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ORIGINAL ARTICLE

# A study of thick plate ultra-narrow-gap multi-pass multi-layer laser welding technology combined with laser cleaning

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**Abstract** In the present paper, the application of laser cleaning technology in thick plate ultra-narrow gap multi-pass multi-layer laser non-autogenous welding process was described. The comparison between weld cross sections and the amount of oxide on the weld surface before and after welding tested by environmental scanning electron microscopy (ESEM) proved the laser cleaning method does play an important role in cleaning the weld. The influence rule of some cleaning parameters to welded joints, including groove angle, laser power, defocusing amount, and cleaning speed, was studied, and the welding defects decreased obviously with the optimal cleaning parameters. Combining this cleaning technology and the laser non-autogenous welding system comprised of the laser autogenous welding, laser wire filling welding, and the laser arc hybrid welding, a 40-mm-thick plate was welded well using a 4-kW fiber laser.

**Keywords** Thick plate · Ultra-narrow-gap · Multi-pass · Laser non-autogenous welding · Laser cleaning

## 1 Introduction

The thick plate welding technology was very important in the fields of ships and submarine building and so on. Only by the means of machining a narrow groove prior to welding process can the thick plate be connected well. However, the traditional arc method has some unforgivable disadvantages including the low work efficiency and poor mechanical property [1, 2]. Accordingly, the narrow-gap multi-pass multi-layer laser non-autogenous welding method might be the best choice. Wang Baiping [3] et al. welded a 16-mm-thick stainless steel by laser wire filling welding in three passes. Munro, Cameron et al. [4] realized 9-mm HSLA-65 thick plate welding by hybrid welding in a single pass. Choi, Hae Woon [5] welded a 15-mm-thick A572 Gr50 steel with a 3.2-mm gap by hybrid welding in six passes. MHI made a great progress in this field with the help of a self-produced super-power (13.5 kW) YAG laser, and a special designed external ray, a 41-mm-thick plate, was welded by laser-GMAW hybrid welding in six passes [6]. With the help of a 20-kW fiber laser in combination with an arc welding process, Michael et al. [7] were able to produce high-quality welds in plates of up to 32 mm in three to five passes, both welded in position PA. Although few pores and lack of fusion defects existed in the transversal section, Hao Shi et al. [8] welded a 20-mm-thick high-strength ship steel with a 5.8- and 8.64-mm gap in six and ten passes respectively by laser wire filling welding.

However, it was impossible to clean the weld bead entirely after every welding pass by traditional mechanical method for the sake of the narrow groove gap machined on the thick plate that might decrease the tensile strength of welded joints. Especially the groove gap in the present paper covering the range from 1.2 to 7.4 mm, so called ultra-narrow-gap, was adopted to finish a 40-mm-thick plate welding using lower power laser. Of course, the laser cleaning method became the best choice.

Laser cleaning was a new developing technology in recent years with the advantages of low injury, zero emission, and freedom from pollution [9, 10]. It was widely used in the fields

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**Table 1** Q235 chemical component

| Element | C | Mn | Si | S | P | Cr | Ni | Cu |
|---|---|---|---|---|---|---|---|---|
| Content (%) | 0.16 | 0.61 | 0.20 | 0.023 | 0.019 | <0.30 | <0.30 | <0.30 |

of microelectronic [11, 12], artifacts and works of art [13, 14], molds [15], and the cleaning of optical mirror [16].

The fundamental of laser cleaning method was that the laser beam could be concentrated as a spot with different diameters through the optical equipment and then shot onto the areas which need to be cleaned, employing the advantages including high energy density, good focusing property, and strong directivity. When the contaminants were shot by the spot, it vibrated, melted, evaporated, burnt, and finally broke away from the base metal so as to realize the cleaning aims.

Many factors can affect the cleaning effect such as the materials of the substance and the substrate, cleaning parameters, angle of incidence, the interactions between the laser and the substances, and so on. Zhang Junxia et al. [17] found that the energy threshold density of dry cleaning depended on the base, mass density of particles, thermal expansion coefficient, and temperature as well as the energy threshold density growing with the increase of particle radius. There existed cleaning threshold and damage threshold in laser cleaning, only by the laser energy density in the optimal range can the contaminants be cleared away and the substrates avoid being damaged [18, 19]. Liu Jianhua [20] proposed that an effective range of the defocusing amount also existed. The cleaning effect would be poor if the defocusing amount is out of the range. Xuyue Wang et al. [21] put forward that the laser incident angle also affected the cleaning efficiency and its optimum value was found to be about 90°. J. M. Lee. et al. [22] proposed an inference process which was conducted to predict whether and how much surface damage would be induced on the substrate as well as a chromatic modulation technique used for monitoring the surface during laser cleaning [23].

In this paper, how the cleaning parameters affected the cleaning effects has been discussed. Machining an ultra-narrow-gap groove prior to welding, combining the laser cleaning method and laser non-autogenous multi-pass multi-layer technology [24], a big-thickness plate can be welded well.

**Table 2** H08Mn2SiA chemical component

| Element | C | Mn | Si | S | P |
|---|---|---|---|---|---|
| Content (%) | 0.06~0.09 | 1.80~1.95 | 0.70~0.85 | ≤0.020 | ≤0.015 |


**Fig. 1** IPG YLR-4000 laser

## 2 Experimental details

### 2.1 Experimental materials and device

The experimental device includes a 4-kW IPG-4000 solid-state Yb-fiber laser system, an IRB special welding robot, a Fronius TPS 4000 inverter power supply, a specially designed push and pull wire feeder, and a 500-W continuous fiber laser cleaning system.

The material used in this study was control Q235 plate steel with dimensions of 150*75*$X$($X$=16, 40)mm$^3$ as well as a 1.2-mm-diameter solid filler wire (H08Mn2SiA). The chemical compositions of the base metal and filler wire are given in Tables 1 and 2 and Figs. 1, 2, 3, and 4.

**Fig. 2** ABB welding robot


**Fig. 3** TPS 4000 inverter power supply

### 2.2 Experimental methods

#### *2.2.1 The general welding idea*

A "Y"-shaped groove was machined before welding which is shown in Fig. 5. The laser autogenous welding was adopted to form a backing weld firstly, and then the laser wire filling welding and laser arc hybrid welding were used to fill the left groove space. After every welding pass, the laser cleaning method was used to clean the weld bead appearance entirely.

