Fig.3c). Specifically, the samples with uneven lines on the side are scored as 6 points, the samples with uneven lines on the upper surface are scored as 7 points, and the samples with smooth overall side or upper surface are scored as 8 – 9 points. The samples with a smooth overall surface and no defects are scored as 10 points (Fig. 3d). Fig. 4 shows the schematic diagram of the parameter measurements of the cross-section of the single-channel multilayer sample, where D is melt width (subscripts 1, 2, 3, and 4 correspond to different layers), H_1 is melt height, and H_2 is melt depth. The measurement method of melting width (D) is the comprehensive average value of melting width measurement results of each layer, and the section measurement of each sample with good shape is taken from

Table 2 Orthogonal test set of single-channel multilayers prepared by Joule heat additive manufacturing

Single-channel multilayer	No.	Printing current/A	Forming speed/mm·min^{-1}	Contact pressure/N
2-layer	1	220	500	0.4
	2	220	400	0.3
	3	220	300	0.2
	4	210	500	0.3
	5	210	400	0.2
	6	210	300	0.4
	7	200	500	0.2
	8	200	400	0.4
	9	200	300	0.3
3-layer	10	180	500	0.4
	11	180	400	0.3
	12	180	300	0.2
	13	170	500	0.3
	14	170	400	0.2
	15	170	300	0.4
	16	160	500	0.2
	17	160	400	0.4
	18	160	300	0.3
4-layer	19	140	500	0.4
	20	140	400	0.3
	21	140	300	0.2
	22	130	500	0.3
	23	130	400	0.2
	24	130	300	0.4
	25	120	500	0.2
	26	120	400	0.4
	27	120	300	0.3

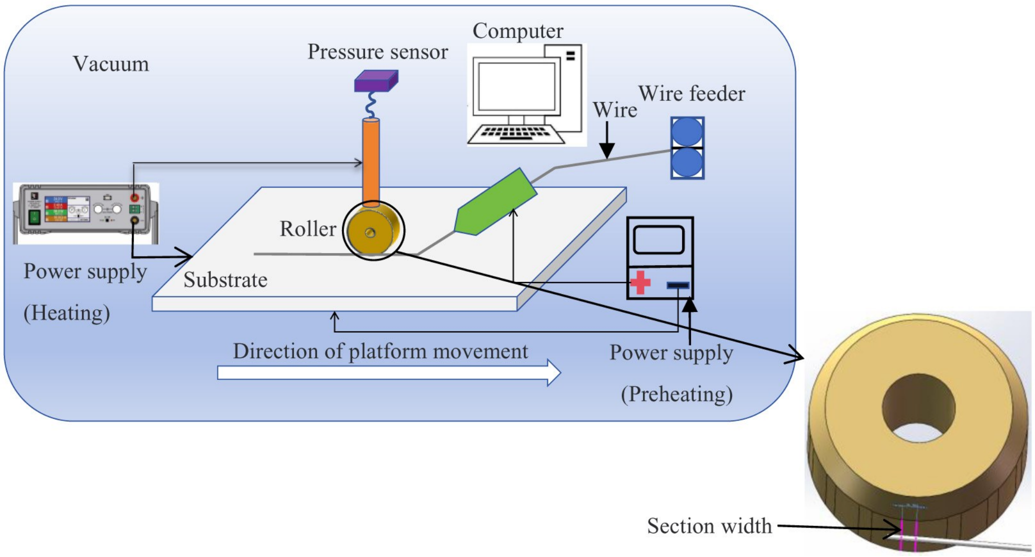


Fig.2 Schematic diagram of forming principle and process parameters

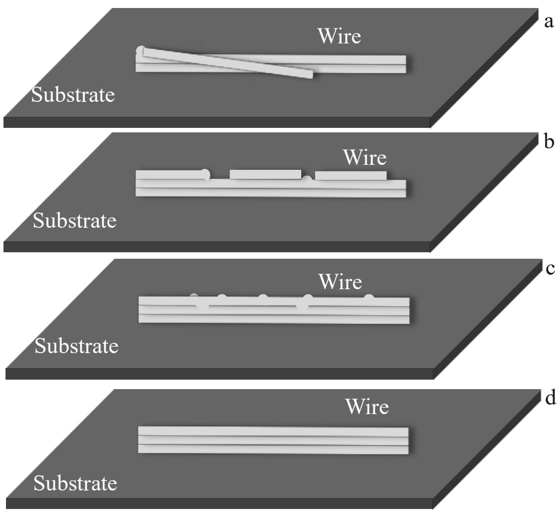


Fig.3 Scoring criteria examples for single-channel multilayers: (a) 0 point, (b) 1–5 points, (c) 6–9 points, and (d) 10 points

