Additive remanufacturing of coupler knuckle based on robotic gas metal arc welding

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Abstract. Take the wear parts of coupler knuckle as an example, the “Modeling—Slicing—Stacking” mode remanufacturing process is studied. First, the 3D model of the worn coupler knuckle surface is acquired by structured light 3D detection. The remanufacturing model of the failure part is built by Boolean operation between the original model and the acquired 3D model. Second, the user can slice layer of the remanufacturing model according to the remanufacturing stacking parameters. The zone that surrounded by the contour of each sliced layer is the robotic GMAW remanufacturing stack region. Third, the robotic GMAW remanufacturing path is planed within the region mentioned above and the executable program is generated to carry out the remanufacturing task layer by layer. Moreover, the worn coupler knuckle was repaired by adopting Robotic GMAW Process. The mechanical performances of component were tested, the results indicate that the remanufactured coupler knuckle satisfying the operating requirements.

1. Introduction
Remanufacturing refers to the production process of professionally repairing waste auto parts, construction machinery and machine tools [1-4]. To carry out the remanufacturing and repair of important parts, the life cycle of the product can be extended and the resources can be recycled. This technology embodies the advanced form of “reuse” in circular economy and has attracted much attention all over the world.

The connection of locomotive-vehicle or vehicle-vehicle is realized through the coupler in the coupler buffer device, so that the distance between the vehicles is maintained. Meanwhile, the traction force and impact force are transferred from the coupler to the traction beam through the buffer, buffer the impact vibration between the vehicles and protect the vehicles and goods. The failure form of couplers is mainly fatigue or brittle fracture. In order to ensure the strength and service life of couplings, it is necessary to have high yield strength, fracture strength, fracture toughness, low temperature impact toughness and so on. The knuckle in the coupler buffer device has the lowest cost and is easy to replace. Therefore, the design strength of the coupler can be minimized, it can be damaged first to protect the buffer and the chassis in case of unexpected large traction force and impact force [5].

The appearance photo of the 13A coupler knuckle is shown in Figure 1, the schematic diagram of the working state of the coupler knuckle is shown in Figure 2. In the train operation, starting, braking, shunting to bear random, alternating stretching, compression, impact and bending moment action.
Especially in the shunting operation, the coupler knuckle is often subjected to a great impact, coupled with the poor use conditions, resulting in its S-surface is easy to wear, need to be repaired, even produce fatigue cracks out of limit scrapped [6]. According to the literature, the coupler knuckle that needs surfacing repair accounts for about 70% - 80% of the total coupler knuckle [7-9]. Song et al. developed an automatic welding system based on PLC to repair the curves plane of coupler knuckles. Their control system can drive welding torch to move in the line of S and drive the workbench of Z orientation to move up and down [10]. Another work of Song is designing a Jig for the automatic welding of the coupler knuckle, the welding precision can be improved a lot with the Jig [11].

Figure 1. The photograph of coupler knuckles.

In the reference works about the remanufacturing of coupler knuckle, the intelligence is lack, the detection, modelling and the path plan are not involved. Moreover, the quality the remanufactured coupler knuckle is unknown. In this paper, the remanufacturing repair of 13A coupler knuckle worn parts (made of ZG25MnCrNiMo low alloy cast steel) was taken as an example to study the implementation process of robot gas metal arc welding (GMAW) additive remanufacturing and the service performance of the remanufactured parts.

2. Coupler knuckle remanufacturing path planning

2.1. Three-dimensional model of the defective part of the worn coupler knuckle

As shown in Figure 2, the working surface of the coupler knuckle is the S-shaped wear surface in Figure 3, this surface is a complex surface produced by the mutual constraints of multiple features. The surface of the part has no feature information that can be used for three dimensional model matching and a reference plane for establishing the user coordinate system of the welding robot. Therefore, the above feature information must be constructed and added to the part, as shown in Figure 3, an auxiliary positioning plate was welded on the left side of the wear surface of the knuckle and a user coordinate system was defined on the positioning plate.

When the wear surface of the knuckle is tested in three dimensions, the positioning plate is regarded as a part of the knuckle, the positional relationship between the points on the S shaped wear surface of the knuckle and the user coordinate system is a known condition. When matching the three-dimensional detection surface features with the original parts, the vertices of the positioning plate are used as the matching feature points, thereby solving the problem of lack of feature information and reference planes on the surface of the part.

