

HYBRID DEPOSITION AND MICRO ROLLING MANUFACTURING METHOD OF METALLIC PARTS

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Abstract

To conquer the bottleneck problems of cracking, deformation, low accuracy and performance in existing additive manufacturing (AM) process, a new hybrid direct manufacturing method of metallic parts which integrates freeform deposition with micro rolling is proposed in this paper. The principle, devices and simulations are introduced and the comparison with Freeform Deposition Fabrication method are made through experiments, showing that hybrid manufactured parts has distinctive features of higher accuracy and better microstructures. The tensile strength is increased by 33% for stainless steel while the elongation percentage is improved more than 2 times. By using the $\Phi 1.6\text{mm}$ wire in a feed rate of 1060mm/min, the deposition rate can get to 10kg/h. This method is appropriate for fabricating large-scale metal parts with outstanding quality, efficiency and low cost.

Keywords: New AM method, HDMR (hybrid deposition and micro rolling), metallic parts, High performance, efficiency and low cost

1. Introduction

With the increasing of manufacture competition, developing an advanced manufacturing technology, which is efficient and low-cost, is particularly important. Freeform Deposition Fabrication (FDF) as a modern advanced manufacturing technology came into being. However, as FDF is used in metal deposition, some technical bottleneck problems must be took into account, such as cracking, deformation, low accuracy and performance.

The deposition layer surfaces of FDF parts are mostly out of flatness and there is always an error between the actual deposition thickness and the theoretical deposition thickness, which increases along the deposition height. The accuracy is not as high as that of traditional manufacturing. During FDF process, metal parts have to suffer a periodic procedure of rapid heating and cooling, which probably cause components deformation and cracking. Zhang et al. studied the freeform deposition

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conditions such as manufacturing path, energy power, traverse speed and cooling methods (Zhang et al., 2003). Under appropriate deposition conditions, components formability can be improved, but the problems of deformation and residual stress are still not fully resolved during thin-wall parts deposition process.

To improve the accuracy of FDF method, some scholars measure the top surface morphology of the deposition layer to modify the deposition of the next layer. But it will reduce the manufacturing efficiency. Others combine traditional manufacturing method with FDF. Akula and Karunakaran, 2006 and Xiong, X.H., Zhang, H.O. et al., 2009 mill the part after deposition. Zhang et al., 2010 proposes a hybrid deposition and micro rolling manufacturing method to significantly improve manufacturing accuracy, efficiency, formability and properties. This method realizes the freeform deposition and the micro continuous rolling integrated in one manufacturing unit and makes the two processes work simultaneously. Components can be fabricated with high quality and high efficiency. So this new method is a solution to the bottleneck problems in the direct manufacturing field.

Similar to the hybrid process, Contour Crafting (CC) is another hybrid rapid additive fabrication process (Khoshnevis et al., 2001). In order to create smooth and accurate planar and free-form surfaces of the object, it adopts the bladed towel instead of the roller to smooth out the striations between consecutive layers under computer control. Therefore, hybrid process is more suitable for metallic materials while CC is more disposed for non-metallic materials such as plastic materials.

2. Principle, devices and simulations

2.1 The principle and devices of hybrid manufacturing method

The principle is shown in Fig.1. In hybrid manufacturing method process, metal parts are fabricated by hot rolling (the temperature is above recrystallization temperature) immediately after deposition. Comparing to FDF process, this method has three advantages. Firstly, the top surface flatness gets significant improvement, from middle-convex to nearly plane. What's more, the residual stress can be reduced under a certain pressure. And the last one is that hybrid method can decompose the coarse grain into fine grains, eliminating cracking and deformation.

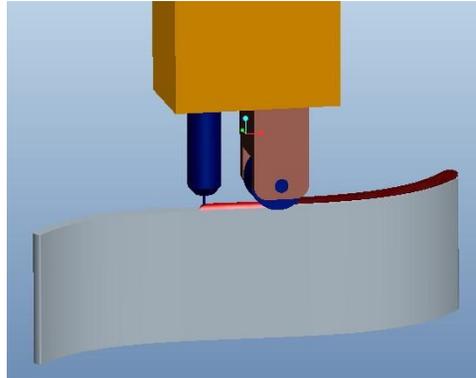


Fig. 1. The principle of hybrid manufacturing method

2.1.1 Energy source followed micro continuous rolling device

As shown in Fig. 2, the energy source followed micro continuous rolling device integrates the energy source and the micro roller together. The roller would follow the energy source and smooth the top surface in deposition process. Even when the deposition path is curve or other complex path, the roller can fix on the top surface by rotating the part. Since the manufacturing temperature is very high, a water cooling system is designed to protect the entire device.

