Study on Fatigue Performance of Non-Uniform Thickness Markless Laser Lap Welding

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Abstract. In this paper fatigue properties of three groups of unequal thickness unmarked overlap laser welding of the external wallboard connected of type A and B vehicle were studied. In addition, a group of overlap penetration welded structures of 1.5mm-301L-HT+0.8mm-301L-DLT is designed to study the impact of penetration rate to the mechanical properties. The influence of the weld geometry and plate combination on fatigue fracture behavior and fatigue property is studied based on the combination of fatigue test and simulation stress analysis. Fatigue studies have shown that in spite of the thickness of the two lap unequal thickness welded plate is disparities — unmarked non-penetration welding outer plate is thicker but it appears fatigue fracture on the outer plate. The safety fatigue limit of three different non-penetration welded structures of plate combinations and weld structures is close which further proofs that the stress state and microstructure of non-penetration outer plate is not conducive to fatigue fracture. It is consistent with the results of the finite element simulation. The fatigue limit of lap welded structure increase with the increase of plate thickness.

Keywords. Fatigue properties, overlap laser welding, fatigue fracture, stress state.

1. Introduction
301L austenitic stainless steel has became the main material of lightweight passenger vehicles because of its high yield strength, good work hardening ability and satisfactory corrosion resistance. Due to its cold rolling hardening and high resistance, it is suitable for resistance spot welding [1]. But resistance spot welding stainless steel car body do not apply to high-speed train region for its poor air tightness and solder joints in appearance [2]. Laser welding has the advantages of high precision, high efficiency, small heat-affected area and high strength. Non-penetration laser welding can both guarantee the tensile strength and make up for the above-mentioned defects of spot welding. It has a tendency to replace spot welding in the welding of stainless steel car body [3].

Stainless steel car body is not required to be coated, and has high requirements on appearance quality. In order to ensure the corrosion resistance and air tightness, the laser welding of the outer wall plate and the frame of the car body is lapped, and the outer wall plat requires no welding marks [4-5]. That is, the depth of penetration of the outer wall of the vehicle body is less than the thickness of the outer plate, and the outer plate has no discoloration. In order to reduce the weight of the vehicle body,
on the premise of meeting the strength requirements, the thinner the skeleton, the better. This paper explores the fatigue performance of non-uniform thickness non-penetration laser welding, which can provide theoretical and experimental basis for the engineering application of lap non-penetration laser welding. This article adopts ascending and descending fatigue testing method to analyze fatigue performance and fracture mode. At the same time, it obtains stress distribution by finite element simulation.

2. Experimental Materials and Methods
Type A and B exterior wall panels are used as unmarked, non-penetration lap panels and are connected with penetration lap panels. In the experimental welding structure, the wall plates of A and B vehicles are EN1.4318 + 2G of 1.5 mm and 2.0 mm, respectively while the overlapping inner plates connected with them are 301L-DLT of 0.8 mm thickness and 301L-HT of 1.5 mm thickness. In addition, a set of 1.5mm 301L-HT and 0.8mm thick 301L-DLT plate lap penetration welding structure were designed as comparison samples. The chemical composition and mechanical properties of the plates are shown in table 1. And the selected laser welded joint combinations are shown in table 2.

| Experimental plate | Chemical composition (wt.%) | Mechanical property |
|-------------------|-----------------------------|--------------------|
|                   | C  Si  Mn  Ni  Cr  N  R_{0.2}  Rm  δ% |
| 301L-DLT          | 0.024 0.37 1.12 7.5 17.5 0.11 | 385 730 53 |
| 301L-HT           | 0.028 0.42 1.05 7.2 17.1 0.092 | 660 850 28 |
| EN.1.4328-2G      | 0.18 0.32 1.56 6.7 17.1 0.21 | 365 840 52 |

Table 2. The combination and joint forms of laser overlap welding.

| Order number | 1-Welding inner plate | 2-Welding outer plate | Joint form | Remark |
|--------------|-----------------------|-----------------------|------------|--------|
| A-1          | 0.8mm-301L-DLT        | 1.5mm-EN1.4318+2G     | Partial penetration lap | Laser welding |
| B-1          | 0.8mm-301L-DLT        | 2.0mm-EN1.4318+2G     | Partial penetration lap |
| B-2          | 1.5mm-301L-HT         | 2.0mm-EN1.4318+2G     | Partial penetration lap |
| C            | 1.5mm-301L-HT         | 0.8mm-301L-DLT        | Complete penetration |