#### *2.2.2 The laser cleaning method*

Compared with Fig. 6, the defects decreased greatly in Fig. 7. It could be seen that the slag and porosity defects in Fig. 6 were mainly located along the fusion line and bonding zone of two closely related welding processes. It was mainly because the left oxides on the weld surface, for the sake of an incompletely mechanical clearing under narrower groove gap conditions, were re-melted, vaporized, and caught before the welding pool was solidified.

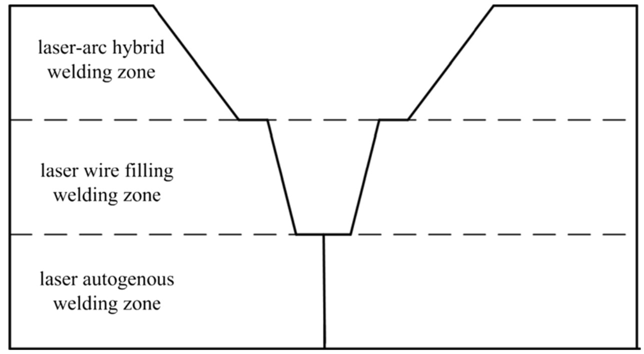



**Fig. 5** The "Y"-shaped groove style

It was obvious that the defects almost disappeared from the weld cross section shown in Fig. 7 using the laser cleaning method for the reason that the oxide was vaporized directly or cracked by the resonant interaction when the laser was shot on the oxide surface.

The welded sample with a length of 40 mm was prepared before welding and then cleared by acetone to avoid the weld surface from being polluted by oil in a wire-cutting process. The long enough guide arc plate and arc splitter plate were placed before and after the welded sample respectively. As shown in Table 3, different laser cleaning parameters were used and the welded sample was divided into four parts—1 zone, 2 zone, 3 zone, and 4 zone—in accordance with the right to left direction shown in Fig. 4.

As shown in Fig. 8, in the laser cleaning process, the position and size of the welds should be confirmed firstly. The incident angle of the laser beam can be adjusted by the galva-

**Fig. 4** Fiber laser cleaning system

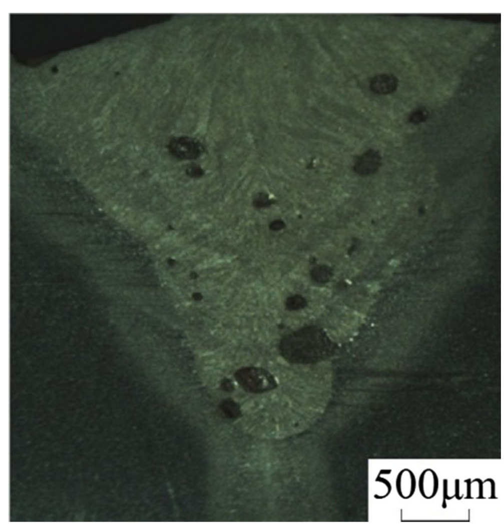



**Fig. 6** The cross section of the welded joints cleaned by mechanical method

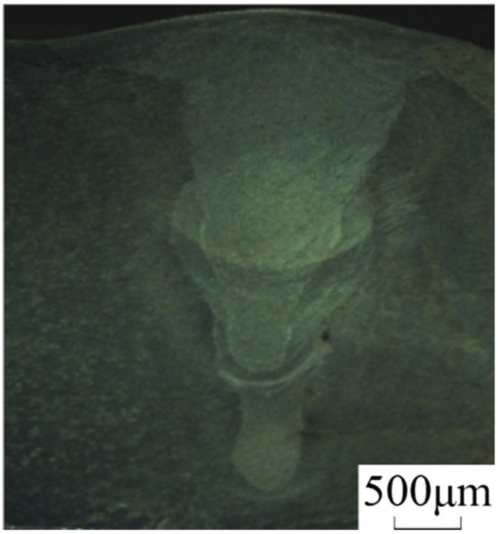



**Fig. 7** The cross section of the welded joints cleaned by laser cleaning method

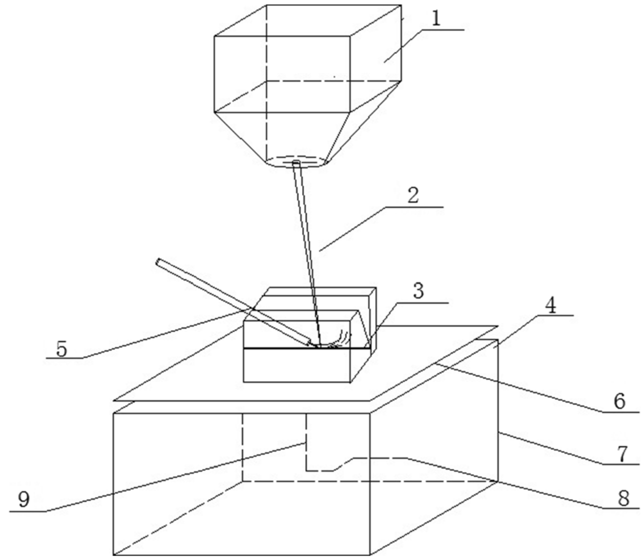



**Fig. 8** The schematic of laser cleaning of the weld: *1* laser head, *2* laser beam, *3* weld, *4* workbench, *5* shielding gas, *6* lifting platform, *7* base of the workbench, *8* hand wheel, *9* lifting screw

nometric scanning system equipped in the laser head, and then the beam reached the weld surface. The angle and the shielding gas flow rate can be adjusted using a 3D regulating system easily so as to prevent the weld surface from being oxidized in the cleaning process. By operating the hand wheel, the lifting screw can change the height of the workbench to adjust the defocusing amount of the welds. Laser power can be set up by a computer control system. After setting all the parameters, the cleaning process would be carried out. There existed obvious brightness difference in the four zones, and the weld zone turned brighter after being cleaned on the whole from Fig. 9. In order to study how the oxide content on the weld surface changed before and after laser cleaning, an environmental scanning electron microscopy (ESEM) test was operated as shown in Figs. 15 and 16.

In order to study further how the cleaning parameters affected the cleaning effect, a 16-mm-thick Q235A plate was used. The groove size is shown in Fig. 10; $\alpha$ was 6° ($b$=3.89 mm) and 15° ($b$=6.82 mm). The first welding region was welded by means of laser autogenous welding and then filling the left groove space by laser arc hybrid welding. According to the large amount of welding experimental results previously, the different welding parameters corresponding to different groove angles and the laser cleaning parameters are shown in Tables 4, 5, and 6 respectively.

