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Study of weld morphology on thin Hastelloy C-276 sheet of pulsed laser welding

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Abstract

In this paper, it was indicated that the laser welding was well suitable to joining of thin Hastelloy C-276 sheet(0.5mm thickness),and also the fine grain were observed in welding zone with invisible HAZ (heat affected zone). In addition, the smooth weld joint could be controlled by means of the laser parameter adjustment. On the other hand, it's proposed that Ni-Cr-Co-Mo and austenite CFe15.1 cubic face-centered crystal structure should be existed in as-received and welding samples, as well as the cause of FWHM (Full Width at Half Maximum) widened and peak offset of joined samples were analyzed

Keywords: Laser welding; Hastelloy C-276; welding zone; heat affected zone; X-ray diffraction

1. Introduction

Hastelloy C-276 as nickel alloy based on Ni-Cr-Mo system with well corrosion-resistant is widely applied in chemical industry, nuclear energy equipment and so on in recent years. In some huge tubular parts and huge vessels manufacturing of C-276, the argon arc welding is mainly used to join the sheet of C-276 together to date. Since 1986, American scholars (M.J. CIESLAK et al.)[1-3] had conducted some experimental investigation on Hastelloy C-276 with 3mm of thickness of arc welding and concluded that the Hastelloy C series alloys possessed the weld ability while the microstructure, characteristic of crystal phase and hot-cracking mechanism were analyzed during arc-welding process, and then proposed the identification of the minor phases (P, σ, μ or MC carbide) in the solidified weld microstructures and developed an equivalent chemical model. In 2003, the researchers from Haynes International Inc. investigated the weld ability of Hastelloy series alloy and obtained the corrosion-resistant ability after arc-welding [4]. In 2005, Pakistan scholars (M. Ahmad et al.)[5] conducted the electron beam weld of

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Hastelloy C-276 of 3mm, and investigated the microstructure and micro-eutectic phases, and further found the fine lamellar structure without detrimental inter-metallic compounds in the welding zone. However, so far there have been no published literatures on laser welding of Hastelloy C-276.

Laser welding, as an advanced joining process, is been comprehensively applied in many industrial fields such as sedan body, mobile phone shell, dissimilar metal joining et al. Taking the advantage of characteristic of narrow weld zone and high-power intensity input, tiny microstructure in welding zone could been obtained, furthermore weld thermal distortion due to narrow size of weld joint, transient thermal input and rapid-cooling could been restricted specially during the thin sheet welding. On the other hand, it doesn't need the special environment during laser welding, meanwhile it could been transmitted by fiber.

The purpose of our work is to investigate the effect of laser welding process on 0.5mm Hastelloy C-276 alloy, and further analyze the weld ability, weld joint morphology and microstructure of thin Hastelloy C-276 joined by pulsed laser.

2. Experiment

In investigation, the Hastelloy C-276 treated at 1170 Celsius degree lasting 0.3 hours before quenching in water is employed, and the nominal chemical composition is shown in Table.1.The sample size is 50 X 25 X 0.5mm^3.After processing, the samples were cut along vertical direction of welding joint, and then grinded sequently by 800,1200,1500 and 3000 SiC grinding paper before etching.

Experiment of pulsed 1064nm Nd:YAG laser with ms magnitude is conducted to join Hastelloy C-276 with 1 bar shielding Argon gas and the schematic of set-up is shown in Fig.1.The laser parameters including single energy, duration, repetition and defocus were varied as investigated parameters to discuss the effect of pulse laser welding on thin Hastelloy C-276 joining. The detail of range is shown in Table.2.

Micro-morphology was observed by Olympus Optics microscope, while the X-ray diffraction analysis was conducted to test the crystal phase changing on welding samples as compared to as-received.

Table 1. Nominal chemical composition of Hastelloy C-276(W. %)

Ni	Cr	Mo	Co	W	Fe	Mn	C	Si	P	S	V
Bal.	≤16.5 ≥14.5	≤17 ≥15	≤2.5	≤4.5 ≥3.0	≤7 ≥4	≤1.0	≤0.10	≤0.08	≤0.04	≤0.03	≤0.35

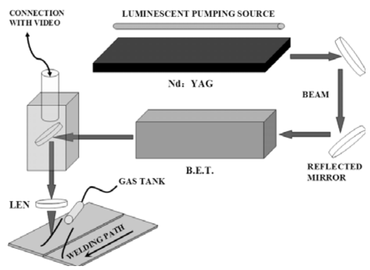


Fig.1 Schematic of set-up

Table 2. Laser parameters range

Single Energy(J)	Velocity(mm/min)	Duration(ms)	Repetition(Hz)	Defocus(mm)
1.5,0.75	100	3,5,6,7	30,60	-1,+1

3. Discussion and analysis

During the experiment, the energy threshold is obtained based on single-scanning and then the transient linear energy E_T is calculated according to the equation (1).