The structure and size of laser lap joints are shown in figure 1. We make weld seam surroundings area to metallographic samples, and then import collected photos into AutoCAD software for dimensioning to get the weld penetration depth and width. The test was carried out on the MTS universal material testing machine. In order to avoid the bending moment of the specimen, a cushion plate with the same thickness was added at both ends of the specimen. The loading method was transverse amplitude pulsating sine wave load, whose cyclic ratio was 0.1. The experimental process was carried out at room temperature. The medium was air medium with dry air, and non-corrosive medium. The frequency was 80 Hz.
3. Experimental Results

3.1. Fatigue Performance of Non-Uniform Thickness Laser Lap Welding

The up and down method was used in the test. The cyclic base number \( N_0 \) was set to be \( 2 \times 10^6 \), and the fatigue limit was estimated. And the grade difference was \( 2\% \sim 5\% \) of the estimated fatigue limit.

The test began with the stress level which was slightly higher than that of the estimated fatigue life limit. If the sample did not fail at the specified cyclic base number, the next sample was carried out at a stress level higher than the upper level. But if a fracture occurred, the next specimen was carried out at a lower level of stress. The load value and life value of each specimen should be recorded until all the tests completed. 14-20 specimens are made for each kind of specimen [6].

The average value of the fatigue life is taken as the limit value, and these data are statistically analyzed to obtain the fatigue limit and standard deviation.

| Order number | Weld dimension (mm) | Unit fatigue limit (N/mm) | Unit safety fatigue limit (N/mm) |
|--------------|---------------------|----------------------------|-------------------------------|
|              | Penetration depth   | Penetration width | Penetration rate of outer plate % |                         |                          |
| A-1          | 1.41                | 0.7               | 40                           | 92.5                      | 82                        |
| B-1          | 1.24                | 0.84              | 22                           | 107.5                     | 82.6                      |
| B-2          | 2.12                | 1.19              | 31                           | 117.5                     | 87                        |
| C            | 2.3                 | 0.9               | 100                          | 107.5                     | 94                        |

Table 3 shows the fatigue test results. It can be seen that the unit fatigue limit of B-2 is the largest, and its plate combination is also the highest. In the meantime, the unit fatigue limit of A-1 is the smallest, and the strength of its plate combination is also the lowest. Therefore, the higher the strength of the plate combination is, the higher the fatigue strength of the joint is. The difference of fatigue limit between A-1 and B-1 is 15N / mm. The inner plates of A-1 and B-1 are 0.8mm, and the outer plates are 1.5mm and 2mmEN1.4318 + 2G, respectively. Both of the two joints are not penetrated. And the difference of penetration depth and width is small, but the difference of fatigue limit is large, which shows that the geometric size of the weld has little effect on fatigue performance.

The inner plates of specimens A-1 and B-1 are the same, and the thickness difference of outer plates is 0.5 mm, and the fatigue limit of specimens B-1 is large, which shows that the fatigue limit increases with the increase of plate thickness. The safety fatigue limit of three kinds of non-penetration lap welding structures with different plate combination and welding seam structure is close, while the safety fatigue limit of the reference sample with complete lap welding is higher, indicating that the stress state and microstructure of the non-penetration outer plate are not conducive to fatigue fracture.

3.2. Fracture Mode of Non-Uniform Thickness Traceless Laser Lap Welding

Figure 2 shows the fracture modes of each specimen. The fracture position of A-1, B-2, C three combinations of different weld geometry structure are all in the outer plate loading end weld edge and the fracture mode are the outer plate through the plate fracture. Although the geometric structure of each weld is different, the fracture mode is the same. The fatigue fracture of sample A-1, whose outer plate thickness is about twice the inner plate thickness, also occurs in the outer plate, which fully shows that the thickness of the outer plate and the geometric structure and penetration rate of the weld have no effect on the fracture mode. The fracture position of specimen B-1 with large thickness difference between the inner and outer plates is that the loading end of the inner plate is close to the weld, which is the fracture of the inner plate through the plate. It can be seen that the gap between the inner and outer plates is large, resulting in the difference between the fracture mode and the fracture mode of the joint with small plate gap. Therefore, the thickness difference between the inner and outer plates has a certain influence on the fracture mode. When the thickness difference is large, the fracture mode changes from the outer plate through the plate to the thin plate.
The part around the weld of the B-1 fatigue fracture specimen was taken as the metallographic specimen, and figure 3 shows the metallographic photos. It can be seen that cracks were generated near the weld between the inner and outer plates, but the upper plate was completely broken. It can be clearly seen in figure 3 that a certain length of crack appears in the outer plate, and the length of the crack is close to the thickness of the inner plate, which indicates that both the inner and outer plates have crack initiation and crack propagation, and the time and speed of crack initiation and propagation are almost synchronous. For the specimens with large thickness difference, both the inner and outer plates have cracks and propagate in the plate, and the thickness of the thin plate is small, so the final fracture position is in the thin plate.

