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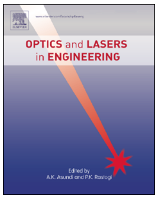

Microstructure evolution and mechanical property of pulsed laser welded Ni-based superalloy

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ABSTRACT

For evaluating the microstructure evolution and mechanical property of Ni-based Hastelloy C-276 weld joint by the pulsed laser welding, the influence of pulsed laser welding on the microstructure and mechanical property of the weld joint is investigated by the analysis of the microstructure morphology, microhardness, phase structure and tensile property. The results indicate that, in the fusion zone three sections are divided on the basis of the patterns of grain structures. In the weld joint, the element segregation is found, but the trend of brittle phase's formation is weakened. The weld microhardness presents just a little higher than that of base metal, and there is no obvious the softened heat affected zone. Meanwhile in the weld joint, the phase structure is still the face-center cubic with the tiny shift of peak positions and widened Full Width at Half-Maximum. The yield strength of weld joint is the same as that of base metal, and the tensile strength is nearly 90% of that of base metal. The decreased tensile strength is mainly attributed to the dislocation piling-up.

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1. Instruction

Hastelloy C-276 as a Ni–Cr–Mo superalloy with well corrosion-resistance is comprehensively applied in the chemical and nuclear industries recently. It is important to develop the welding method of Hastelloy C-276. Kane and Tawancy [1,2] carried out the study of the surface segregation of Hastelloy C-276 at the high temperature and proposed the basic mechanism of the phase transformation, which provided the theory basis for the high-temperature process of Hastelloy C-276. Cieslak and DuPont et al. [3–7] conducted the experimental investigation on the 3 mm thick Hastelloy C-276 of arc-welding, and the microstructure, crystallinities, involved hot-cracking mechanism and formed brittle phases (p and μ) during the arc-welding process of Hastelloy C-276 were analyzed. Also, the major element compositions in p and μ were obtained. Researchers in Haynes International Inc. [8] investigated the weldability of Hastelloy series alloys under the arc-welding condition and analyzed the corrosion-resistance ability of their welding samples. They suggested that the joining of Hastelloy C-276 could be achieved by many welding methods, including the high energy beam welding, but they did not investigate the effect of high energy beam welding on the characteristic of Hastelloy C-276. Ahmad et al. [9,10] conducted the electron beam welding of 3 mm thick Hastelloy C-276. They found a fine lamellar structure without the detrimental intermetallic compounds in the welding zone after examining the aging effect on the phase composition of Hastelloy C-276. However, as the thin Hastelloy C-276 has been applied in the nuclear and chemical fields recently (such as the manufacture of huge tubular and vessels), due to severely decreasing the mechanical property, grain coarsening and formation of brittle phases, the traditional argon arc welding could not satisfy the welding of thin Hastelloy C-276 sheet, as well as the electron beam welding demands much tougher welding environment. Although there are few literatures [11–14] on the laser welding of Hastelloy C-276 to date, these investigations just focused on the macrostructure of weld, the high-temperature mechanical properties, the weld forming mechanism under the different welding parameters and the shear strength of welded sheets. The microstructure and mechanical property of weld joint, which directly decide the weldability of material, were not deep analyzed. Hence it is necessary to investigate the influence of laser welding on the microstructure and mechanical property of Hastelloy C-276.

Laser welding, being characteristic of the narrow weld zone, rapid cooling and refined grain during the welding, has been extensively applied in many industrial fields, such as the aerospace and automotive. Osoba, Yu and Yilbas [15–17] welded the Haynes 282, K418 and Haynes 188 using the laser beam, respectively. They found laser welding could achieve the well welding of nickel-based superalloy

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used in the gas turbine engines. Especially, during the pulsed laser welding, the cooling rate would be much faster than that during the continuous wave laser welding, and this could weaken the formation of p and μ phases in Hastelloy C-276 during the welding [18].

In this paper, it is to investigate the effect of pulsed laser welding on microstructure and mechanical property of Hastelloy C-276, and to further analyze the characteristic of the laser weld joints. This investigation is not only to reveal the effect of pulsed laser welding on the microstructure and mechanical property of Hastelloy C-276, but also to thoroughly understand the metallurgy process of Hastelloy C-276 under the pulsed laser welding condition.

2. Experimental procedure

In this experiment, the 0.5 mm thick Hastelloy C-276, which is treated at 1170 °C for 0.3 h before quenching in the water, is used, and the nominal chemical composition is shown in Table 1. The welded sample size is 50×25 mm^2, and the welded length is 50 mm. The pulsed Nd:YAG laser with 0.6 mm irradiated spot diameter on the material surface is employed to join the butt joint without gap, and the pure Ar (99.99%) is utilized as the side blowing shielding-gas with the 9 L/min of flow and 3 mm diameter nozzle. The side blowing shielding-gas could prevent the welding pool and its front from the strong oxidization. Fig. 1 shows the schematic of laser welding setup. In this setup, there are the pumping lamp, the reflector, the beam expander transmission (B.E.T), the len and the online computer-controlled-display (CCD). The online CCD was used to calibrate the welding path and monitor the welding process. The laser welding parameters include the single energy, duration, repetition, welding velocity and defocus. According to the previous investigation [11–13], the well smooth weld joint without defects or visible heat affected zone (HAZ) could be obtained under the parameters of 1.5 J, 6 ms, 30 Hz, 100 mm/min and -1 mm defocus condition. Hence, in the present work, the welding parameters are set to the values mentioned above.

