Microstructure and Properties of Nickel - Based Superalloy C-276 Pulse Laser Weld Joints Based on 0.381mm Thickness

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Abstract. Based on Hastelloy C-276 sheet materials, the microstructure, element segregation and mechanical properties of weld joints were studied using pulse laser welding technology. It is noted that there are three morphological grains in the weld zone, which is columnar dendrites, cellular crystals and equiaxed grains, respectively. Compared with the base metal, the microstructure of the weld zone is obviously refined. Element segregation exists in the weld zone where no secondary phases formed. In addition, the microhardness of the weld joints is greater than that of the base metal by 12%. Its yield strength is equivalent to the yield strength of the base metal, and the tensile strength is 93% of that of the base metal. There are plenty of dimples in the fracture of the weld joints and the base metal, and the fracture modes of both are all ductile fracture.

1. Introduction

Hastelloy C-276 derived from Hastelloy C alloy is a kind of solid solution strengthened alloy, which exhibits good thermal stability and resistance to intergranular corrosion because of more Mo elements and a small amount of C and Si elements [1]. Having high strength and good toughness, Hastelloy C-276 is widely used in many fields, such as aerospace industry, petrochemical industry, nuclear industry and so on [2].

Hastelloy C-276 is also austenite alloy, so it is not surprising that many academics are researching the weldability of Hastelloy C-276. M. Manikandan et al. [3] studied Hastelloy C-276 with a thickness of 4 mm using a gas argon arc welding method. The authors found the metal in the weld poor is cooled slowly, which results in a coarse microstructure for the weld joints, the consequent elements segregation and the formation of harmful secondary phases due to the large heat input during the gas argon arc welding process. The strength of the weld joints reduced eventually. Cieslak et al. [4] welded 3mm thick Hastelloy C series alloy (C-4, C-22, C-276) using gas tungsten arc welding (GTAW). Analyzing the solidification process, it can be concluded that the microstructure of Hastelloy C-276 weld joints comprises of a P and μ phase. The sensitivity of C-276 alloy to hot cracking is much higher than that of the other two(C-4 and C-22). Apparently, fusion welding is difficult to control the formation of a harmful second phase. The electron beam has an advantage in welding the sheet materials because of large energy density, heat concentration, rapid melting and solidification process and so on. Mahmad et al. [5] tested the Hastelloy C-276 with a thickness of 3mm using the electron beam welding method. The experimental results show the thin-layer structure is formed and the micro-eutectoid rich in Mo and W elements after analyzing the microstructure in fusion area. The weld joints get a higher strength than as-received materials. Compared with the electron beam welding method, the laser welding method also has the characteristics of large power...
density, strong penetrating power and small heat-affected zone. However, the electron beam welding test needs to work under a vacuum condition, resulting in high cost. Ma Guangyi et al. [6,7] used pulsed laser welding technology to explore the 0.5mm thick Hastelloy C-276 sheet. The authors thought, compared with the fusion welding, the segregation tendency is far lower and the trend of brittle phase is weakened, at the same time, weld joints are still with high strength.

In summary, few scholars have studied the Hastelloy C-276 with a thickness of 0.381mm. The 0.381mm thickness Hastelloy C-276 is used in the stator shield sleeve of the nuclear main pump, in which weld joints should have higher performance. Therefore, the microstructure and performance characteristics of the pulse laser weld joints were analyzed.

2. Material and Experiments
The material is the Hastelloy C-276 precision rolling sheet (water cooled after solution annealing) with 0.381mm. The chemical composition of the material is given in Table 1. Figure 1 displays the microstructure of Hastelloy C-276 base metal, which consists of single equiaxed austenite grains.

During the welding process, the HK5W-1050 laser welding system was used. Butt joint was adopted as the type of the weld joints. Double-sided protection was performed using 99.99% argon gas as the shielding gas at a flow rate of 15 L/min. In order to observe the macromorphology and microstructure of the weld joints, the weldments were cut along the vertical welding direction. After the samples were moulded, ground and polished down to 0.05 micron, its surface was etched using the aqua regia. The microstructure of the weld joints was observed with an Optical Microscopy (OM, Axio.Scope.A1) and Scanning Electron Microscopy (SEM, EVO18). The elements in the weld joints were examined quantitatively with the Energy Dispersive Spectrometer (EDS). In order to examine the variation of the microhardness of the weld joints, the microhardness tester was used to measure at equal intervals along the weld joint center position from one end to the other. The test force was 100g and the dwell time was 15s. In terms of the tensile test, the tensile geometry dimension (Dimension: mm) was given in figure 2. The number of tensile specimens of base metal and weld joints is three each to avoid the testing repetitiveness. A MTS-810 universal testing machine was used at displacement rate of 5mm / min.