Paul et al., (2013) also uses hybrid high-pressure rolling to deal with the deposition parts. But the improvements of accuracy and performance are limited since the rolling position of the device is far away from deposition position. Parts are not fabricated by hot rolling immediately after deposition. What's more, their device can only be used in linear deposition. Through the comparison we can find our hybrid method is more flexible and space-saving since it can be used for manufacturing curved surface in one workstation.

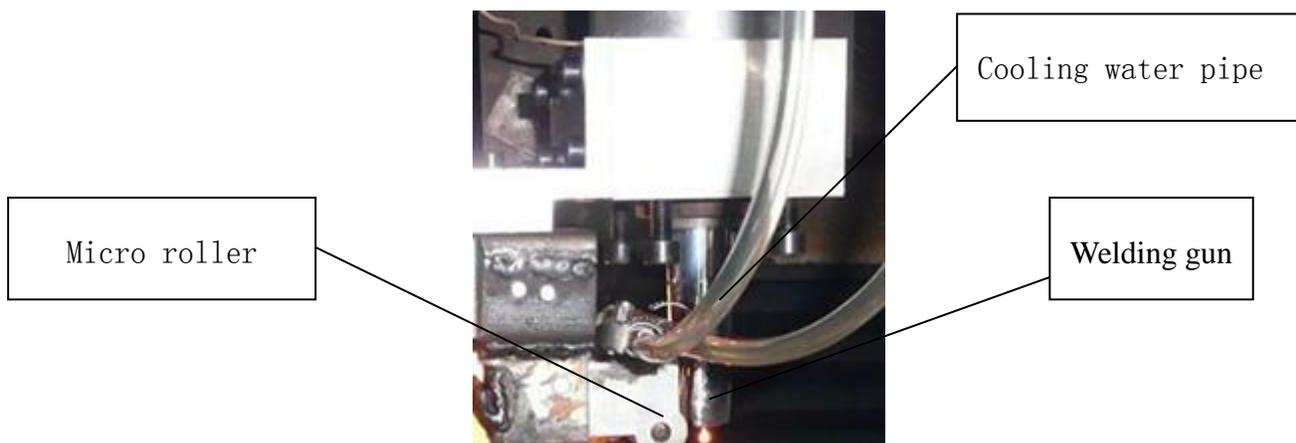


Fig. 2. Energy source followed micro continuous rolling device

2.1.2 Deposition width adjustable micro continuous rolling device

Considering that some large-scale parts have broad-area slices, a width adjustable device is added to improve the deposition efficiency. In this way the device can produce a larger deposition width, in the range of 0 to 30 mm, by means of the energy source swinging along the direction perpendicular to the forward direction.

2.2 Simulations of hybrid manufacturing devices

Since the stress and strain field in the deposition manufacturing process is difficult to be measured, it is necessary to make process simulations for the hybrid manufacturing devices. And the results reveal the important role of hybrid manufacturing devices.

2.2.1 Stress field simulations

The maximum principal stress field simulations are shown in Fig.3. The deposition material is stainless steel and the roller is made of 45# steel. The initial temperature of the part is 293K while that of the roller is 313K. The deposition current is 220A and the voltage is 28.6V with 70% thermal efficiency. The part is 90mm long, 8.5 wide and 10mm height. The roller diameter is 30mm and the length is 30mm. Moving speed of the energy source is 0.01m/s. The rolling reduction is 0.5 mm and the energy-roller distance is 50mm.

The hybrid manufacturing method makes an upside-down change to the maximum principal stress field of FDF parts. The maximum principal stress moves from bottom of the parts to the top surface, which is of great effect for reducing the warping deformation of the base plate and leads to the improvement of manufacturing accuracy in deposition process.