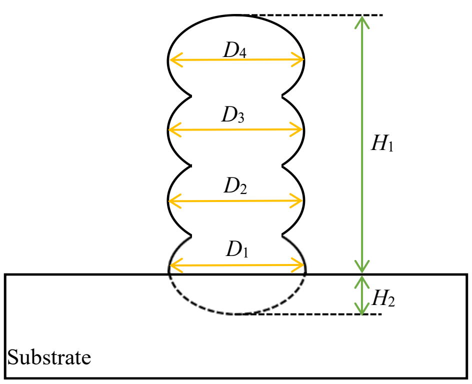


Fig.4 Schematic diagram of parameter measurements of single-channel multilayer

the measurement position of melting height. The appearance and scoring results of single-channel multilayers obtained by the parameters are listed in Table 3, and the measured melting width and melting height are also shown in Table 3.

The experiment results show that with the decrease in the printing current, the shape of the single-channel multilayer sample is greatly improved. Within a certain range, at high currents, the system generates more heat, resulting in a higher degree of wire melting. Consequently, the width of the single-channel multilayers increases slightly while the height decreases significantly. Conversely, as the current decreases, the heat generated within the system also decreases, leading to better control over the height and width of the single-channel multilayer samples, thereby improving the overall formation quality. Since the principle of sliding pressure Joule heat fuse additive manufacturing relies on heat generation through contact resistance to melt wire for forming, the surface quality of the initial forming layer significantly impacts the thermal stability of subsequent forming processes. This standard can serve as a basis for judgment whether the single-channel multilayer samples achieving the score of 6 points or even higher can proceed with lower layer bonding.

The range analysis of the orthogonal experiment results was performed to obtain the range of each process parameter, and the results are shown in Fig. 5. It can be observed that the influence of printing current on the forming quality of single-channel multilayers is significantly more pronounced than that of forming speed and contact pressure. The influence and significance of different process parameters on the forming quality of samples with different numbers of layers shows no significant variation. Therefore, the printing current, which exerts the most significant influence on forming quality, was further analyzed using the effect curve graph. Its impact on the weld width and melt height of the single-channel multilayer sample is depicted in Fig. 6. It is evident that as the printing current decreases, the weld width of single-channel multilayer samples gradually decreases, whereas the melt height gradually increases, resulting in a significant

Table 3 Multilayer forming and grading in orthogonal experiment

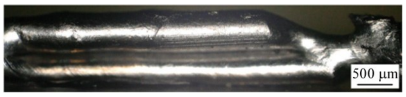
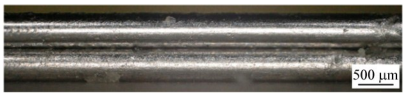
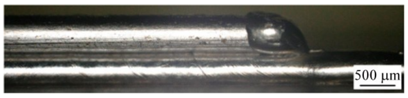
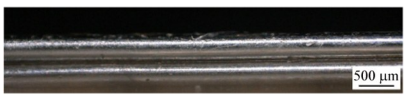
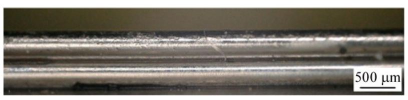
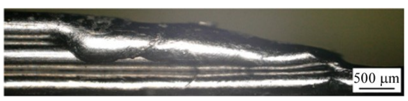
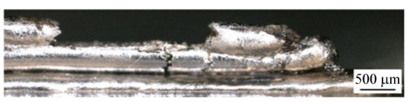
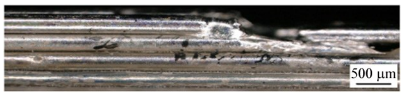
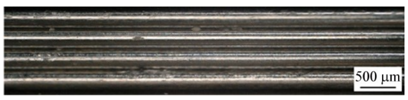
No.	Multilayer appearance	Score	Weld width/μm	Height/μm
1		5	452.76	592.34
2		3	432.95	581.27
3		2	505.31	515.60
4		6	423.62	670.32
5		4	462.46	601.50
6		7	404.65	687.26
7		9	405.70	690.50
8		7	406.92	685.46
9		8	423.62	670.32
10		4	437.62	986.75
11		2	501.63	915.26
12		1	462.46	601.50
13		7	412.69	979.34
14		5	426.57	964.51
15		6	413.50	975.23
16		9	405.62	1019.85
17		8	403.18	1021.50

Table 3 Multilayer forming and grading in orthogonal experiment (continued)