3. Results and analysis
3.1. The analysis of microstructure and microsegregation
3.1.1. The analysis of microstructure. Figure 3 shows the macromorphology of Hastelloy C-276 weld joints. The laser welding process parameters are the pulse current of 60A, the welding speed of 260mm / min, the pulse width of 7ms, the pulse frequency of 8Hz and the defocus amount of 0.5mm,
respectively. Under those parameters, the top surface of the weld joints has a slight concave and the bottom surface is flat. There are not any welding defects.

![Figure 3. The macromorphology of Hastelloy C-276 laser weld joints.](image)

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Figure 4 shows the microstructure of the Hastelloy C-276 weld zone. There are three morphological grains in the weld zone, such as columnar dendrites, cellular crystals and equiaxed grains, as showed in figure 4(a). Figure 4(b) and (c) respectively show the microstructure of the top and bottom surface in the weld center zone, in which the columnar dendrites grow toward the interior of the weld along the weld surface. There are three different morphological grains in the weld center zone, which is caused by different cooling rates of molten metal in different locations of the weld pool. From figure 4(d), there are a large number of columnar dendrites and cellular crystals distributed inside the weld near the fusion line, and no obvious equiaxed grains are formed. Most of the columnar dendrites are generated along the fusion line, pointing to the center of the weld. Due to the rapid cooling of the laser welding, the solidification of the metal in the weld pool has relatively high degree of undercooling, and the microstructure of the weld is significantly refined [8].

![Figure 4. The microstructure of Hastelloy C-276 weld zone (a) Weld center zone (b) Weld top surface (c) Weld bottom surface (d) Weld boundary zone.](image)

Figure 4. The microstructure of Hastelloy C-276 weld zone (a) Weld center zone (b) Weld top surface (c) Weld bottom surface (d) Weld boundary zone.

### 3.1.2. The analysis of microsegregation.

SEM photographs of the weld zone are presented in figure 5. The point scanning of EDS at 20kV with a spot size of 1μm is performed on the four different sites (site1 ~ site4) identified in the figure 5(a) and (b), and the scanning results are shown in figure 6. In terms of the elemental content, it can be found in both weld center zone and weld boundary zone, compared with the grain interior, the contents of Mo in the grain boundary are large and the contents of Ni are less. It is made clear that the element segregation in the pulse laser welding process is relatively slight. At the same time, compared the content of several elements in the second phase P and μ[4], it is concluded that no second phase will be generated in both weld center zone and weld boundary zone during laser welding process.

![Figure 5. SEM photographs in the Hastelloy C-276 weld zone (a) SEM photograph of the weld center zone (b) SEM photograph of the weld boundary zone.](image)

Figure 5. SEM photographs in the Hastelloy C-276 weld zone (a) SEM photograph of the weld center zone (b) SEM photograph of the weld boundary zone.
3.2. Microhardness analysis of weld joints

The microhardness of Hastelloy C-276 weld joints is shown in figure 7. The hardness of the alloy can be affected by solid solution strengthening, phase formation and microstructure refinement. It can be noted that the microhardness value of the weld zone is 12% higher than that of the base metal. The dense grain structure in the weld zone is shown in figure 4, where grain size is much smaller than that of the base metal. It is precisely because of the dense arrangement of these fine-sized grains that the microhardness of the weld zone increases. In addition, the weld structure contains Mo, Cr and W elements which can play a role in solid solution strengthening and thereby increase the microhardness value of the weld zone.

3.3. The results of tensile test

In the tensile test, three weld joint tensile specimens were marked as #1, #2 and #3, respectively, and the parent material tensile specimens were marked as #4, #5 and #6. The macromorphologies of Hastelloy C-276 weld joint tensile specimens is illustrated in figure 8. It can be found that after the tensile test, specimens are broken at the weld center.
To further illustrate the tensile fracture behavior of base metal and weld joints, Table 2 shows the Yield Strength (YS), Ultimate Tensile Strength (UTS) and elongation of the base metal and weld joints after tensile test. It can be consulted that the YS of weld joints is equivalent to that of base metal, and its UTS reaches over 93% of that of the base metal. In terms of elongation, the elongation of the weld joints is about 40%, while the elongation of the base metal reaches 67.7%. The YS of the materials is primarily related to the lattice type of the materials and the second phase formed. The YS of weld joints is similar to that of base metal, which can be understood that both of them are face-centered cubic structures and there are also no second phases at the weld zone. Figure 3 shows that the weld zone presents the incomplete structure and the slight concaves exist on the top surface where it is easily produce stress concentrations. With the increase of the loading force, the internal stress and the external loading force act together to generate a fracture at the weak part of the weld center verified in figure 8(b). Therefore, the UTS of weld joints is less than that of the base metal.