In this paper, the S-shaped wear surface of the coupler knuckle was firstly detected by three dimensional detection, then the three-dimensional information of the surface was calculated. Figure 4 shows the three-dimensional point cloud of the S-shaped wear surface of the coupler knuckle obtained by the line structured light three-dimensional detection and sensing system and the three-dimensional model of the STL format generated by the three-dimensional point cloud. The three-dimensional model of the defective part of the coupler knuckle can be obtained by Boolean operation between this model and the original model of the coupler knuckle, as shown in Figure 5.
2.2. Remanufacturing path planning of wear failure couplings

Based on the analysis of the three-dimensional model of the defective part of the coupler knuckle, it was found that the wear amount of the S-shaped surface was about 2mm, and it was only necessary to apply a layer on the worn surface of the coupler knuckle by using robotic GMAW additive remanufacturing method.

According to the characteristics of the profile curve of the weld bead, it was reasonable to believe that there was an optimal centerline spacing of the weld bead, so that two adjacent weld beads overlap appropriately, and the deposited layer formed was the smoothest. Figure 6 is a schematic diagram of the formation process of the welding build-up layer, where D is the centerline spacing of the weld bead and W is the width of the weld bead.

It can be concluded from Figure 6 that the optimal D value should make the area of $S_1$ equal to the area of $S_2$ in the figure, so D should satisfy $\frac{1}{2}W < D < W$.

According to the regulations of Railway Freight Car Factory Repair Regulations [12] in Tieyun (2002) No. 72 document, the design thickness dimension of the S-surface of 13A type train knuckle is 73mm. When the residual thickness of abrasion reaches 69mm, it needs to be repaired. Firstly, the process experiments were carried out by using DC GMAW arc as heat source, the deposition welding wire is H08Mn2SiA. The appropriate deposition parameters were selected as follows: voltage 25.3V, current 272A, deposition speed 8.33mm/s, dry elongation about 15mm, protective gas composition: 95%Ar+5%CO2, gas flow rate 17L/min, according to the experimental verification data, the width of a single pass at this time was about 11mm, the optimal centerline spacing of the weld bead was calculated to be 6.7mm.

The path planning result of robot GMAW remanufacturing is shown in Figure 7, the welding test result is shown in Figure 8 according to the robot program generated by path planning.
3. Service performance of additive stacking layer of coupler knuckle

3.1. Test of compression and shear properties at room temperature

The working condition of the coupler knuckle is subjected to a certain compression shear force, and the compression shear tests of the base metal and the deposition layer were carried out at room temperature respectively. According to its working condition, the sample was cut perpendicular to the deposition direction on the cladding layer and the base metal. The test equipment was INSTRON5569 electronic universal material testing machine, the loading speed was 1mm/min. The test results were shown in Table 1. Compared with the shear strength of the cladding layer and the base metal, it can be seen that the overall shear property of the cladding layer meets the requirements of use, but it is uneven and fluctuates greatly.

![3D modeling of the worn coupler knuckle](image)

(a) Points cloud of worn surface  (b) STL model of worn surface  (c) Remanufacturing model of coupler knuckle

**Figure 5.** The 3D modeling of the worn coupler knuckle.

![Tool path plan model](image)

**Figure 6.** The tool path plan model of robot GMAW remanufacture.

![Remanufacturing path](image)

**Figure 7.** The remanufacturing path of the coupler knuckle.

![Remanufacturing result](image)

**Figure 8.** The remanufacturing result of the coupler knuckle.
Table 1. Results of compression shear test.

| Sample | Procedure       | shear strength (MPa) | Average Value |
|--------|-----------------|----------------------|---------------|
|        | Surfacing Layer | 564                  |               |
| 1      |                 |                      | 509           |
| 2      |                 | 496                  |               |
| 3      |                 | 468                  |               |
| 4      |                 | 489                  |               |
|        | Base Metal      | 516                  | 499           |
| 5      |                 |                      |               |
| 6      |                 | 493                  |               |

3.2. Bonding strength test at room temperature

The worn surface of the coupler knuckle was repaired by buildup, and the metallurgical combination between the cladding layer and the base metal can be achieved by partial melting of the base metal. The bonding strength was tested to verify its mechanical properties. Samples were cut from the cladding layer and the base metal. The test equipment was the INSTRON5569 electronic universal material testing machine. The loading speed was 2mm/min. The test results were shown in Table 2. The bonding strength of the cladding and the base material meets the requirements of use.

