Experimental study on repairing of damaged cast iron cylinder heads by 3D printing arc welding system

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Abstract. To realize repairing of damaged cast iron cylinder heads by 3D printing arc welding system mainly composed of an industrial robot and an arc welding machine, the remanufacturing process flow of 3D printing arc welding system was introduced, and a single straight wall stacking experiment was designed. The effects of process parameters on the appearance quality and mechanical properties of welding pieces were studied. The forming laws of welding piece were obtained. The main conclusions include: The higher the preheating temperature, and interlayer temperature, the more obvious the effects of process parameters on the hardness of welding pieces, and the effects of preheating temperature are more evident than that of interlayer temperature. With the increase of layer number, the hardness of welding pieces decreases gradually. When welding piece is lower than eight layers, the rise of width and height of the welding piece is approximately proportional to the increase of layers. Those conclusions of this paper provide general guidance and technical support for the repairing of cast iron cylinder heads and welding of other cast iron parts.

1. Introduction

Due to advantages of low price, durability, and high strength, cast iron cylinder heads are still widely used in high-powered engines and turbocharged engines [1]. During handling, cast iron cylinder heads will be damaged for cracks, porosities, wear, and other problems. At present, the disposal method of rusted cast iron cylinder heads has been gradually changed from recycling to remanufacturing to reduce energy and resource waste and environmental pollution [2]. 3D printing arc welding system mainly composed of industrial robot and arc welding machine has the characteristics of high efficiency, good flexibility, energy saving and so on [3]. The application of the system to repair damaged cast iron cylinder heads can realize the high efficiency and high quality remanufacture of cylinder heads.

For cast iron having poor weldability and producing cracks efficiently in welding [4, 5], it is necessary to reasonably select welding specifications and process parameters to repair damaged cast iron cylinder heads by 3D printing arc welding system. Besides, when slicing treatment and path planning are carried out, it is necessary to know height and width of welding pieces under selected process parameters to determine rising height of welding gun and welded channels per layer [6]. Those process parameters need to be obtained by experiment.

Therefore, a single straight wall stacking experiment is designed, the influence of welding process parameters on the appearance quality and mechanical properties of welding pieces is studied, and the welding forming laws are obtained, which provide reference process parameters for 3D printing arc welding system to repair damaged cast iron cylinder heads. The research results in this paper can guide...
actual repairing of damaged cast iron cylinder heads by arc welding, and also provide technical guidance and technical support for welding of other cast iron parts.

2. Remanufacturing process flow of 3D printing arc welding system

The remanufacturing of 3D printing arc welding system is a process of repairing damaged metal parts by melting and depositing with welding robots. The remanufacturing process flow is shown in figure 1. Firstly, 3D digital model of welding piece is got through 3D digital models of the intact metal part and damaged metal part obtained by 3D scanning and modeling softs. Then, the 3D digital model of welding piece is sliced, and the geometric shape of each slice is formed along a particular path (path planning). Finally, the welding piece is welded, and the damaged metal part is repaired.

In the process of slicing, path planning and welding of the 3D model of welding piece, it is necessary to set process parameters including forming parameters (such as layer numbers, welding direction and so on) and the welding parameters (such as wire feeding speed, welding speed, damaged piece's height, etc.). Those forming parameters and welding parameters affect appearance quality, mechanical properties of repairing part and bonding strength between repaired part and substrate. Therefore, the forming welding experiment should be carried out before repairing to determine the forming laws and obtain the optimal repairing process parameters.