No.	Multilayer appearance	Score	Weld width/μm	Height/μm
18		7	403.50	1017.52
19		4	438.26	1172.52
20		3	434.28	1174.63
21		2	492.35	1085.60
22		6	414.57	1289.60
23		4	426.70	1276.30
24		7	412.66	1310.45
25		8	405.16	1328.70
26		7	404.25	1341.60
27		6	411.27	1312.56

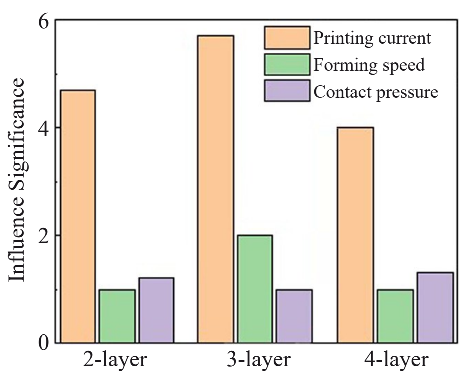


Fig.5 Influence significance of different process parameters on different single-channel multilayers

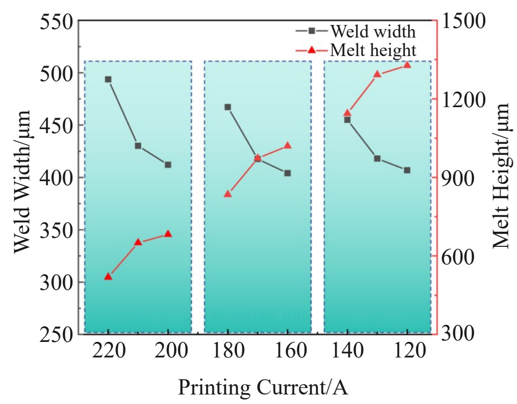


Fig.6 Effect of printing current on weld width and melt height of different single-channel multilayers

improvement in forming quality.

3.2 Analysis of different process parameters on forming quality of single-channel multilayer

The change in heat production during the multilayer forming process of Joule heat fuse additive manufacturing is a crucial factor affecting the quality of multilayer forming. The size of heat production resulting from different process parameters directly influences the effectiveness of multilayer forming. Heat production in additive manufacturing processes can be calculated according to Joule's law, as follows:

$$Q = \int_0^t I^2(t) R(t) \mathrm{d}t \tag{1}$$

where $I(t)$ represents the current output from the programmable power supply; $R(t)$ is the total resistance, including the roller resistance, the total resistance of the substrate and the front layer of the forming parts, the contact resistance between the roller and the filament, and the contact resistance between the pre-printed filament and the front layer of the filament; t is the total printing time.

Fig. 7 illustrates the heat transfer diagram of Joule heat additive manufacturing. In the Joule heat additive manufacturing process, which occurs in a vacuum environment, heat loss is only considered through heat conduction and heat radiation. The heat (Q_0) absorbed by the fusion between the filaments can be expressed by Eq.(2), as follows:

$$Q_0 = Q - Q_1 - Q_2 \tag{2}$$

where Q denotes the total system heat production, Q_1 denotes the heat transferred in the system, and Q_2 denotes the heat radiated in the system.

In the forming process of single-channel multilayer, the heat transfer in the system has two main directions: towards the rollers and along the forming layer down to the substrate. The experimental roller is made of chromium-zirconium copper, because the thermal conductivity of chromium-zirconium copper is greater than that of 316L stainless steel wire. Therefore, the heat transferred to the roller is on the high side. This experiment follows Fourier's law of heat conduction, as follows:

$$Q_1 = -kS_1\frac{\mathrm{d}T}{\mathrm{d}H} \tag{3}$$

$$R_{\mathrm{H}} = \frac{\Delta T}{Q_1} = \frac{H}{kS_1} \tag{4}$$

where k is the heat transfer coefficient, S_1 is the heat transfer area, R_{H} is the thermal resistance to conduction, T is the initial heat source emission temperature, and H is the thickness in the direction of heat transfer.

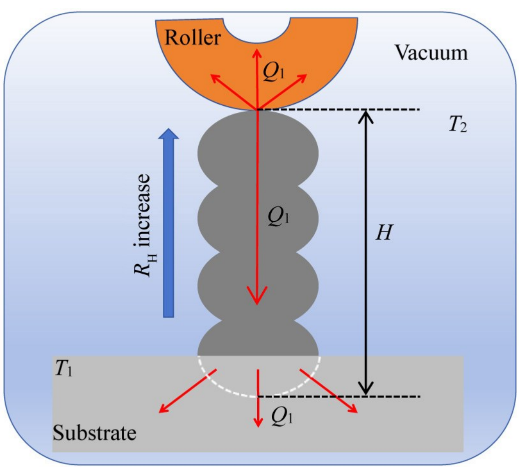


Fig.7 Heat transfer map of Joule heat additive manufacturing for single-channel multilayers (T_1 is substrate temperature; T_2 is atmosphere temperature; R_{H} is thermal resistance to conduction; H is the thickness in the direction of heat transfer)