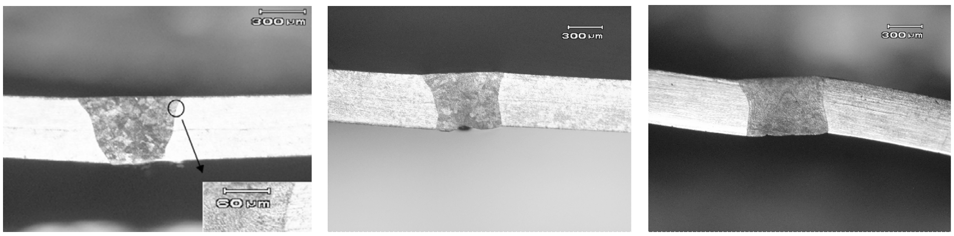
$$E_T = \frac{E}{\upsilon \cdot t} \qquad (1)$$

Where E, v and t stand for single-pulse energy, velocity and pulse duration respectively. Due to the fixed velocity, E_T just depends on single-energy and duration and is in the order of 10^2J/mm during the experiment; consequently the process of laser welding belongs to the style of low energy input. On the other hand, the effective action period of laser equalling to duration multiplied by repetition is applied to investigate the formation of weld morphology.

3.1 Micro- morphology

The welding morphology is shown in Fig.2.It's observed that just with changing the duration stepped by 1 ms, the cross-section morphology of welding joint is significant varied. The welding width ratio of top to bottom is decreased as the duration up while the trend of tight waist with width of ～0.6mm is obviously found on 7ms duration. The top surface welding width is ～0.6mm with a little more than 0.3mm on bottom surface on 5ms duration, whilst top-bottom is more than 0.6mm-～0.4mm and ～0.7mm-～0.7mm respectively on 6ms and 7ms duration. According to the ratio variation, it's considered that the duration could maintain local melting time and further ensure the sufficient thermal diffusion causing larger melting area, despite the transient power intensity decreases as the duration up. Owing to the low thermal conductivity(less than half of traditional stainless steel) and longer thermal input, the thermal accumulation could consistently be strengthened despite of low energy input while the cooling period during the pulsed cycle also prevents the temperature surge. Consequently, the duration is primary taking on the effect of widening melting area. It's indicated that the welding process changing duration could obtain the morphology of weld joint required under the same condition of energy.

It's proposed that the trend of tight waist stems from long thermal action and further boundary effect strengthened. According to the variation trend of tight waist in Fig.2, the tight waist is determined by duration, since the longer duration would raise the thermal accumulation of bottom surface and then induce the thermal diffusion along bottom interface. It's also indicated that the long duration could accomplish the smaller temperature difference between top and bottom surface to some extent and be negative for aiming to get narrow bottom melting area.



(a) 5ms (b) 6ms (c) 7ms

Fig. 2. Weld morphology: 1.5J, 30Hz,-1mm defocus, 100mm/min

On the other hand, it's found that the welding morphology is impacted critically by minus and plus defocus on full weld penetration during the experiment. In Fig.2 (b) and Fig.3, it is obviously found that the plus defocus could cause much wider top melting area as compared to the minus defocus and the obvious "nail" shape is observed on +1mm defocus. According to the theory of laser beam focus, the effect of minus and plus defocus on melting area could be applied to explain the phenomena. The size of laser spot on top surface is the same no matter which is -1 or +1mm defocus theoretically and the size of spot deviated from focus would gradually enlarge as the distance. But it's not meant the same spot size on the bottom surface (in Fig.4), and further the enhanced laser power intensity could be obtained in -1mm defocus relative to the decayed power intensity in +1mm defocus. Taking account for the penetration of laser and characteristic of pool flow during welding, the enhanced power intensity would be in favour of gaining well welding morphology and shrinking bottom melting area under the condition of the same laser radiation period. In contrast, when the power intensity is decayed, accompanying the extended spot size, the thermal accumulation would be impacted by both thermal conductivity of ambient area and external thermal input, hence the widened melting area is obtained. Though the laser parameter is varied, the smooth top and bottom surface could be achieved during experiment. It is considered that the pulsed laser could provide suitable heat and just perfect cooling period so that the pool flow would be well-distributed along the direction of cross-section.