Table 2. Experimental results of adhesive strength test at room temperature.

| Procedure | Adhesive Strength |
|-----------|-------------------|
| 1         | 968               |
| 2         | 941               |

The macroscopic and microscopic morphology of the sample fracture were shown in Figure 9. There is macroscopic plastic deformation near the fracture, and obvious necking occurs, forming a cup-cone fracture, as shown in Figure 9a, the fracture is divided into fiber zone and shear lip zone from the inside to the outside. The fiber area is located in the center of the fracture, showing a gray fiber shape, which is a ductile fracture morphology formed in the stable expansion stage, its microscopic morphology is shown in Figure 9b, which is an equiaxed dimple. The shear lip area is located on the outside of the fracture, the color is dark, the surface is smooth, the angle to the tensile axis is about 45 degrees. When the crack spreads near the surface, the stress state changes to the plane stress state, the ductile fracture is formed along the direction of the maximum shear stress. There is no radiation zone in the entire fracture, the specimen undergoes ductile fracture, the material has good plasticity.

(a) Macrograph photograph  (b) Microstructure photograph of fibrous zone

Figure 9. S surface micrograph after adhesive strength test
3.3. Impact toughness test at low temperature

Under the working condition of coupler knuckle (-40 40°C), withstand the impact load, test the low temperature (-40°C) impact toughness of the cladding layer, get its low temperature impact performance. According to the Charpy pendulum impact test method of GB/T229-2007 metal material, the specimen with V-notch was selected and the test equipment was INSTRON 9250HV all-digital instrumented drop hammer impact testing machine. The loading speed was 5mm/m. The results of impact toughness test at low temperature (-40°C) were shown in Table 3. The fracture surface of the low temperature impact toughness sample was shown in Figure 10. Which is divided into fiber zone, shear lip area and no radiation area on the fracture surface, indicating that the material has good plasticity.

![Figure 10. Fracture surface macrograph after impact toughness test at -40°C.](image)

### Table 3. Results of compression shear test.

| Procedure | Cross-sectional Area (cm²) | Impact Energy (Akv) | Impact toughness(J/cm²) |
|-----------|---------------------------|--------------------|------------------------|
| 1         | 0.04                      | 43                 | 1076                   |
| 2         | 0.04                      | 53                 | 1328                   |
| 3         | 0.04                      | 44                 | 1099                   |

3.4. Hardness distribution test

According to the hardness test method of GB2654-89 welded joint and hardfacing metal, the hardness distribution of cladding layer (including remelting zone and non-remelting zone), heat affected zone and base metal was tested by HB- 3000B Brinell hardness tester on macroscopic samples. The diameter of the indenter was 5mm, the load was 562.5kg, the loading time was 30s. The sample of Brinell hardness test is shown in Figure 11, the test results were shown in Table 4.

Compared the above-mentioned mechanical performance test results with the performance requirements for train knuckles in the standard GB17425 freight car coupler and tail frame procurement and acceptance technical conditions, it meets the requirements for use.

### Table 4. Test results of Brinell hardness.

| Procedure | Position          | HBS  | Procedure | Position          | HBS  |
|-----------|-------------------|------|-----------|-------------------|------|
| 1         | Base Metal        | 202  | 7         | Un-remelted zone  | 193  |
| 2         | Base Metal        | 197  | 8         | Un-remelted zone  | 185  |
| 3         | HAZ               | 288  | 9         | Remelted zone     | 211  |
| 4         | HAZ               | 309  | 10        | Remelted zone     | 193  |
| 5         | HAZ               | 278  | 11        | Remelted zone     | 195  |
| 6         | Un-remelted zone  | 202  | 12        | Remelted zone     | 207  |
4. Conclusion
Taking the worn parts of coupler knuckle as the research object, the implementation process of coupler knuckle repair was studied, and the performance of cladding layer was tested. The main results are as follows:

(1) The three-dimensional wear surface of coupler knuckle was restored by the method of line structured light three-dimensional scanning, and the three-dimensional model of the defective part of coupler knuckle was obtained by Boolean operation.

(2) Through the robot GMAW additive remanufacturing test, the optimal deposition weld bead centerline spacing was calculated, and the path planning was carried out based on this, and the robot GMAW additive remanufacturing path was generated.

(3) Test the mechanical properties of the cladding layer and base metal, including room temperature compression shear performance, room temperature bonding strength, low temperature impact toughness, and hardness distribution test. The results show that the cladding layer material has high plasticity and meets actual requirements.

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Declaration of Competing Interest
The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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