![Figure 1. Remanufacturing process flow of 3D printing arc welding system](image)

3. The experiment on welding forming laws

3.1. Experimental equipment and materials

Experimental equipment: 3D printing arc welding system selected by the experiment is mainly composed of MotoMan-Up20 industrial arc welding robot produced by Yaskawa Company of Japan and MotoWeld-S350 automatic arc welding machine. The wire feeding speed of the welding machine is automatically matched according to the current, and they are proportional to each other.

| Chemical composition | C     | Si    | Mn    | S     | P     |
|----------------------|-------|-------|-------|-------|-------|
| Z308                 | ≤2.00 | ≤2.50 | ≤1.00 | ≤0.03 | ≤1.00 |

Experimental materials: welding wire Z308 with a diameter of 1.2 mm (see table 1 for chemical composition) is selected as the experiment material. The welding wire Z308 is a pure nickel-based cast
iron welding wire which has strong crack resistance and good machinability and can be used for surface repairing of thin-walled workpiece [4]. HT300 is selected as substrate.

Hardness testing of welding pieces is carried out by HVS-1000 digital microhardness tester.

3.2. Experimental scheme

To repair damaged cylinder heads, it is necessary to obtain the influence of process parameters on the geometric size and mechanical properties of welding piece. Therefore, a single straight wall stacking experiment is designed. In the experiment, welding voltage, welding current, welding speed, preheating temperature of substrate and interlayer temperature are selected as process parameters.

In the experiment, a single straight wall welding piece with a length of about 100 mm and eight layers are welded with each group of process parameters. The welding adopts one-way welding path, and the arc is extinguished after each layer is finished. The interlayer temperature is controlled within the set range. After a layer is completed, welding gun is raised, and the raising height kept consistent with that of the previous layer, width and height of welding piece are measured at the front, middle and rear positions of the middle part of the welding piece. The average value of the three values is recorded as welding width and height in this layer. After the 8th layer is finished, the welding piece is divided into three layers with the same interval along the vertical direction. The hardness of each layer is measured at the front, middle and rear positions. The average value is used as the hardness of this layer. The average value of the hardness of the three layers is taken as the hardness of the welding piece.

In order to prevent welding pieces from whitening, inclusion porosity, refractory oxides, cracks, or deformation, the following measures are adopted in the experiment: polishing substrate to eliminating oxide skin, removing impurities such as surface oil and dirt, preheating substrate before welding, increasing welding speed when welding current increase in order to control heat input and tapping welding pieces with hammer to reduce internal stress immediately after welding. Considering that repairing methods should be convenient and fast, preheating temperature of the substrate should be as low as possible and should be conveniently realized. In the experiment, the preheating temperature is controlled within the range of (60-120) °C.

Before the straight wall stacking experiment, the range determination experiment of welding parameters is carried out by observing the appearance quality of welding pieces. The experiment results show that when welding voltage is 50%, the welding current is within (230-270) A and the corresponding welding speed is within (40-60) (cm/min), the appearance quality of the welding pieces is the best, and the welding pieces are in good contact with the substrate.

4. Experimental Results and Analysis

4.1. Hardness

| Group | Preheating temperature (°C) | Interlayer temperature (°C) | Welding current (A) | Welding speed (cm/min) | Hardness (HV) |
|-------|-----------------------------|-----------------------------|---------------------|------------------------|---------------|
| 1     | 100-120                     | 60-70                       | 230                 | 40                     | 237.7         |
|       |                             |                             | 250                 | 50                     | 374.6         |
|       |                             |                             | 270                 | 60                     | 310.5         |
| 2     | 60-70                       | 60-70                       | 230                 | 40                     | 334.9         |
|       |                             |                             | 250                 | 50                     | 287.7         |
|       |                             |                             | 270                 | 60                     | 359.2         |
| 3     | 60-70                       | 30-40                       | 230                 | 40                     | 324.1         |
|       |                             |                             | 250                 | 50                     | 294.8         |
|       |                             |                             | 270                 | 60                     | 334.7         |
Table 2 shows the hardness of some welding pieces which are higher than that of the substrate of 220 HV and also higher than or within the range of (179-235) HB required by the design of cast iron cylinder heads [7].

The following conclusions are drawn from table 2 that when interlayer temperature, welding voltage, welding current and welding speed are the same and preheating temperature differences are about (30-60) ℃, the minimum hardness difference is 48.7 HV, which indicates that the variation of preheating temperature has effects on hardness at the interval (30-60) ℃.