The thermal radiation Q_2 in the system can be expressed by Eq.(5), as follows:

$$Q_2 = \varepsilon\delta\left(T^4 - T_2^4\right)S_2 \tag{5}$$

where ε represents the radiative heating rate, ranging from 0 to 1; δ is the Stefan-Boltzmann Hertz constant; T is the initial heat source emission temperature; T_2 denotes the temperature inside the vacuum chamber; S_2 represents the surface area for thermal radiation.

As the number of layers in single-channel multilayers increases, both R_{H} and H gradually increase, whereas the heat transfer area decreases. Consequently, the heat transferred along the substrate direction gradually decreases, resulting in longer cooling and solidification processes for the layer formation. Meanwhile, the heat transferred along the roller direction experiences only slight variation. According to Eq.(5), the preheating source and the output heat source can increase the initial temperature T_0 of the single-layer forming region. As the height of the forming layer increases, its overall surface area is also gradually larger, i. e., the surface area of thermal radiation S_2 gradually increases. Theoretically, the proportion of heat loss through thermal radiation Q_2 increases. However, within the actual system, heat conduction and thermal radiation gradually reach a balanced state, ensuring that the heat input in the melting region remains stable. Therefore, adjustments of process parameters are necessary during the initial forming processes to ensure a balanced total input heat to the system. Consequently, investigating the impact of process parameters on forming quality during the initial forming stages holds significant importance.

3.2.1 Influence of printing current on forming quality of single-channel multilayer

According to Joule's law, the magnitude of the printing current is a primary determinant of heat input, and its impact on the quality of single-channel multilayer forming is depicted in Fig. 8. With other parameters fixed, increasing the printing current leads to an increase in the total heat input into the system. The excessive heat prolongs the duration that the filaments in the melting region remain at the liquid state. This is accompanied by lower viscosity of the liquid metal in the high-temperature region, facilitating more rapid flow spread and a slower cooling rate. In single-channel multilayer forming, as the number of printing layers increases, the fusion area between the wire and the substrate shifts to the area between the wires. Greater heat input enlarges the melting area, causing the wires between multilayers to repeatedly melt into liquid form and solidify, resulting in a superheated state. This phenomenon can lead to interlayer collapse and cause the formation of failure. Besides, as the number of printing layers increases, greater heat input causes more heat in the previously formed layers, leading to cracks in the formed positions. Conversely, when the printing current is too low, the total heat input to the system decreases, resulting in smaller melting areas between the wires, making it impossible to create favorable metallurgical bonding conditions between the wires.

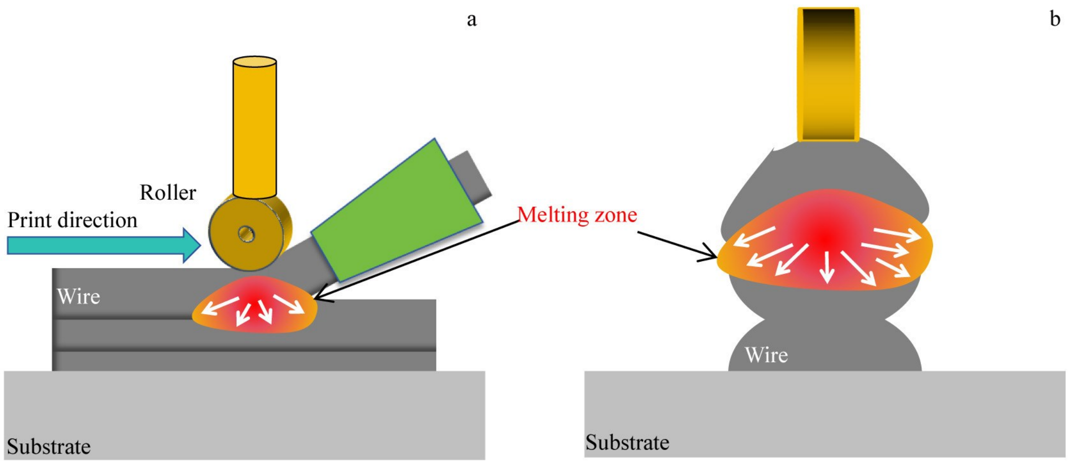


Fig.8 Influence of printing current on forming quality: (a) front view and (b) cross-section view