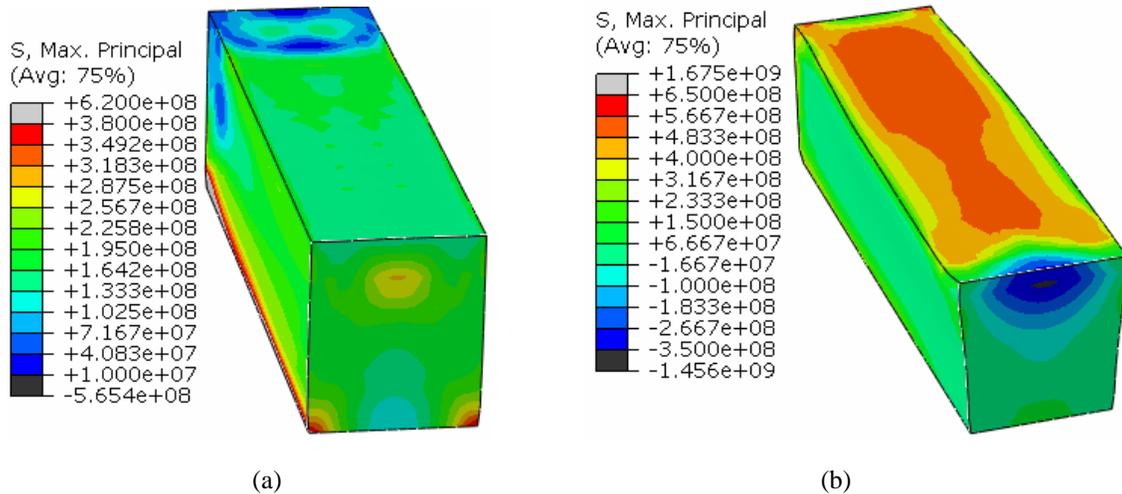


Fig. 3. Maximum principal stress (Pa) field simulations of parts made by FDF (a) and hybrid manufacturing method (b)

What's more, the maximum principal stress fields of the faces where the roller last leaves (the faces near us) are analyzed. The stress distributions are shown in Fig.4. After hybrid manufacturing, the original tensile stress of FDF parts decreases or even changes into compressive stress. Compressive stress has a tendency to compensate for deformation, which is of great help to the inhibition of cracking and deformation.

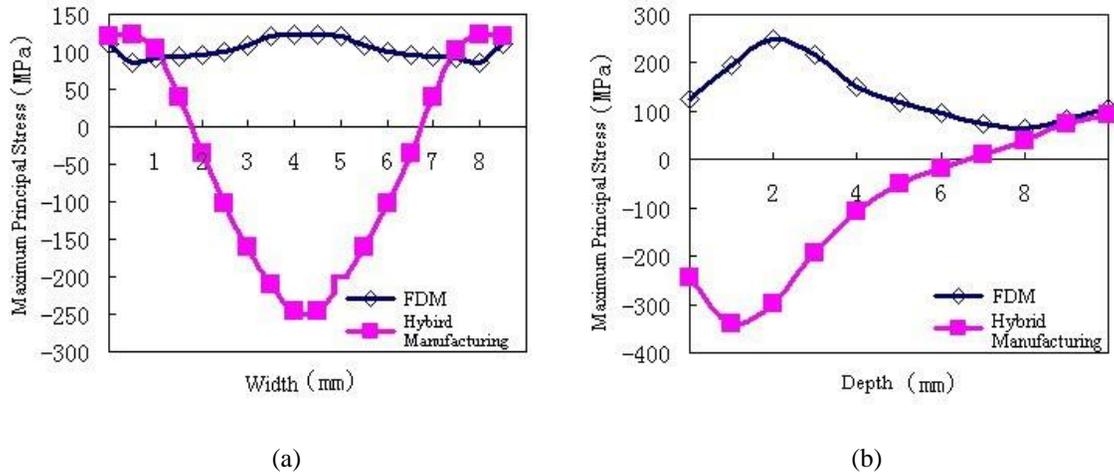


Fig.4. Width direction (a) and depth direction (b) maximum principal stress of the faces where the roller last leaves

2.2.2 Strain field simulations

The strain field simulations of FDF part and hybrid manufacturing part are shown in Fig.5-6. As is known to all, metal parts would contract with cold after deposition, which is a key problem to affect the dimensional accuracy. With hybrid manufacturing method, the strain values in both sides of metal parts increases, meaning the tensile deformations happen. These deformations compensate the cooling deformation, reducing the impact of cooling on the metal parts to some extent.