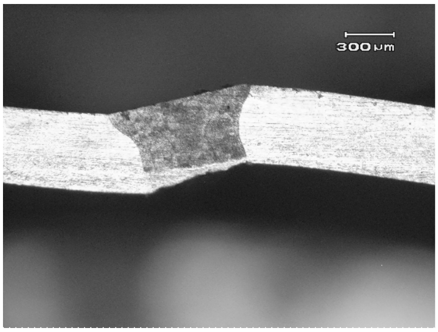


Fig.3. 1.5J, 30Hz,100mm/min,6ms,+1mm defocus

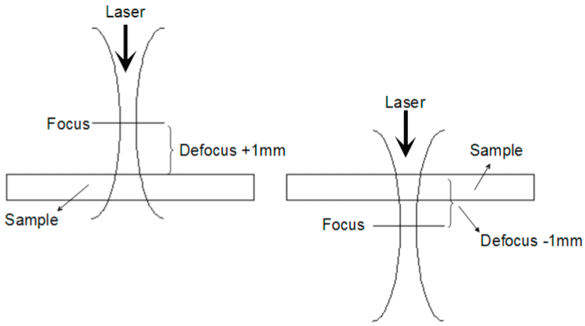
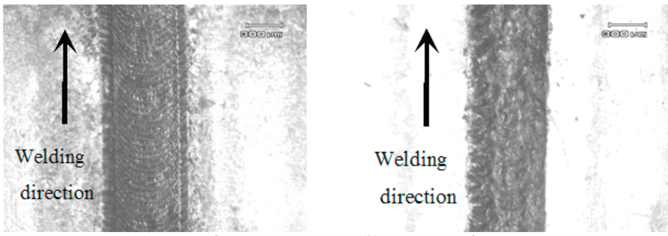


Fig.4. Defocus schematic

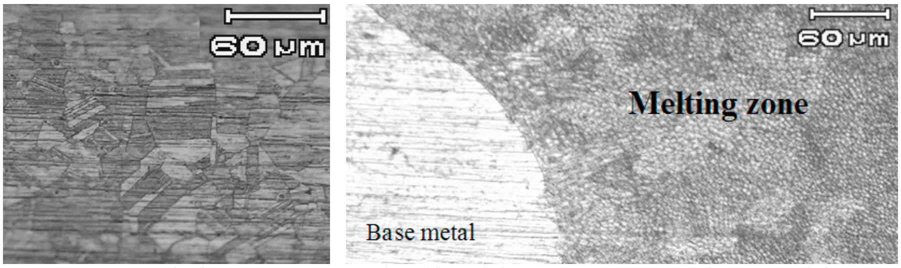
The morphology of top and bottom surface is shown in Fig.5. It's found that the regular profile appears on top surface without obvious spatter due to low energy input. On the contrary, just the welding margin could be observed with no regular morphology on the bottom. According to the top profile, it's considered that the solidification boundary of pool induced by laser is contributed to form the morphology. The pool presents the edge of regular cycle in "tail" due to the short action period of pulsed laser as compared to the lengthy tail during CW laser welding, therefore the thermal accumulation is not be persisted long period, and further the heat affected zone should be restrained during welding process, what's well in favour of thin sheet welding. In addition, the formation of bottom morphology should potentially attribute to the integrated action of thermal diffusion and weakened melting which is due to laser decaying along depth. Thermal diffusion could ensure sufficient thermal accumulation on interface, and then weakened melting overlaying thermal diffusion causes the free-solidification. Finally, the significant difference between top and bottom morphology is emerged.



(a) Top surface (b) Bottom surface

Fig. 5. Weld morphology: 1.5J, 30Hz,-1mm defocus,100mm/min,7ms

The Fig.6 shows the grain changing in welding zone as compared to base metal. According to Fig.6 (a), as-received Hastelloy C-276 is consisted of most equiaxed grains with annealed twin. But after laser welding, it's found that the grain size is so tiny and there is the trend of grain growth oriented to as-received due to thermal gradient induced by laser radiation. Moreover, the heat affected zone (HAZ) is invisible in Fig.2 and Fig.6 (b). It's considered that the phenomenon without visible HAZ is associated with short energy action and low linear energy intensity. Due to the low linear energy intensity and short energy action time, there isn't sufficient energy input and sustainable time for grain growth, consequently HAZ is not observed obviously. Therefore it's concluded that the pulsed laser welding avoiding severe HAZ is well suitable for joining thin Hastelloy C-276.