3.2.2 Influence of forming speed on forming quality of single-channel multilayer

The influence of forming speed on the forming quality of single-channel multilayer is shown in Fig.9. When the printing current and contact pressure are constant, the forming speed mainly affects the melting amount of wire per unit time, which is an important factor to control the size of single-channel multilayer forming. During a relatively stable printing process, as the forming speed increases, the amount of wire melted per unit of time is relatively less. Consequently, the overlap rate of the forming layers is relatively low, resulting in larger layer heights but smaller melt depths. At slower forming speeds, there is a larger heat input per unit of time, resulting in smaller residual height and larger melting width and depth, potentially leading to defects. Moreover, a lower forming speed also affects the disturbance velocity of the liquid wire in the fusion area. The liquid metal spreads slowly to the surroundings, resulting in the formation of ripples or pits on the surface of the forming layer, thereby reducing the surface quality. Therefore, an appropriate forming speed can improve the surface quality of single-channel multilayers.

3.2.3 Influence of contact pressure on forming quality of single-channel multilayer

On the one hand, the contact pressure affects the contact resistance between the roller and the wire, as well as that between the wires. Eq.(6)[27] shows the calculation formula of contact resistance, as follows:

$$R_c = \frac{K}{(0.102F)^m} \tag{6}$$

where R_c represents the contact resistance, K is the material coefficient, F denotes the contact pressure, and m represents the contact form. For the contact between the roller and the wire, the contact form is linear with m ranging from 0.5 to 0.8.

With the constant printing current and forming speed, as the contact pressure increases, according to Eq. (6) [27], the total contact resistance R_c decreases, resulting in a reduction in the total heat input Q to the system. Consequently, it becomes impossible to create favorable metallurgical bonding conditions between the wires. Similarly, when the contact pressure is too small, the contact resistance is too large, and the total heat input of the system is too high, which will lead to the deformation and fracture of the wire due to high temperature.

On the other hand, excessive contact pressure can cause disturbance-induced upward movement of the liquid metal in the fusion region. This upward shift of the maximum temperature point in the fusion region affects the bonding point of the wire, resulting in increased heat loss. This result

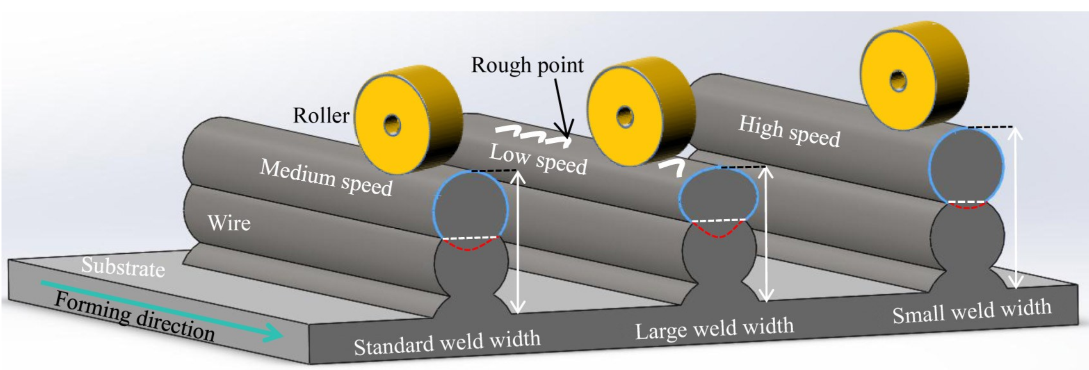


Fig.9 Influence of forming speed on forming quality

only applies to pre-printed wires processed by thermal wire treatment. Fig.10 shows the influence of large contact pressure on the forming quality of single-channel multilayers. It is observed that the actual heat production area gradually increases with the movement of printing direction. Under the influence of large contact pressure, the actual heat production area shifts along the back and upward direction of the roller movement. Therefore, selecting a small contact pressure within a reasonable range can well control the heat input required under the combination of process parameters and the flow state of liquid metal in the fusion area, which is more conducive to the formation of single-channel multilayer parts with good quality.

4 Control and Detection of Single-Channel Multilayer Forming Quality

4.1 Quality control of single-channel multilayer

According to the abovementioned orthogonal experiment results and the analysis of the influence of process parameter on the forming quality, small current and small pressure are conducive to the improvement in forming quality of single-channel multilayer prepared by Joule heat fuse additive manufacturing. In the orthogonal experiments, the optimal process parameters of single-channel 2-layer, single-channel 3-layer, and single-channel 4-layer were obtained by combining the scores and shape morphology, as follows: printing current of 200, 160, and 120 A, respectively; forming speed of 400 mm/min; contact pressure of 0.2 N. Using the optimal process parameters, appearance, weld width, melt height, and overlap rate of the forming samples with 2, 3, and 4 layers were obtained, as listed in Table 4. The appearances of cross-section fusion are shown in Fig.11. The appearance is continuous and complete, the surface is smooth, and the cross-section fusion is good.