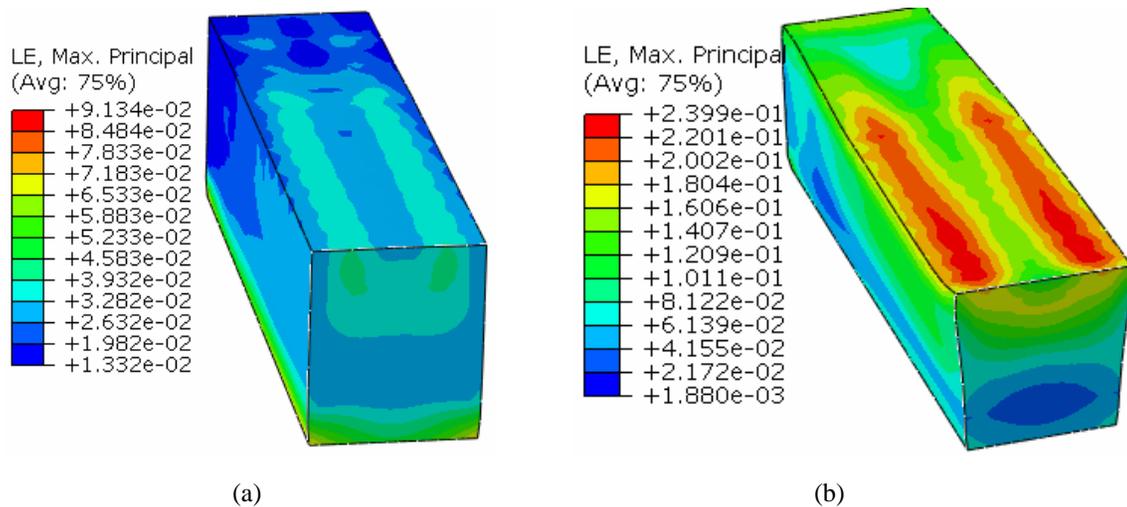


Fig. 5. Maximum principal strain field simulations of parts made by FDF (a) and hybrid manufacturing method (b)

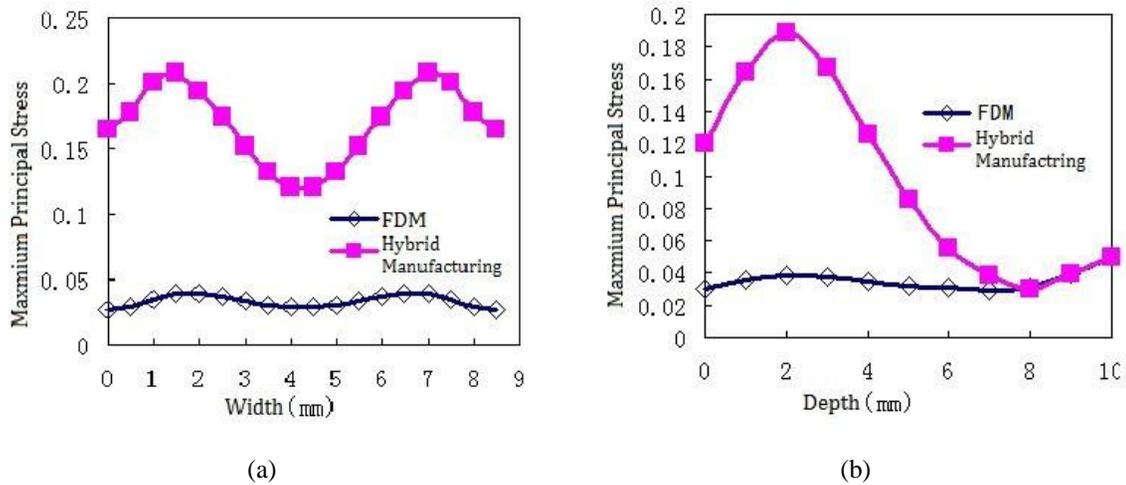


Fig. 6. Width direction (a) and depth direction (b) maximum principal strain of the faces where the roller last leaves

2.2.3 Temperature field simulation

To research on the microstructure of the deposition parts, temperature field simulations are necessary. As shown in Fig.7, because of the cooling system of the roller (the location of the black vertical lines) in hybrid manufacturing process, the heat-affected zone of the part made by hybrid manufacturing method is much smaller than that of the part made by FDF method. It means the material would be cooled faster and the grains would be smaller since they would stop grows after a certain temperature. The temperature curves of the parts simulated in Fig.7 are shown in Fig.8. The temperature of the part made by hybrid manufacturing method plummets during the cooling of the roller, which contributes to the smaller grain size and better performance.