### 2.2.3 The method to weld the 40-mm-thick plate

The 40-mm-thick plate, with a 5-mm root face and a 0.6-mm platform at each side, was welded by a comprehensive welding method: the first, second, and third welding regions were welded by means of laser autogenous welding, laser wire filling welding, and laser arc hybrid welding respectively [25]. In the first welding region, a 5-mm root face with a 0.6-mm platform can be fully penetrated at 4 kW laser power, at 1 m/min welding speed, and at 0 mm defocusing amount, and a high-quality weld seam could be obtained which was beneficial to suppress some welding defects in the next welding process by the former experimental results. A 1.2-mm (0.6 mm*2) platform at the groove bottom, shown in Fig. 12, could keep the maximum

**Table 3** Laser cleaning parameters

| Zone number | Laser power (W) | Defocusing amount (mm) | Speed (mm/s) |
|---|---|---|---|
| The first zone | – | – | – |
| The second zone | 150 | +5 | 750 |
| The third zone | 200 | +1 | 250 |
| The fourth zone | 500 | +1 | 250 |

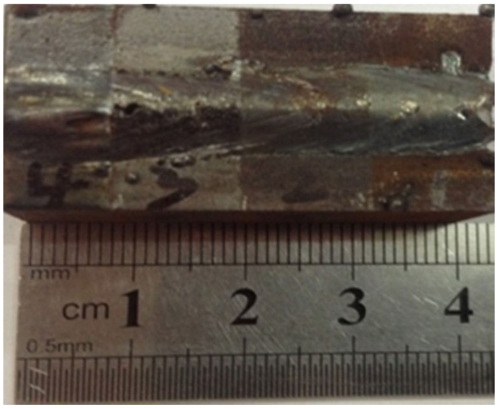



**Fig. 9** Photo of the laser cleaning zone

straightness of the welding wire with 1.2 mm diameter so as to keep the wire laser distance in a proper range in the laser wire filling process on the one hand; on the other hand, the smaller groove could be melted well with less energy and the lack of fusion defects would be suppressed a lot. In the second welding region, the welding wire should reach the groove bottom as straight as possible to assure the laser wire distance in a proper range during the welding process, but the wire feeder was too big to enter the groove space. Accordingly, the groove height was mainly decided by the wire stiffness so as to guarantee the welding quality. Under the condition of high fluency of wire feeding, the groove angle ought to be as small as possible; if not, a larger groove space might not be heated enough and the lack of fusion defects may occur. Therefore, the groove maximum gap of the second welding region should be less than 2.5 mm, calculated by the 2° groove angle, on the base of a large amount of experimental results. In the third welding region, the groove size was decided by the droplet transfer state

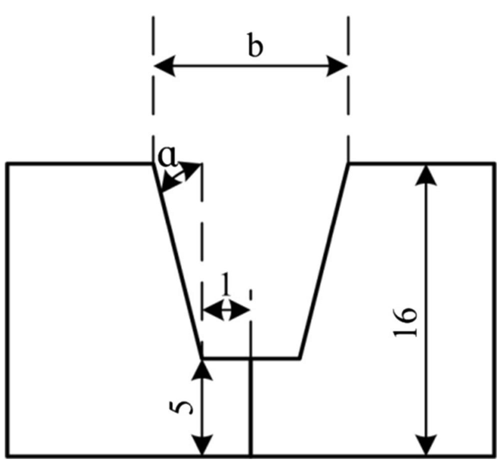



**Fig. 10** The groove style and size

and weld quality. A narrower groove space would make the droplet transfer to the side wall directly, which actuates lack of fusion and non-fusion between layer defects as shown in Fig. 11a; meanwhile, a larger groove space would increase welding passes and the uneven surface might disturb the next welding pass shown in Fig. 11b. As shown in Fig. 11c, the weld defects almost disappeared with optimal groove size. So, the groove gap was kept in the range of 4.5 to 7.5 mm. The overall design of the 40-mm-thick plate groove is shown in Fig. 12.

In order to guarantee that the welding wire can enter into the groove bottom as straight as possible and keep the wire laser distance in a proper range, the special wire feeder was designed as shown in Fig. 13. Figure 14 is the real photo of the wire feeder.

The welding parameters of the 40-mm-thick plate are shown in Table 7.

## 3 Experimental results and discussions

### 3.1 The effect of the laser cleaning method on the oxide on the weld surface

In Fig. 15, ×250 ESEM photos of the four zones are shown; Fig. 15a represents the ESEM photo of the weld bead surface without laser cleaning. The white granular substance with different sizes distributed randomly on the weld surface. Figure 15b–d represents the weld surface cleaned using different parameters respectively. It could be seen that the amount of white granular substance decreased relatively. Figure 16 shows ×1000 ESEM photos of the above four zones.

From Fig. 16, ×1000 ESEM photos of the four zones, we can see that there existed many white granular substances and they mixed with the gray matrix evenly in Fig. 16a, some white granular substances distributed individually on the gray matrix in Fig. 16b, while the white granular substances almost disappeared in Fig. 16c, d. In order to make sure of the component of the white granular substances and the gray matrix, EDS test was done and the test results are shown in Figs. 17 and 18.

The major components of the white granular substances were $Fe_2O_3$ and $SiO_2$ from Fig. 17, and the gray matrix

**Table 4** The constant welding parameters of narrow-gap laser welding

| | |
|---|---|
| Defocusing amount | 0 mm |
| Shielding gas | Ar+20 % $CO_2$ |
| Wire laser distance | 2~3 mm |
| Shielding gas flow rate | 1.2~1.5 $m^3$/h |

**Table 5** The variable parameters of narrow-gap thick plate welding

| Groove angle<br>Welding method | Welding parameters | 6° | 15° |
|---|---|---|---|
| Laser autogenous welding | Laser power (kW) | 4 | 4 |
| | Welding speed (m/min) | 0.72 | 1 |
| | Shielding gas glow rate ($m^3$/h) | 1.2 | 1.5 |
| The first-pass laser arc hybrid welding | Laser power (kW) | 2.5 | 2.5 |
| | Current (*I*) | 200 | 200 |
| | Welding speed (m/min) | 1.2 | 1 |
| The second-pass laser arc hybrid welding | Laser power (kW) | 2.5 | 2.5 |
| | Current (*I*) | 200 | 200 |
| | Welding speed (m/min) | 1 | 0.72 |
| The third-pass laser arc hybrid welding | Laser power (kW) | 2.5 | 2.5 |
| | Current (*I*) | 200 | 200 |
| | Welding speed (m/min) | 0.72 | 0.54 |

almost did not contain O element from Fig. 18. The laser cleaning method plays an important role in decreasing the oxide content on the weld surface that can be proved by the disappeared white granular substances after being laser cleaned. This phenomenon can also explain why the slag defects decreased greatly after being cleaned by laser shown in Fig. 7.