After welding, the welded samples are cut along the vertical direction of weld joint by the wire-electrode cutting, and then grinded sequentially by 800#, 1200#, 1500# and 3000# SiC grinding paper, respectively. Then, the grinded surface is etched for 30 s in the nitro-hydrochloric acid to obtain the cross-section profile of weld joint.

The microstructure of weld joint is examined by the Philips XL-30TMP scanning electron microscope (SEM) equipped with the Energy Dispersive Spectrometer (EDS), and the microhardness is measured by MH-6 microhardness device. The analysis of X-ray diffraction (XRD) is done by the Rigaku Corporation D/MAX-Ultima$^+$ to evaluate the phase structure of the weld joint.

The tensile test is carried on the CSS-44100 equipment with gauge length 50 mm, and the tensile velocity 5 mm/min. The prepared tensile sample size (shown in Fig. 2) is according to the GB/T 2651-2008. After the tensile test, the phase structure of the fracture is tested by SEM and Bruker D8 DISCOVER GDDDS 2D face scanning XRD, respectively.

3. Results and discussion

3.1. Microstructure morphology

Table 1
Chemical composition of Hastelloy C-276 sheet (wt%).

Ni	Cr	Mo	Co	W	Fe	Mn	C	Si	P	S	V
Bal.	16	15.7	0.1	3.3	5.6	0.5	0.004	0.03	0.01	0.00	0.01

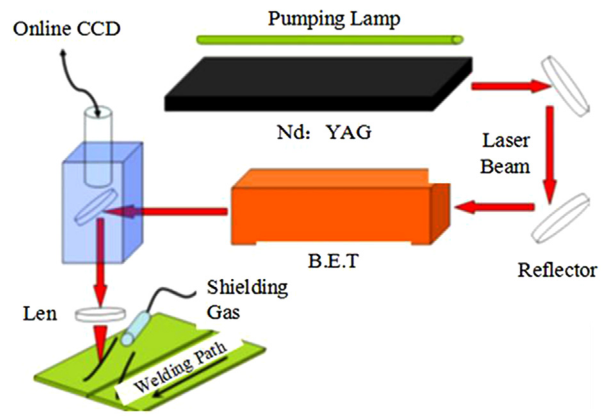

Fig. 1. Schematic of laser welding setup.

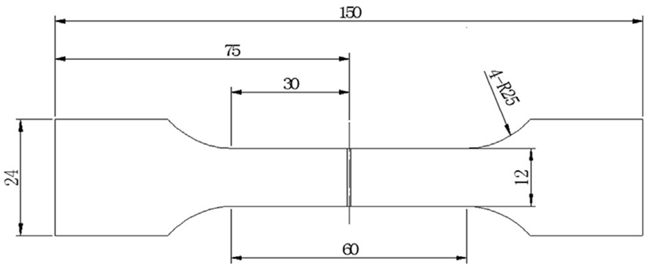

Fig. 2. Size of welded sample (mm).

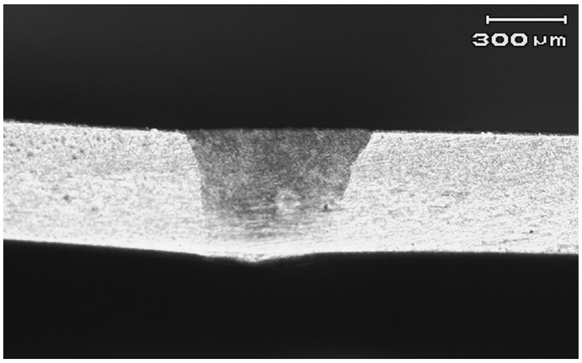

Fig. 3. Cross-section of the weld joint.

Fig. 3 shows the cross-section profile of the weld joint. On the surface of the weld joint, there are no evident convex or undercut shapes without obvious HAZ. In the previous work, we have found that, in the base metal, there are the equiaxed grains with twins. In comparison, the much finer subgrains and dendrite morphology are observed in the weld joint [18]. This result indicates that the grains in the weld joint are refined and the elements should have been re-distributed upon the welding process. There are two primary factors taking effect on the grain microstructure during the welding, including temperature gradient (G) and growth rate (R). During the pulsed laser welding, the temperature would rapidly oscillate due to the alternation between lasers on and off within a whole repetitive pulse cycle, hence the G is large. On the other hand, R, depending on the time of solidification, which benefits from the pulsed nature of laser operation, is also high. Consequently, high $G \times R$ causes a high cooling rate, and thus the finer grains are obtained in the weld joint [20,21]. In addition, the

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