(a) as-received (b)Weld morphology: 1.5J, 30Hz, +1mm defocus,100mm/min,6ms

Fig. 6. Micro-structure of samples

For investigating the effect of effective action period of laser on welding morphology, the velocity, transient power and defocus is fixed at 100mm/min, 250W and -1mm respectively, and the compared parameters are 1.5J, 30Hz, 6ms and 0.75J, 60Hz, 3ms. In Fig.7, it's obtained that the bottom area is narrowed with larger ratio of top-bottom without visible HAZ and the top is also smooth as compared to Fig.2 (b). In addition, the pulsed cycle could cause distinction for the morphology of welding despite of the same action time of laser equalling to 180ms (6ms X 30Hz or 3ms X 60Hz).The cooling time is 27.3ms in 30Hz relative to 13.3ms in 60Hz, considering the laser action of 6ms and 3ms respectively. Less action time is negative for thermal accumulation and further prone to resulting in non-full penetration welding due to shrinking melting depth. However the repetition lifted could also decrease the cooling time, what is positive for thermal accumulation of next pulsed action in order to achieve higher temperature and increase melting depth. Finally, the conflict would neutralize each other and tend to the equilibrium. According to morphology feature in Fig.2 (b) and Fig.7, it's proposed that the duration should be the more significant influence on the morphology formation compared with repetition, and further the melting area is susceptible to thermal accumulation at the same laser action time, therefore the larger ratio of top-bottom without visible HAZ could be observed in 60Hz. Based on the analysis, the weld morphology should be controllable via the reasonable adjustment of laser parameters under the certain condition of power.

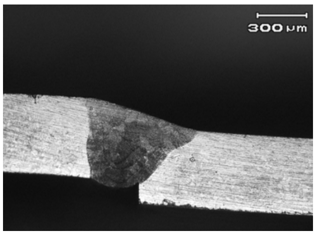


Fig. 7. Weld morphology: 0.75J,60Hz,-1mm defocus,100mm/min,3ms

3.2 X-Ray Diffraction Analysis

The X-ray diffraction test is carried out to analyze the crystal lattice changing after welding as compared to the as-received. During the test, the X-ray scanning area including base metal and welding area is 5 X 10mm^2, and hence the qualitative analysis is developed. The scanning schematic is shown in Fig.8.

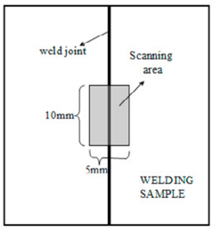


Fig. 8. Schematic of scanning area

Fig.9 shows the distribution of peak position in as-received and welding samples. In line with the phase card of X-Ray diffraction, it's suggested that Ni-Cr-Co-Mo and austenite CFe15.1 cubic face-centred crystal structure should be existed. The minor elements including W, V and Si and so on should also emerge in the spectrum according to the chemical composition in Table.1, but the crystal structure including the minor elements isn't found while the intensity ratio and peak position are not well accordance with the data in phase card. It's attributed to the probable special preferred orientation of crystal and elements solid solution.

As compared to as-received, it's indicated that there aren't obvious new peaks or peak vanishing, with just peak position offset which is attributed to the potential residue stress forcing the lattice distortion in welding samples. According to Bragg Equation [6], the half-diffraction angle has to decrease in order to reach the diffraction qualification when crystal face distance increases, and further the increased crystal face distance results from tensile stress. Hence the peak position would offset to small angle in spectrum, concluding the existence of residue tensile-stress in scanning area which shows up the peak offset shifted to small angle in 7ms-sample (in Fig.9). On the other hand, the FWHM (Full Width at Half Maximum) is widened after process, which is due to the potential micro-strain emerging and grain size refinement.

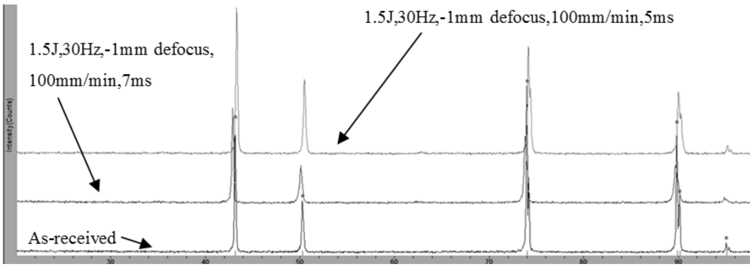


Fig. 9. X-Ray diffraction spectrum

4. Conclusion

According to the experiment results, it's indicated that the pulsed laser welding process is well suitable to the joining of thin C-276 sheet. Also, the tiny grain could be observed in welding zone with invisible HAZ due to the low energy input and short laser action time. In addition, the smooth weld joint could be controlled by means of the laser parameter adjustment, and further the cause of formed weld joint profile is discussed according to the characteristic of laser welding process. It's found that the key cause of shaping weld joint is the duration taking effect during welding under the certain condition of single-energy and power. On the other hand, based on XRD test, it's obtained that crystal structure of Hastelloy C-276 is not significantly varied after laser process. According to the analysis of X-ray spectrum, it's proposed that Ni-Cr-Co-Mo and austenite CFe15.1 cubic face-centred crystal structure should be existed in as-received and welding samples based on C-276 chemical composition. Meanwhile the peak position offset is attributed to the potential residue stress forcing the lattice distortion in welding samples, and the FWHM widened is due to the effect of potential micro-strain emerging and crystal grain size variation induced by laser welding.

Acknowledgements

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