**Table 6** The parameter setup of the laser cleaning system

| Waveform | Rectangular wave |
|---|---|
| PRF (pulse repetition frequency) | 20 kHz |
| Laser spot diameter | 0.06 mm |
| The fixed *Q* pulse width | 8 μs |
| Line spacing | 0.05 mm |
| Sweeping direction | Single direction |

Above all, the laser cleaning method did make a great effect to remove the oxide on the weld surface. However, some cracks appeared on the weld surface in Fig. 16d on accounting of too large laser energy beyond the damage threshold that might decrease the property of welded joints. Accordingly, how the cleaning parameters affected the cleaning effect so as to affect the mechanical property of the welded joints should be studied further.

### 3.2 The influence of laser cleaning parameters on the welded defects of the 16-mm-thick plate welded joint

#### *3.2.1 The effect of groove angle on the welded defects*

In the laser cleaning process, the role blockages of the groove to shielding gas also impacted on the cleaning effects. Theoretically, the blockages would be stronger that can increase the

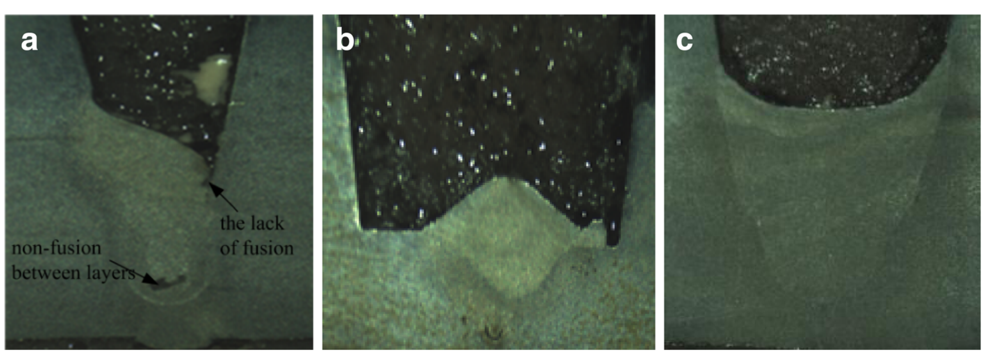



**Fig. 11** The weld cross section with different groove sizes

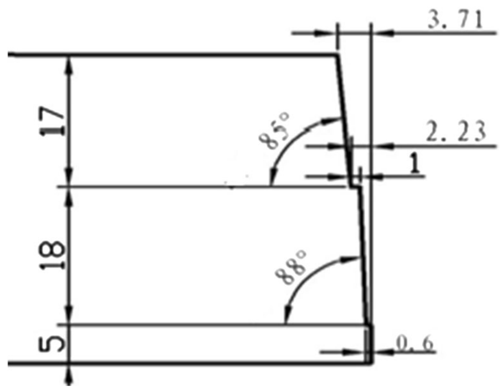



**Fig. 12** The groove style and size of the 40-mm-thick plate

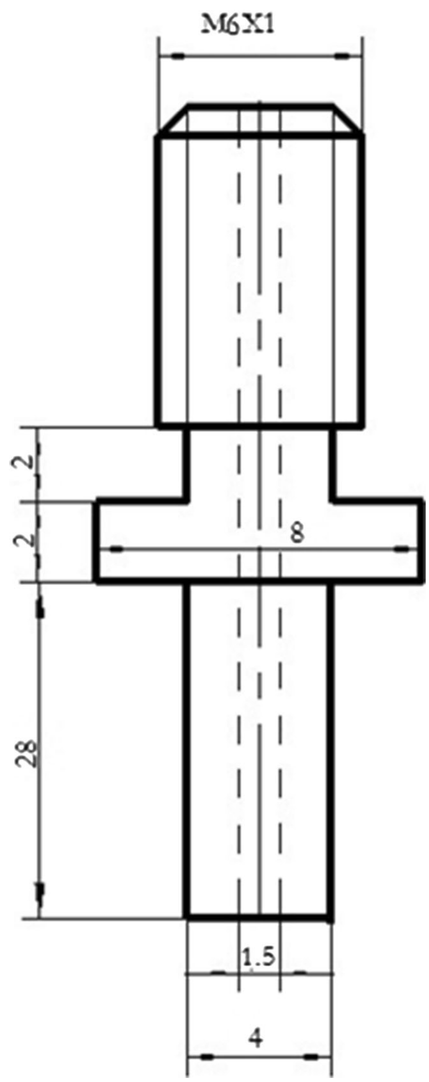



**Fig. 13** Wire feeder

shielding gas density inner groove so as to prevent the weld surface from being oxidized as the groove became narrower and deeper. 6° and 15° grooves were chosen and different cleaning parameters are shown in Tables 8 and 9.

It can be known from the welded cross sections in Tables 8 and 9 that the amount of the welded defects may not vary much using the same parameters. No matter what the groove angle was, the weld defects almost disappeared with +1-mm defocusing amount shown in Table 8 while some defects existed with +3-mm defocusing amount shown in Table 9. Accordingly, the groove angle did not affect the cleaning effect a lot employing the same parameters, which was mainly for the reason that the incompletely melted or un-melted weld surface metal can be protected well in a relatively purer shielding gas atmosphere. So, both of the two kinds of groove angle can meet the requirement in the cleaning process, but in order to obtain a better weld appearance which can eliminate the distraction of the uneven weld surface to the cleaning effect, a 15° groove angle was chosen in the following experiments.