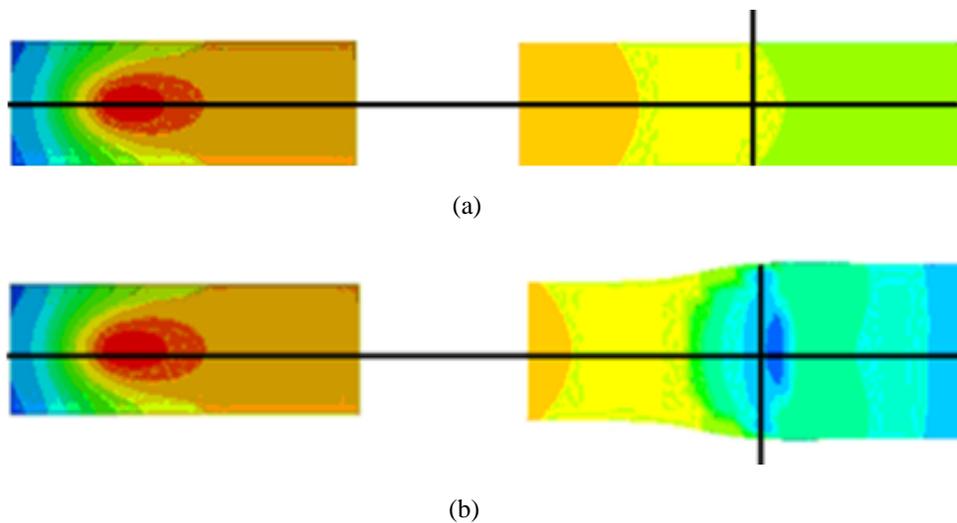


Fig.7. Temperature simulations of parts made by FDF (a) and hybrid manufacturing method (b)

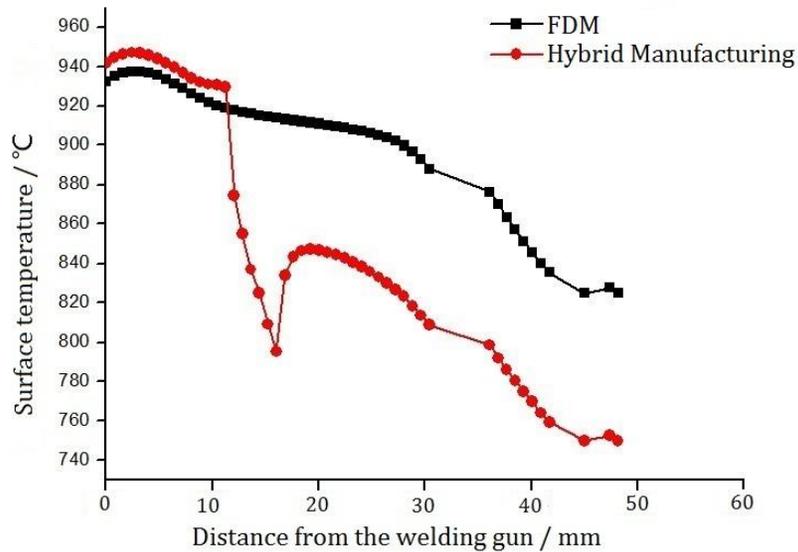


Fig.8. Surface temperature curves of parts made by FDF and hybrid manufacturing

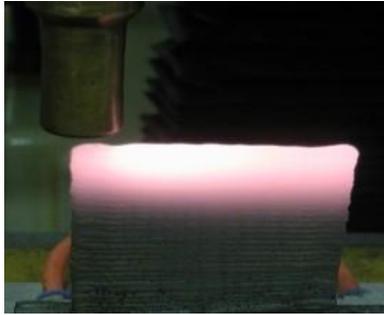
3. Experiments of the hybrid direct manufacturing process

3.1 Conditions

A 3-axis Computer Numerical Control (CNC) machine is employed to fabricate a linear thin-wall part. The stroke of X is 230 mm and that of Z is 160 mm. The raw material is stainless steel and plain carbon steel wire with 1.2 mm diameter. A Metal Inert-Gas welding gun is set and a micro continuous rolling device following the welding gun is used to realize hybrid manufacturing process. The special G codes, consisting of the starting and ending instruction of deposition, are generated from self-developed software to make the hybrid process controlled automatically.

3.2 Process

The manufacturing experimental process and temperature fields during the process are shown in Fig. 9. The high-temperature zone of part in FDF process is much larger than that of part in hybrid manufacturing process. And the temperature of the part after cooling of the roller is much lower than that in FDF process. In order to verify the accuracy of the temperature simulations above, the temperature of part made by hybrid manufacturing method is shown in Fig.10.

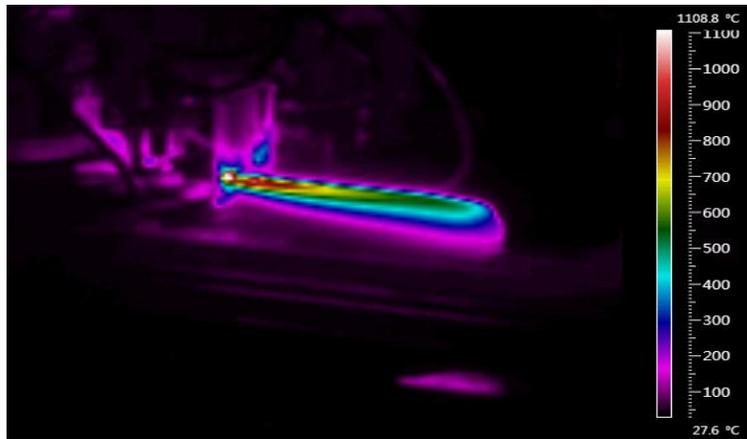


(a)