4.2 Forming quality inspection

The forming quality of additive manufactured parts mainly depends on the surface quality and internal performance. Surface roughness and hardness are the important criteria for evaluating the surface quality and internal performance of forming parts, respectively. The surface roughness and cross section of a single-channel 3-layer part formed under optimal process parameters (printing current of 200 A, forming speed of 400 mm/min, and contact pressure of 0.2 N) were measured.

4.2.1 Roughness

Because the surface quality of the top layer of the forming part has a great influence on the thermal stability of the next printing pass, it is important to measure the surface roughness of the top layer to judge the forming quality. Fig. 12a shows the 3D topography of the upper surface of the forming layer scanned by the laser confocal microscope along the printing direction. It can be seen from Fig. 12c that the surface fluctuation contour curve in the forming direction shows no

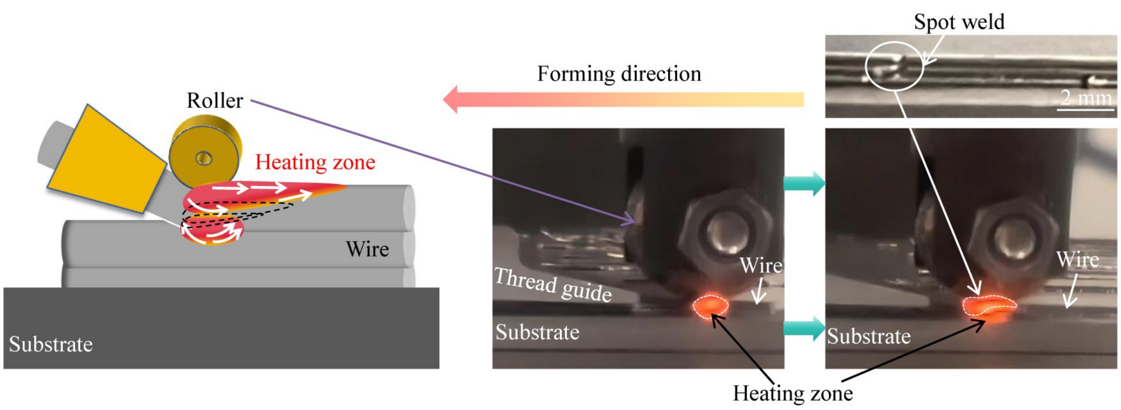
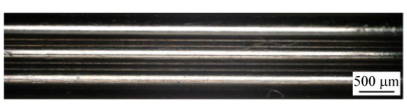
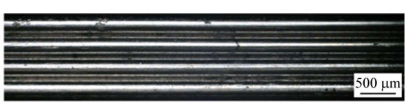


Fig.10 Influence of contact pressure on forming quality shown by schematic diagram and experimental appearances

Table 4 Results of single-channel multilayer optimization forming

Single-channel multilayer	Macroscopic appearance	Weld width/μm	Melt height/μm	Overlap rate/%
2-layer		408.34	678.20	15.2
3-layer		416.52	1013.97	15.5
4-layer		411.23	1319.50	17.5

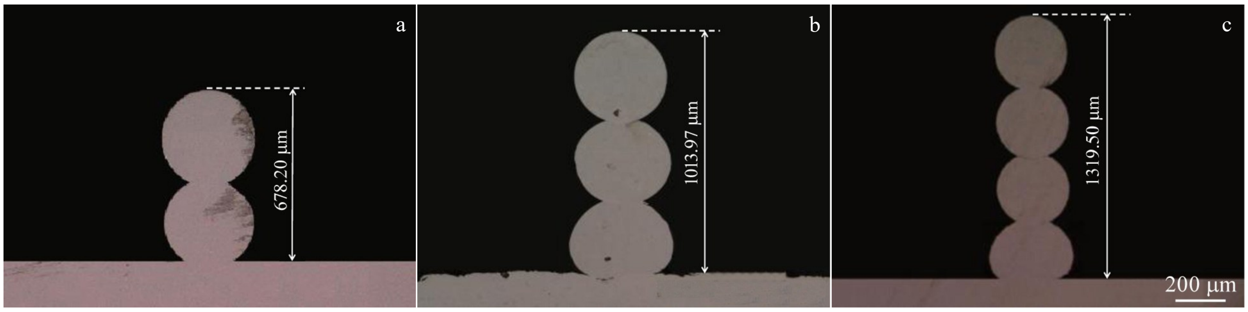


Fig.11 Cross-section fusion appearances of single-channel 2-layer (a), single-channel 3-layer (b), and single-channel 4-layer (c) samples