From table 2, it is also concluded that when preheating temperature, welding voltage, welding current, welding speed are the same and interlayer temperature differences are about (20-40) ℃, the maximum hardness difference is 24.5 HV, which indicates that the variation of interlayer temperature has effects on hardness at the interval (30-60) ℃. However, the results are not apparent.

Table 3. Hardness variation amplitude of welding pieces

| Groups | Preheating temperature (℃) | Interlayer temperature (℃) | Maximum hardness (HV) | Minimum hardness (HV) | Variation amplitude of hardness (HV) |
|--------|-----------------------------|-----------------------------|-----------------------|-----------------------|--------------------------------------|
| 1      | 100-120                     | 60-70                       | 374.6                 | 237.7                 | 136.9                                |
| 2      | 60-70                       | 60-70                       | 359.2                 | 287.7                 | 71.5                                 |
| 3      | 60-70                       | 30-40                       | 334.7                 | 324.1                 | 39.9                                 |

The maximum and minimum hardness of each group in table 2 are subtracted to obtain the variation amplitude of hardness under this group of process parameters (where the welding current varies within the range of (230-270) A, and the welding speed varies within the range of (40-60)(cm/min), as shown in table 3. From table 3, it is concluded that the higher the preheating temperature and interlayer, the greater the hardness variation amplitude is. The results indicate that the effects of process parameters on hardness are more apparent when preheating temperature and interlayer temperature are higher.

Besides, it is also concluded that hardness tends to decrease with increasing of layers, which is the same as that in references [2, 8].

4.2. Welding Forming Laws

![Figure 2](image-url)

Figure 2. Welding forming laws

Figure 2 shows the forming laws of the welding pieces when the preheating temperature is (100-120) ℃, and the interlayer temperature is (60-70) ℃. In figure 2, lines 1, 2 and 3 are the curves of relationship between weldingpiece width, welding piece height and layer number when welding currents are 230 A,
250 A, and 270 A, and corresponding welding speeds are 40 (cm/min), 50 (cm/min), and 60 (cm/min), respectively. According to figure 2, the welding piece width and welding height increase approximately proportionally with increasing of layer number.

Lines 1’, 2’, and 3’ in figure 2 are linearly fitted curves corresponding to lines 1, 2, and 3, respectively. The equations for lines 1’, 2’, and 3’ are as follows.

\[ w_i = 1.30n + 8.51, \quad w_2 = 1.23n + 7.58, \quad w_3 = 0.86n + 8.63 \] 
\[ h_1 = 2.42n + 0.87, \quad h_2 = 2.16n + 1.60, \quad h_3 = 2.00n + 1.35 \]

(1) (2)

Here, \( w_i \) and \( h_i \) are the width and height of the welding piece \( i \), respectively, while \( n \) is the layer number.

It was also found that after the 6th layer is finished, the new coating did not affect the width of the first layer of the welding piece. When the welding piece exceeds ten layers, the change in the width of the welding piece becomes smaller and tends to be fixed.

5. Conclusions

To successfully apply 3D printing arc welding system to repair damaged cast iron cylinder heads, a single straight wall stacking experiment is designed. The effects of process parameters on appearance quality and mechanical properties of welding pieces are studied. The welding forming laws of welding pieces are established and analyzed. The following conclusions are obtained.

✓ Preheating temperature of substrate and interlayer temperature have effects on the hardness of welding pieces, and the effects of the preheating temperature are more visible. The higher the preheating temperature and the interlayer temperature, the more obvious the effects on the hardness of welding pieces.

✓ Even though the hardness of welding pieces at different welding process parameters is different, the hardness variation law along the normal direction of the bonding interface is consistent, and the hardness decreases gradually with the increase of the number of layers.

✓ When the welding piece has less than eight layers, the welding piece width and height increase nearly proportionally with the number of layers. After that, the welding piece width tends to be fixed.

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