### *3.2.2 The effect of laser cleaning speed on the welded defects*

It was obvious that several minor porosities existed in the welded cross sections shown in Table 10. When the cleaning speed was lower than 250 mm/s or faster than 500 mm/s, some welded defects existed in the overlap regions of two welding passes. As can be seen in Table 10, the welded defects can be

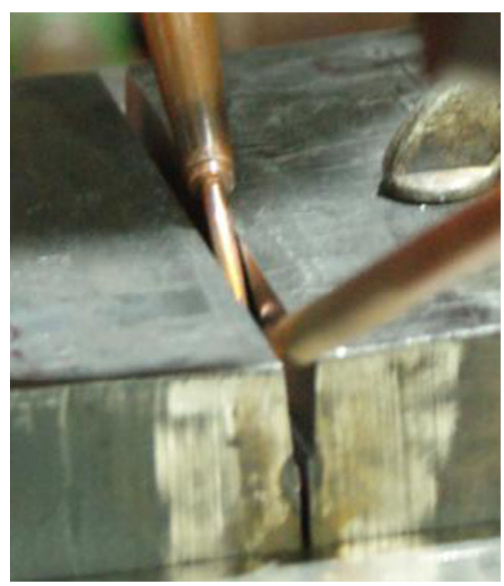


**Fig. 14** Real photo of the wire feeder

**Table 7** The laser non-autogenous multi-layer multi-pass welding parameters

| Welding pass | Laser power (kW) | Welding speed (m/min) | Wire feeding speed (m/min) | Current (A) | Wire laser distance (mm) | Defocusing amount (mm) |
|---|---|---|---|---|---|---|
| 1 | 4 | 0.72 | | | | |
| 2 | 4 | 0.42 | 3.3 | | | |
| 3 | 4 | 0.36 | 3.3 | | | |
| 4 | 4 | 0.3 | 3.3 | | | |
| 5 | 2.5 | 0.54 | 6.9 | 200 | 3 | 0 |
| 6 | 2.5 | 0.42 | 6.9 | 200 | 3 | 0 |
| 7 | 2.5 | 0.42 | 6.9 | 200 | 3 | 0 |
| 8 | 2.5 | 0.42 | 6.9 | 200 | 3 | 0 |
| 9 | 2.5 | 0.36 | 6.9 | 200 | 3 | 0 |
| 10 | 2.5 | 0.36 | 6.9 | 200 | 3 | 0 |

eliminated entirely with a 250-mm/s cleaning speed, but whatever the cleaning speed was, only several minor defects occurred in the cross sections. This phenomenon meant that the cleaning speed might not be a key factor in the cleaning effects. However, there was an optimal range which can decrease the defects as much as possible. Of course, the 250-mm/s cleaning speed was an optimal parameter.

*3.2.3 The effect of laser power on the welded defects of welded joints*

The oxides on the weld surface cannot be removed efficiently that led to some slag and porosity defects in welded joints when the laser power was less than a certain value. As can be seen in Table 11, when the laser power was in the range