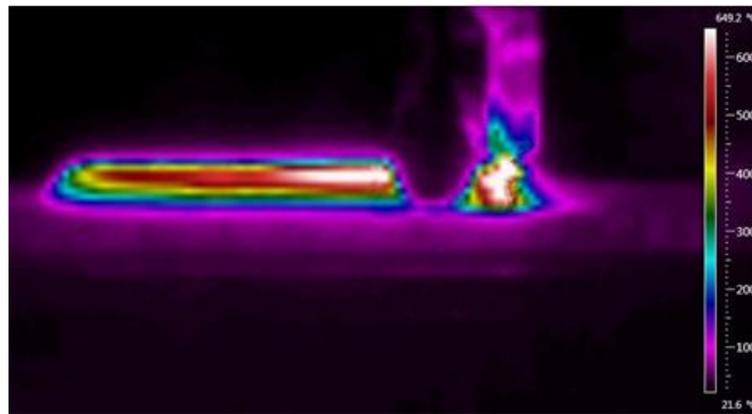


(b)

Fig.9. Manufacturing experimental process of FDF method (a) and hybrid manufacturing method (b)



(a)



(b)

Fig. 10. Temperature fields of manufacturing experimental process of FDF method (a) and hybrid manufacturing method (b)

3.3 Experimental results

3.3.1 Accuracy

As shown in Fig.11, the middle-convex top surface which occurs in FDF process would be flat after hybrid deposition. The problem of surface undulation and cracking has been solved effectively. And the problem of porosity in most deposition method can be suppressed to some degree. What's more, the flowing phenomenon is alleviated and material utilization rate becomes higher. Above all, the thickness of each layer constant (1.2mm in the experiment), which means the thickness can be controlled accurately. That could be a breakthrough to solve the low accuracy problem of FDF brought by the error between the actual deposition thickness and the theoretical deposition thickness.

3.3.2 Structure and properties

As shown in Fig. 12, the grain size of hybrid manufactured part is smaller. The density is higher and the microstructure is more homogeneous. A contrast tensile test (Fig. 13) was carried out to evaluate mechanical properties. For plain carbon steel, the tensile strength is increased by 33% and the tensile deformation is improved more than 2 times for hybrid manufactured part than those for FDF part.

The same as the simulations, we can conclude from the result that the hybrid manufacturing method is capable to refine the microstructure and improve the tensile properties significantly. There might be two reasons why those happen. One clear reason is the utilization of water cooling system since the grain growth will be subjected to restraining. Micro hot rolling may be another considerable factor since it can decompose the coarse grain into fine grains and transform as-cast microstructure into deformed microstructure.

It is worth noting that there are two cooling sources for each layer during hybrid manufacturing process. One is the roller and another is the substrate for the first layer and previously deposited layers for the other layers. In general, the first layer has highest cooling rate because cold roller and cold substrate can absorb heat quickly. As with any other layered manufacturing process, there is a significant heat accumulation since layers (except for the first layer) are deposited on the previous layer which is already hot. In addition, surfaces of the roller have also been hot in subsequent rolling. Thus, the cooling rate decreases along the deposition height. In order to maintain almost equivalent cooling rate for each layer, the suitable roller position should change as the build progresses.