| Name             | Number | YS/Average YS (Mpa) | UTS/Average UTS (Mpa) | Elongation/Average elongation (%) |
|------------------|--------|---------------------|-----------------------|----------------------------------|
| Weld joints      | #1     | 423                 | 795                   | 38.6                             |
|                  | #2     | 421 422             | 801 802               | 40.5 40.2                        |
|                  | #3     | 423                 | 810                   | 41.5                             |
|                  | #4     | 418                 | 866                   | 67.6                             |
| Base metal       | #5     | 421 419             | 870 866.6             | 67.1 67.7                        |
|                  | #6     | 417                 | 863                   | 68.5                             |

Figure 9. The fracture morphologies of Hastelloy C-276 weld joints and base metal (a) The fracture morphology of weld joints at low magnification (b) The fracture morphology of base metal at low magnification (c) The fracture morphology of weld joints at high magnification (d) The fracture morphology of base metal at high magnification.

Figure 9 shows the fracture morphologies of the base metal and the weld joints. The fracture morphology of weld joints at high magnification is shown in figure 9(c), in which the weld joints show full of dimple and there are no any other defects. The surface of the dimple is smooth and no other impurity particles cover. Figure 9(b) and 9(d) are the micromorphologies of fracture at the low and high magnification of base metal, respectively. It can be obviously seen that the dimple features small amounts and large size and it is a typical tensile shear dimple morphology. The dimple of the weld joints is denser than the parent material, which is related to the refined grain structure at the joints. Through the above analysis, it can be assumed that the fracture methods of base metal and weld joints are ductile fracture.
4. Conclusions
In this paper, the microstructure, element segregation, microhardness and tensile properties of weld joints were detected. The conclusions are as follows:

1. Welding Hastelloy C-276 sheet by laser welding method can get defect-free weld joints. The large degree of supercooling existing at the solid-liquid interface is an important factor that causes grain refinement and different grain morphologies.

2. Element segregation exists in the weld zone but there is no secondary phase formed.

3. The microhardness of the weld zone is 12% higher than that of the base metal. The yield strength of weld joints is comparable to that of base metal but the tensile strength of weld joints is 93% of that of base metal. In terms of elongation, the elongation of weld joints is about 40%, while the base material elongation is up to 67.7%. There are dense dimples in the fracture of the weld joints and the base metal, both of which are ductile fracture.

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References
[1] Mehta, K. K., Mukhopadhyay, P., Mandal, R. K., Singh, A. K. (2014) Mechanical properties anisotropy of cold-rolled and solution-annealed ni-based hastelloy c-276 alloy. Metallurgical & Materials Transactions A, 45: 3493-3504.
[2] Li, Z., Han, J., Lu, J., Chen, J. (2015) Cavitation erosion behavior of hastelloy c-276 nickel-based alloy. Journal of Alloys & Compounds, 619: 754-759.
[3] Manikandan, M., Arivazhagan, N., Rao, M. N., Reddy, G. M. (2015) Improvement of microstructure and mechanical behavior of gas tungsten arc weldments of alloy c-276 by current pulsing. Acta Metallurgica Sinica(English Letters), 28:208-215.
[4] Cieslak, M. J., Headley, T. J., Romig, A. D. (1986) The welding metallurgy of hastelloy alloys c-4, c-22, and c-276. Metallurgical Transactions A, 17: 2035-2047.
[5] Ahmad, M., Akhter, J. I., Akhtar, M., Iqbal, M., Ahmed, E., Choudhry, M. A. (2005) Microstructure and hardness studies of the electron beam welded zone of hastelloy c-276. Journal of Alloys & Compounds, 390: 88-93.
[6] Ma, G., Wu, D., Niu, F., Zou, H. (2015) Microstructure evolution and mechanical property of pulsed laser welded ni-based superalloy. Optics & Lasers in Engineering, 72: 39-46.
[7] Ma, G., Wu, D., Guo, D. (2011) Segregation characteristics of pulsed laser butt welding of hastelloy c-276. Metallurgical & Materials Transactions Part A, 42: 3853-3857.
[8] Wu, D., Ma, G., Guo, Y., Guo, D. (2010) Study of the weld morphology on thin hastelloy c-276 sheet of study weld morphology on thin hastelloy c-276 sheet of pulsed laser welding pulsed laser welding. Physics Procedia, 5: 99-105.