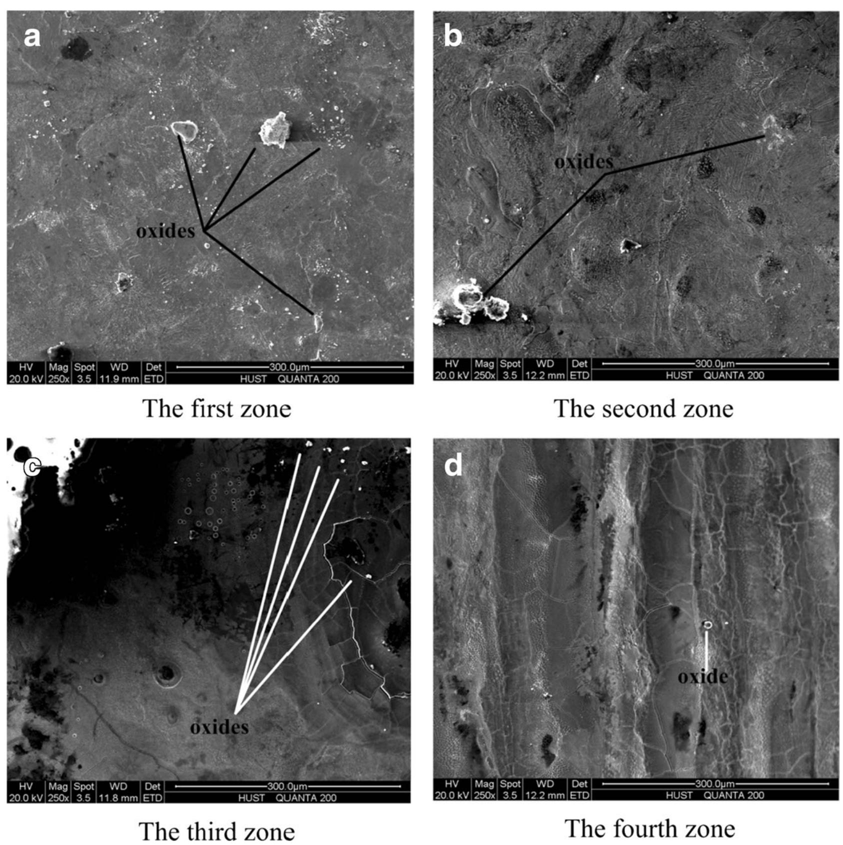



**Fig. 15** ESEM photos (×250) of the four zones

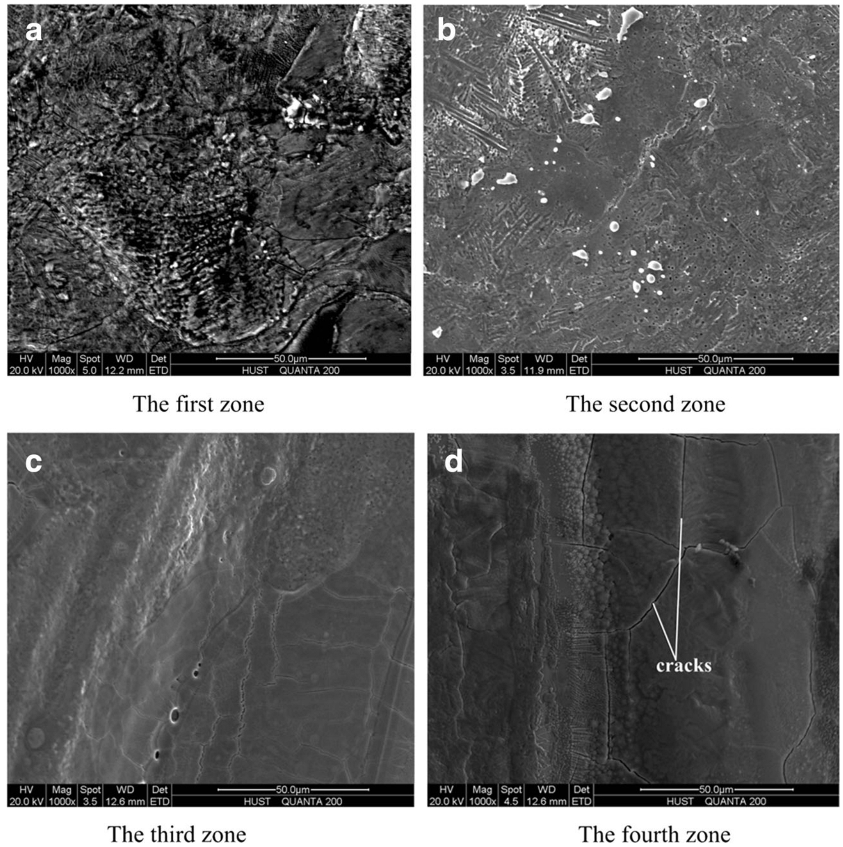
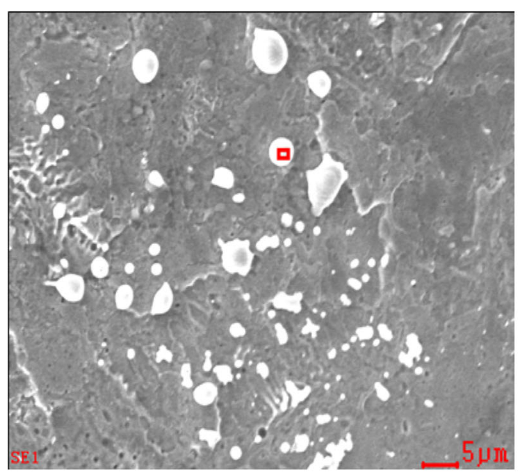
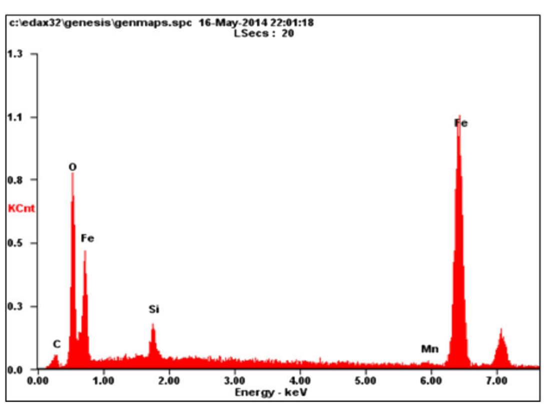


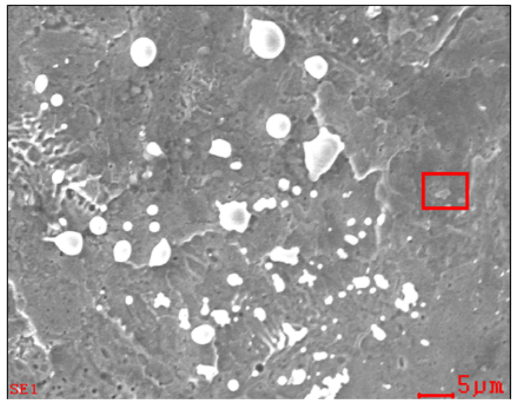

**Fig. 16** ESEM photos (×1000) of the four zones

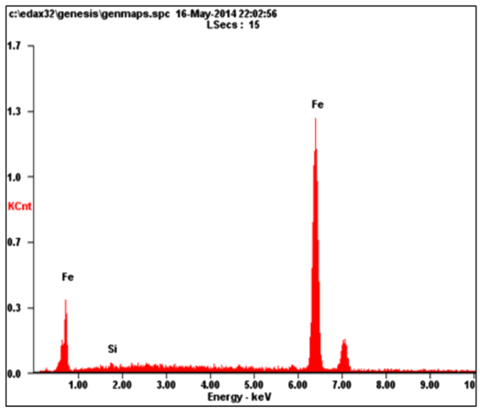



| Element | Wt% | At% |
|---|---|---|
| CK | 06.17 | 16.75 |
| OK | 18.42 | 37.55 |
| SiK | 02.88 | 03.34 |
| MnK | 00.93 | 00.55 |
| FeK | 71.60 | 41.81 |
| Matrix | Correction | ZAF |

**Fig. 17** The EDS test results of the white granular substances




| Element | Wt% | At% |
|---|---|---|
| SiK | 01.03 | 02.03 |
| FeK | 98.97 | 97.97 |
| Matrix | Correction | ZAF |

**Fig. 18** The EDS test results of the gray matrix

**Table 8** The effect of groove on the welded defects

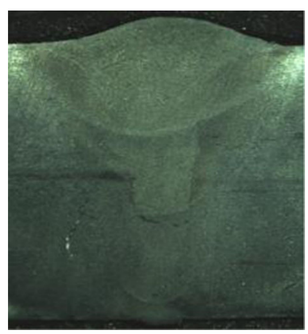
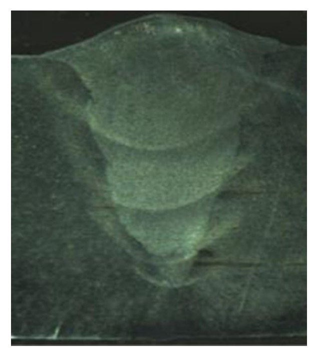
| Defocusing amount +1 mm laser Power 250 W cleaning Speed 250 mm/s shielding gas Flow rate 1.5 $m^3$/h | 6° groove | 15° groove |
|---|---|---|
| |  |  |

**Table 9** The effect of groove on the welded defects

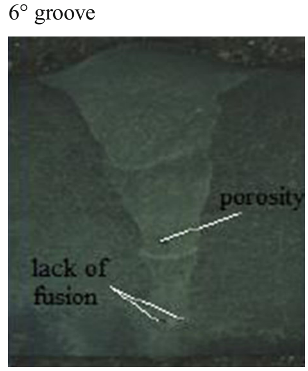
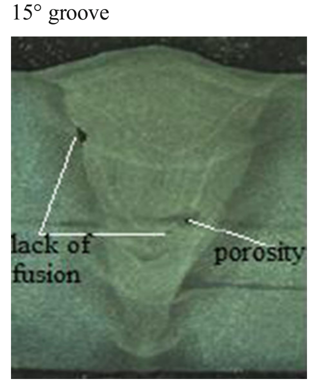
| Defocusing amount +3 mm laser Power 250 W cleaning Speed 250 mm/s shielding gas Flow rate 1.5 $m^3$/h | 6° groove | 15° groove |
|---|---|---|
| |   |   |