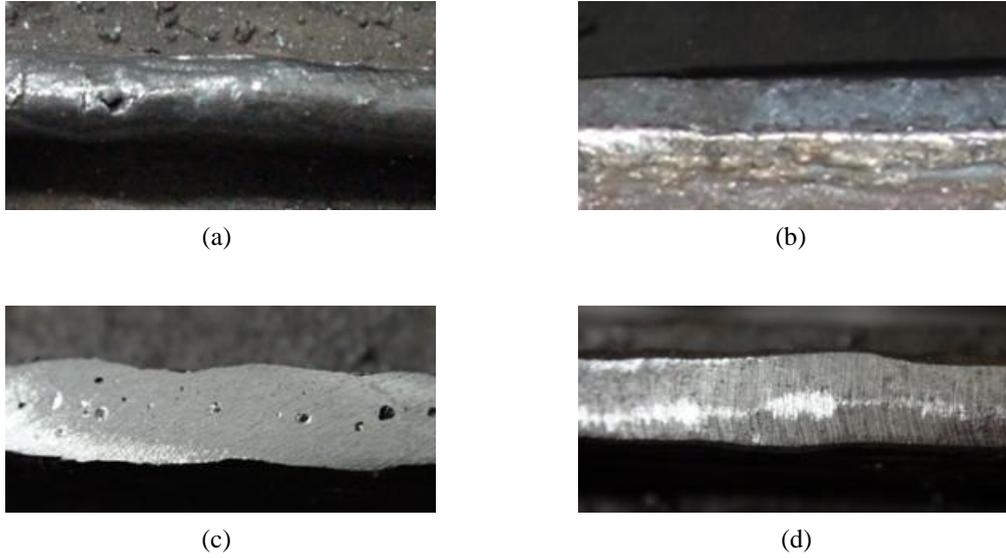


Fig. 11. Surface and profile comparison between parts made by FDF (a, c) and hybrid manufacturing method (b, d)

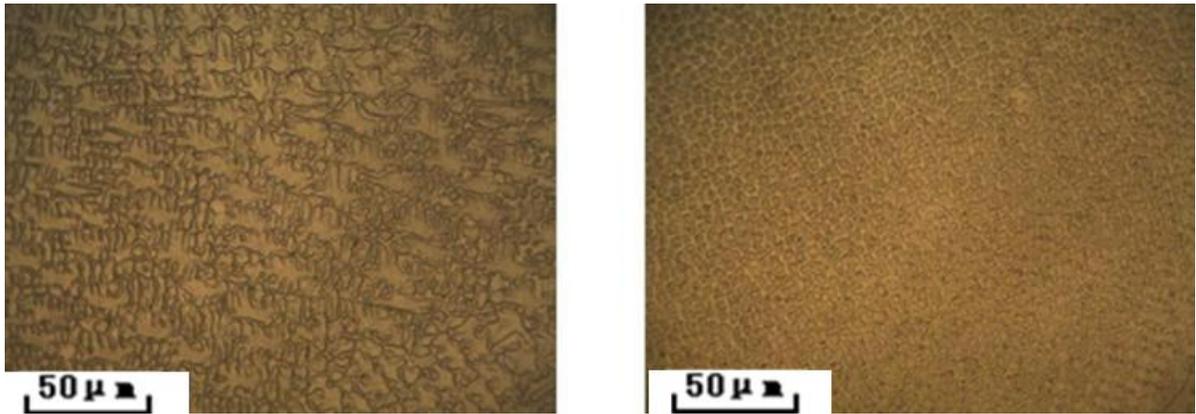


Fig. 12. Optical microscope microstructure comparison between parts made by FDF (a) and hybrid manufacturing method (b)

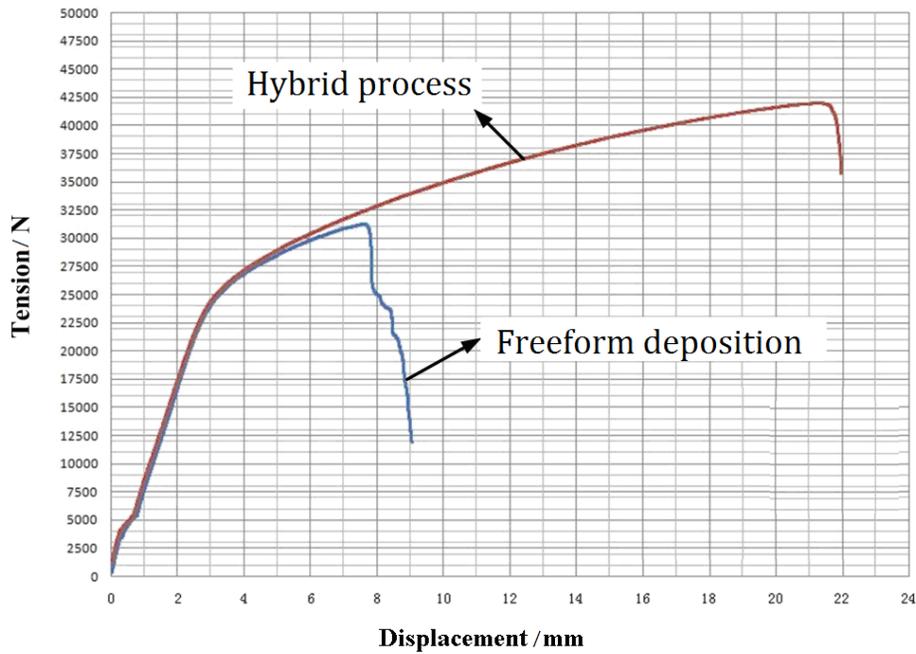


Fig. 13. Tensile test results comparison between parts made by FDF and hybrid manufacturing method

4. The manufacture of a large-scale metallic part using hybrid manufacturing method

4.1 Manufacturing conditions

The thin-wall part with a complicated surface locally similar to the saddle could be fabricated by direct deposition manufacturing method. The 3-D CAD model of the part represented in STL format is shown in Fig. 14. A 6-DOF industrial robot is used in the manufacturing process. The welding gun and the hybrid manufacturing device are mounted on the end-effector of the robot. The raw material is welding wire with 1.6 mm diameter. As the width of each slice of the metal part, namely wall thickness of the part, is beyond the maximum width of single-pass deposition, the deposition width adjustable micro continuous rolling device is used to realize hybrid manufacturing.