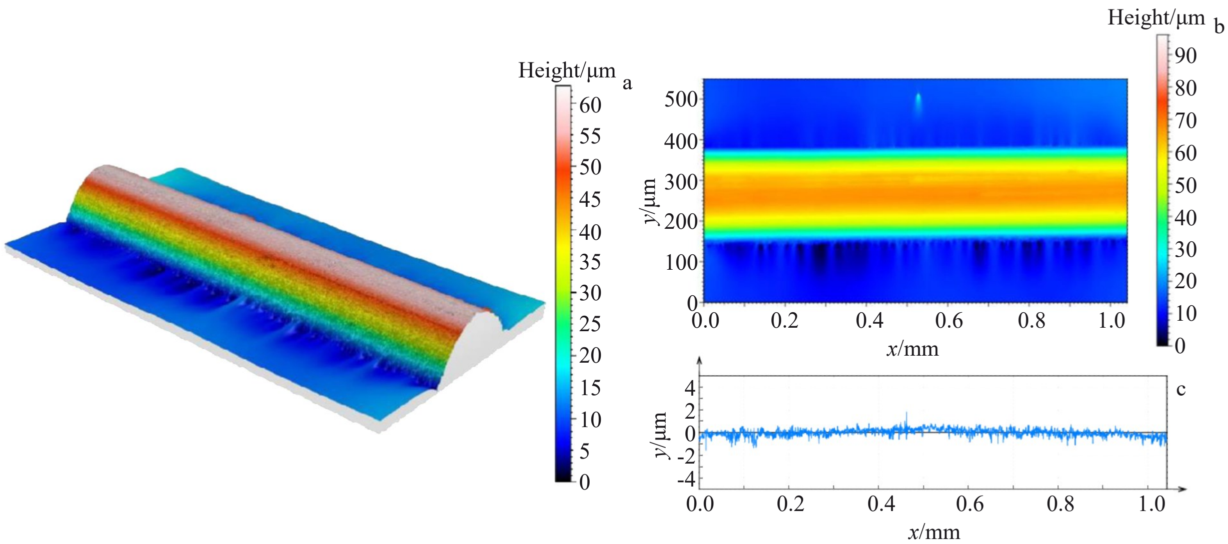


Fig.12 Roughness test results of single-channel 3-layer sample: (a) 3D version; (b) 2D version; (c) surface fluctuation

obvious fluctuation within 1 mm, the peaks and troughs are relatively uniform, and the average surface roughness R_a is 0.16 μm.

4.2.2 Hardness

Fig.13 shows the distribution of the hardness of the single-channel 3-layer sample formed under the optimal process parameters. The measurement was conducted using the HM200 Vickers microhardness tester. The intervals between measurement points were 0.06 mm for regular areas and 0.03 mm for fusion areas. A load of 0.25 N was applied for 15 s. It can be seen that the hardness increases gradually from the substrate to the fusion zone between the first and the second layers, and then decreases. This variation trend can be observed in every transition zone between layers. Whole forming layer suffered multiple heat treatment and cooling processes, so the hardness value fluctuates. Fig.14 and Fig.15 show the microstructure and EBSD cross-section diagram of the fusion zone between the substrate and the first layer, respectively. It can be seen that the hardness value of the fusion zone between the substrate and the first layer is the highest, which is attributed to the evident heat transfer of the substrate in the vacuum environment, resulting in rapid nucleation. As a result, the planar crystal grains in this area are fine with concentrated ferrite near the fusion line, leading to higher hardness. Different regions exhibit slight variations in grain morphology: the central and top regions mainly contain equiaxed crystals and columnar crystals. This is because multiple heat treatments cause varying temperature gradients within the wire, leading to differences in grain nucleation and growth rates. The cooling rate in the central region is slow and close to the heat affected zone, and the grains can grow, so the hardness is lower than that in the fusion zone. The top of the