**Table 10** The influence of laser cleaning speed on the welded joints

| Defocusing amount：+1mm, laser power：250w, groove angle:15°, shielding gas flow rate：1.5m$^3$/h | | | |
|---|---|---|---|
| Cleaning speed: 100mm/s | Cleaning speed: 250mm/s | Cleaning speed: 500mm/s | Cleaning speed: 750mm/s |
|  |  |  |  |

**Table 11** The influence of laser power on the welded joints

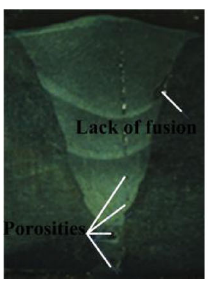
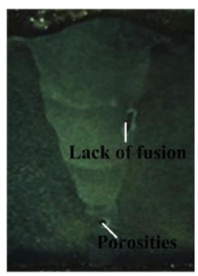
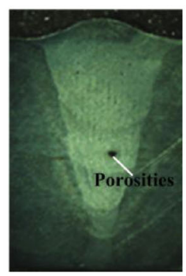
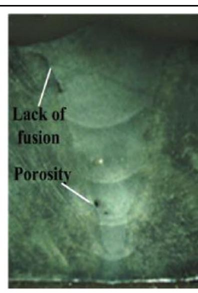
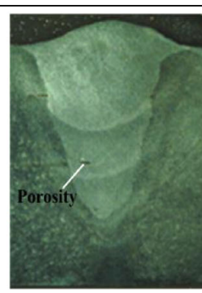
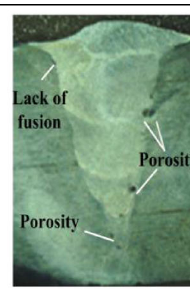
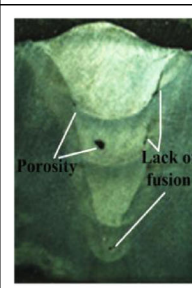
| Defocusing amount：+5mm, cleaning speed：500mm/s, groove angle:15°, shielding gas flow rate：1.5m$^3$/h | | | | |
|---|---|---|---|---|
| 100W | 200W | 300W | 400W | 500W |
|  |  |  |  |  |

**Table 12** The influence of defocusing amount on the welded joints

| Laser power:250W, cleaning speed：250mm/s, groove angle:15°, shielding gas flow rate：1.5m$^3$/h | | | | |
|---|---|---|---|---|
| -1mm | 0mm | +1mm | +2mm | +3mm |
|  |  |  |  |  |

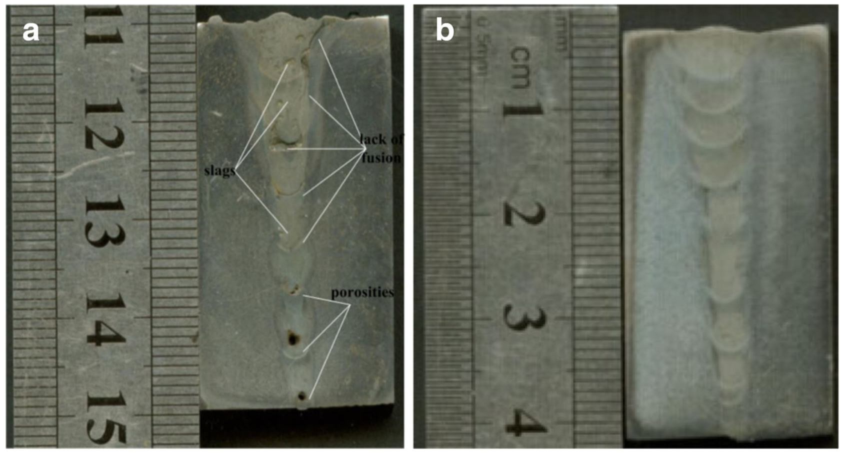



**Fig. 19** The cross section of welded joints

of 200 to 300 W, the slag and porosity defects decreased greatly. However, the welded defects did not decrease obviously when the laser power was higher than 300 W. So, we can get a conclusion that the laser cleaning method can remove the oxide usefully in a certain range; it would not be very effective to remove oxides to keep adding laser power.

### *3.2.4 The effect of defocusing amount brought to the welded defects on welded joints*

The defocusing amount was an important factor to remove the oxide on the welded surface. From Table 12, it can be seen that the welded defects existed in almost all the welded joints. When the defocusing amount was less than 0 mm or larger than +2 mm, some more welded defects occurred. Only when the defocusing amount was about +1 mm can the welded defects be eliminated greatly. This was similar with the experimental results in Tables 8 and 9.

According to the former experimental results, the defocusing amount and the laser power were two major factors to remove oxides on the weld surface. So, we selected the laser cleaning parameters of +1 mm defocusing amount, 200 W laser power, 250 mm/s laser cleaning speed, and 1.5 $m^3$/h shielding gas flow rate to weld the 40-mm-thick plate by the laser non-autogenous multi-pass multi-layer welding method.

## 3.3 The 40-mm-thick plate welded by the combination of laser cleaning and laser non-autogenous multi-pass multi-layer welding method

In the experiments, mechanical cleaning and laser cleaning were adopted to clean the oxide on the weld surface. Figure 19a, b are the weld cross section photos using the two kinds of cleaning methods respectively.