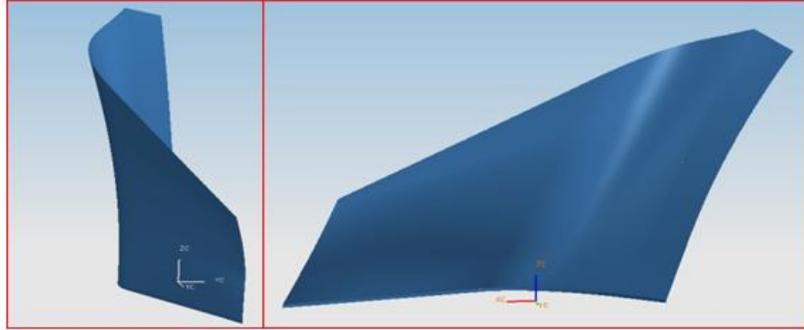


Fig. 14. STL model of the thin-wall part

4.2 Manufacturing process

The STL model of the part is decomposed into a series of slices by intersecting itself with a set of horizontal planes under a certain tolerance parameter such as the maximum allowable cups height. At the same time, the hatching paths for each slice are generated by appropriate process parameters such as hatching width and the pattern of hatching. The above procedures occur in the computer. Then the hatching paths represented in JBI format are sent to the fabricator, namely Motoman robot. Similar to the G code above mentioned, a JBI extension that consists of the starting and ending instruction of the MIG welding machine is applied. The robot reads and identifies a JBI file, then make the end-effector move along the defined paths. Since this part is large-scale, lots of heat would be generated and built up during the manufacturing process and the water cooling method was used to reduce thermal deformation of the substrate. To make sure there was no porosity in the part, the shield gas was enable before the manufacturing starting and disable after the manufacturing ending. The manufacturing parameters are demonstrated in Table 1.

Table 1. The hybrid manufacturing parameters of the large-scale metal part

Energy power (kW)	Energy source speed (mm/min)	Energy source-roller distance (mm)	Energy source swinging frequency (Hz)	Wire speed (m/min)
10	450	20	0.83	5.0

4.3 Manufacturing results

As shown in Fig.15, the maximum height of the part is 1200 mm, the maximum width is 1600mm and the average wall thickness is 15 mm. There is no obvious flowing phenomenon. Air-tightness test shows there is no hot cracking and porosity inside the part. The manufacturing accuracy is improved significantly, and by using $\Phi 1.6\text{mm}$ wire in a wire feed rate of 1060mm/min in the fabricating process, the deposition rate of hybrid manufacturing method can get to 10kg/h.



Fig. 15. The finished part

5. Conclusions

This paper proposed the HDMR manufacturing method and developed hybrid manufacturing devices. Simulations and experiments were carried out for the hybrid manufacturing process. The results and conclusions are as follows:

(1) The top surface of the hybrid manufacturing deposition layers is flat instead of middle-convex and the profile has no cracking and porosity. The tensile strength is increased by 33% for stainless steel while the elongation percentage is improved more than 2 times. So this new method can reduce flowing phenomenon and improve the components formability and accuracy.

(2) The deposition layers' thickness can be controlled accurately using this method, which can resolve the common problems in present FDF technology brought by the error between the actual deposition height and theoretical deposition height.

(3) The simulations of stress, strain and temperature fields show that the hybrid manufacturing method makes contributions to the more compact microstructure with smaller grains.

(4) A large-scale metal part is fabricated using this new method, which shows the hybrid process is capable to fabricate large-scale metal parts with low cost, high quality and great efficiency. By using $\Phi 1.6\text{mm}$ stainless steel wire in a wire feed rate of $1060\text{mm}/\text{min}$ in the

fabricating process, the deposition rate of hybrid manufacturing method can get to 10kg/h, which is much more than LENS. So it has great value for industrial application.

So far, this hybrid manufacturing method has been utilized with top surface rolling only, expanding it into top and side surface rolling at the same time is the trend for this new method.

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