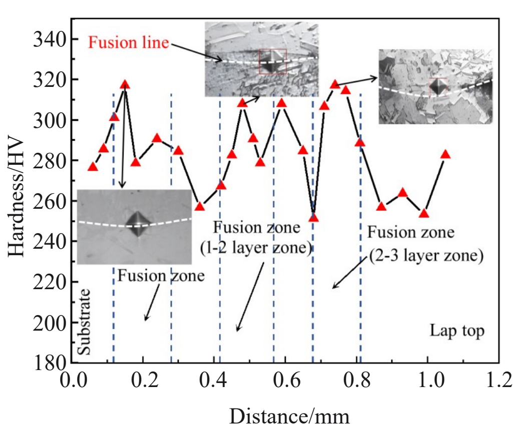


Fig.13 Hardness distribution of single-channel 3-layer sample

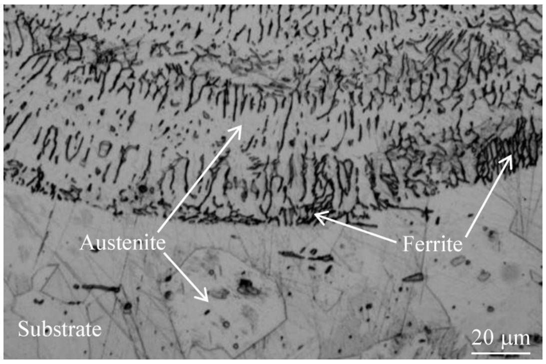


Fig.14 Microstructure of substrate and fusion zone between substrate and the first layer

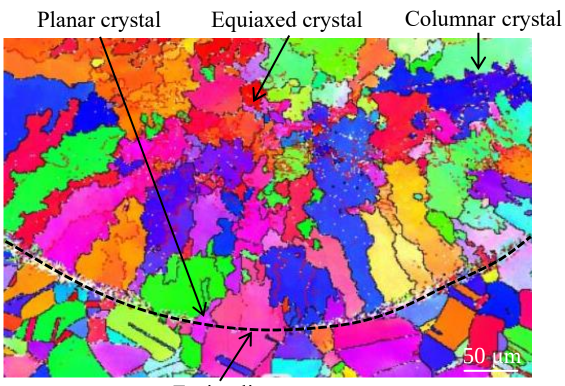


Fig.15 EBSD cross-section between substrate and fusion zone between substrate and the first layer

forming layer has only undergone heat treatment one time and the cooling rate is long, so the grains are thicker and the hardness is lower than that of the fusion zone. Under the optimal process parameters, the average Vickers hardness of the cross-section fusion zone is 317 HV.

5 Conclusions

1) The influence significance of printing current on the forming quality of single-channel multilayer is greater than that of forming speed and contact pressure. With the proper forming speed and contact pressure, reducing the printing current can greatly improve the forming quality of single-channel multilayer. To improve the forming quality of single-channel multilayer, the initial printing current should be reduced by equal amplitude during the formation of the first few layers of single-channel multilayer.

2) The superheated input caused by the printing current increases the existence duration of the liquid metal and expands the fusion region to form the overmelt state. The contact pressure affects the highest point of the central temperature of the heat affected region by changing the distribution of the liquid metal in the fusion region, and the printing current has a significant influence on the state of the fusion region than the contact pressure. The forming speed mainly affects the surface quality and bonding rate of the forming layer by affecting the spreading speed of liquid metal in the fusion area and the melting amount of wire per unit time.

3) The optimal process parameters for single-channel 2-layer, single-channel 3-layer, and single-channel 4-layer are as follows: printing current of 200, 160, and 120 A respectively; forming speed of 400 mm/min; contact pressure of 0.2 N. Under these process parameters, the surface roughness of the single-channel 3-layer sample is 0.16 μm, and the average Vickers hardness of the cross-section fusion zone is 317 HV.

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工艺参数对焦耳热熔丝增材制造单道多层成形质量的影响

李素丽，樊龙飞，陈继超，高　壮，熊　杰，杨来侠

(西安科技大学 机械工程学院，陕西 西安 710054)

摘　要：针对太空舱制造中设备复杂、体积大及能耗高等不足，提出了一种体积小、低能耗的滑压式焦耳热熔丝增材制造技术。工艺参数的不合理性会导致焦耳热增材制造技术单道多层成形质量一致性差，很难达到成形薄壁件的条件。设计了正交实验成形出了不同层数的单道多层样件并对其进行成形质量评分，分别分析了打印电流、成形速度及接触压力对单道多层成形质量的影响，得出了最优工艺参数并对实验结果进行了定量表征。结果表明：打印电流对单道多层成形质量的影响最显著，在最优工艺参数下，成形截面熔合好，表面连续光滑，其中单道3层表面粗糙度为0.16 μm，截面熔合区平均维氏硬度317 HV，为后续利用焦耳热增材制造技术成形薄壁件奠定了基础。

关键词：焦耳热；增材制造；单道多层；工艺参数；成形质量

作者简介：李素丽，女，1981年生，博士，教授，西安科技大学机械工程学院，陕西 西安 710054，E-mail：Lsl15802949318@xust.edu.cn