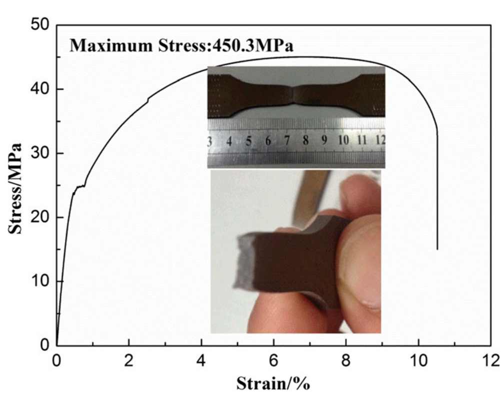



**Fig. 20** The tensile strength results of the base metal

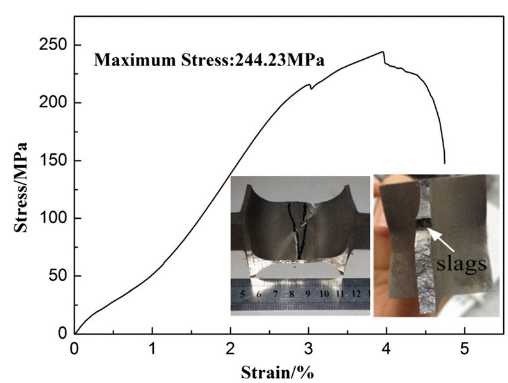



**Fig. 21** The tensile strength results of welded joints cleaned by mechanical method

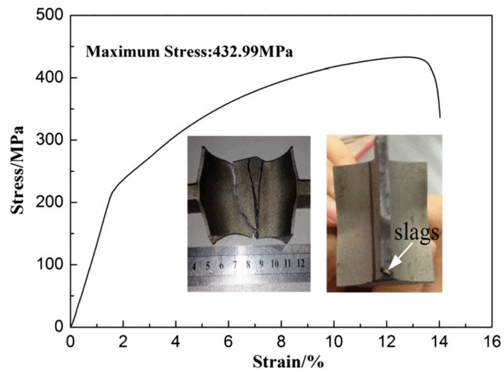



**Fig. 22** The tensile strength results of welded joints cleaned by laser cleaning method

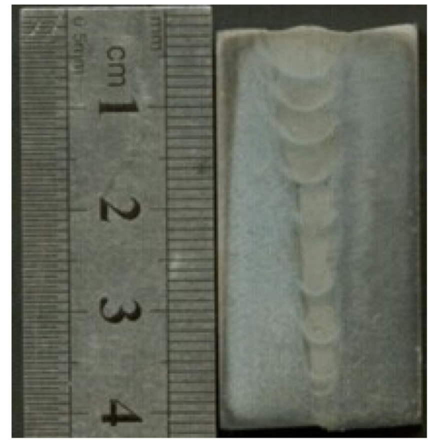


**Fig. 24** The weld cross section of the 40-mm-thick plate

Compared with the two photos in Fig. 19, it could be seen clearly that more welding defects occurred because of the incomplete cleaning of impurities between two welding processes when using mechanical cleaning method. The slag defects mainly existed at the fusion line, and the lack of fusion defects mainly occurred at the upper part of the groove with a larger gap. However, the welding defects almost disappeared using laser cleaning method. A tensile test of the base metal and welded joints was carried out, and the results are shown in Figs. 20, 21, and 22.

The tensile strength of the welded joints was 244.23 Mpa with mechanical method. However, the strength was up to 432.99 Mpa, 96 % of the base metal, cleaned by laser. As shown in Figs. 21 and 22, the slags were the weak point of the welded joints because the cracks arise from the black impurities where stress concentrated on the tensile fracture surface. Almost all the fracture line began from the fusion line closer to base metal in the laser arc hybrid welding part to the slags in the welding center and ended to the base metal. Some hardness tests were carried out to study the reason shown in Fig. 23.

Enough dots were ranged in the laser arc hybrid welding zone, the laser wire filling zone, the autogenous welding zone, the fusion zone of laser arc hybrid welding, and the base metal. The hardness of the five zones, laser autogenous welding zone, laser wire filling zone, laser arc hybrid welding zone, fusion zone of laser arc hybrid welding, and base metal, is in accordance with the descending order shown in Fig. 23. The hardness of the fusion zone of laser arc hybrid welding and base metal is lower relatively and the slags in welded joints were easy to be the point of stress concentration, so the fracture line obeys a special way mentioned above. The fusion zone became the weak part of welded joints for the composition and organization uneven distribution led by the partly fusion of the crystal line and inner crystal.

**Fig. 23** The hardness test results of welded joints by different cleaning methods

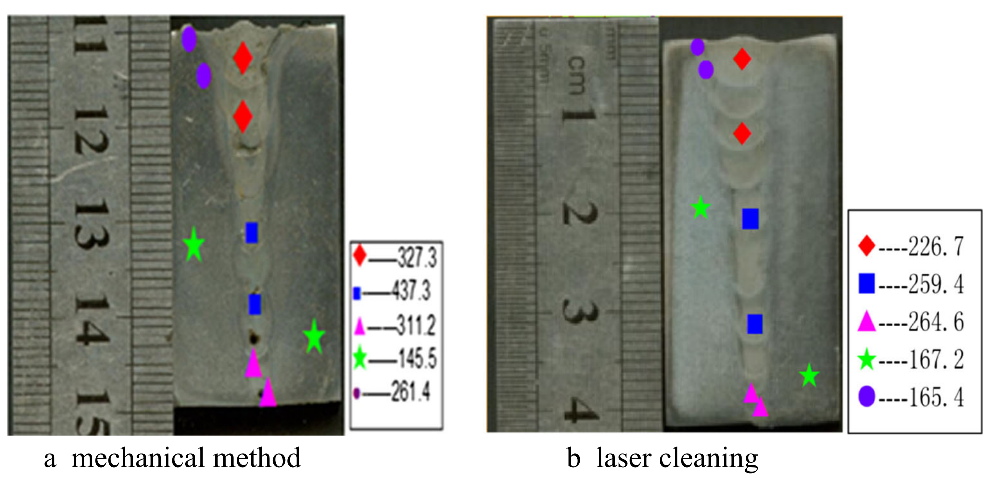


**Fig. 25** The weld macro appearance of the 40-mm-thick plate

As shown in Figs. 24 and 25, although there still are some minor defects in the weld cross section using the selected cleaning parameters mentioned in "Section 3.2.4," it brought less impact to the mechanical property of welded joints.

## 4 Conclusions

(1) The laser cleaning method can remove the oxide on the weld surface effectively in the narrow-gap non-autogenous multi-pass multi-layer laser welding process, and the slag and porosity defects were suppressed greatly.
(2) The groove angle and laser cleaning speed played a less important role in affecting the cleaning effect than the defocusing amount and laser power. The smaller defocusing amount and bigger laser power were more beneficial to remove the oxide on the weld surface so as to decrease the weld defects in a certain range. As the defocusing amount decreased, the tensile strength increased margin became more obvious.
(3) Hardness test was carried out on the laser arc hybrid welding zone, laser wire filling zone, laser autogenous welding zone, fusion zone of laser arc hybrid welding, and base metal. The hardness of these five zones, according to the order from high to low, was as follows: laser autogenous welding zone, laser wire filling welding zone, laser arc hybrid welding zone, fusion zone of laser arc hybrid welding, base metal. The tensile strength results showed that most fracture lines obey a rule: from the fusion line closer to the base metal of laser arc hybrid welding to the slags in the welding center and then to the base metal.
(4) The 40-mm-thick plate was welded well by the combination method of laser cleaning, laser autogenous welding, laser wire filling welding, and laser arc hybrid welding using low-power laser though several little defects existed occasionally.

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