Combined with the fatigue limit, it can be seen that the fatigue performance of B-1 is better than that of A-1, indicating that the fatigue resistance of the welded joint fractured in the inner plate is better. Although the fracture positions of the fatigue specimens are different, the outer plates are all fractured, and the inner and outer plates of the joints with large thickness differences are fractured.

3.3. Stress Analysis of Non-Uniform Thickness Laser Lap Welding

Ansys software was used for stress simulation analysis. In the simulation, one end of the specimen was subjected to full constraints, the other end was subjected to constraints in the Y and Z directions and loads in the X direction. The load value greater than 20 % of the fatigue limit was applied to each welding structure model, and the stress nephogram of each specimen was output to further understand the fatigue fracture mechanism [7].
From figure 4 (a) (b), it can be seen that the A-1 lap joint appeared serious stress concentration at the weld edge of the loading end of the outer plate, and the maximum stress value was 418 MPa. The stress of the outer plate (1.5mmEN1.4318) showed that the thickness direction force increased from the maximum to the minimum, and then increased. About 2/3 of the interface was tensile stress, and the other 1/3 was compressive stress. The stress in the thickness direction was gradient distribution, which indicated that the outer plate produced bending moment and was subjected to compressive stress. The high stress zone of the upper plate is wide along the plate direction, and the high stress zone of the lower plate is narrow. The maximum stress value is large, and the specimen is subjected to tensile stress, so the fatigue crack initiates in outer plate of specimen and propagates along the plate.

It can be seen from figure 4 (c) (d) that the maximum stress of B-1 appears at the weld edge of the loading end of the inner plate. The maximum stress value is 415 MPa, and the maximum stress of the outer plate is 414 MPa. The difference between the outer and the inner plate is very small, and the difference is less than 1 MPa, indicating that both of them may become the sources of fatigue cracks. In the fatigue experiment, two cracks were generated simultaneously. However, due to the thin inner plate, the propagation time of cracks in the thin plate was small, so the inner plate was completely fractured.

Figure 5. Fatigue crack initiation and propagation.
resistance of the weld is better than that of the plate. The crack initiation point is at the edge of the weld at the loading end of the welded outer plate. The stress concentration near the weld at the loading end of the inner and outer plates of weldments with large thickness difference is very serious, and fatigue cracks are generated at both ends. The crack propagation direction can be toward the plate or toward the weld. As shown in figure 5, the weld shows a trapezoidal structure with upper width and lower width. When extending to the weld, due to the very fine grain of the weld, the diameter is 10-20, and it is perpendicular to the edge of the weld, the crack propagation in this direction needs to cut off the grain, and the propagation in this direction is hindered, and the propagation speed is slow. When the crack propagates to the plate, due to the large grain size of the plate and the smooth expansion of the shear band, the crack propagates along the thickness direction of the plate, resulting in fatigue fracture on the plate [8].

Although the safety fatigue performance of fully welded specimens is better, the stress concentration caused by lap structure itself has not been eliminated. The fracture mode is still plate fracture, and the weld geometry has no effect on the fracture mode. In the fatigue test, the specimen A-1 with the thickness difference of 0.7 mm is broken in the outer plate, and the specimen B-1 with the thickness difference of 1.2 mm is broken in the inner plate, which shows that when the thickness difference is satisfied, the stress distribution will change, and the fatigue fracture position will change from the simple outer plate to the inner and outer plates.

5. Conclusions
  (1) The geometric shape of the weld has little effect on the fatigue performance of the unwelded laser welding structure, and the plate strength and plate combination are the most important factors affecting the fatigue performance. The fatigue limit of lap welding structure increases with the increase of plate thickness.

  (2) There are two kinds of fatigue fracture modes of non-uniform thickness laser lap welded joints: the outer plate through the plate fracture and the inner plate through the plate fracture. Although the thickness of the two lap non-equal thickness plate is very different, the outer plate is thicker, but the outer plate is fatigue fracture; The inner and outer plates of the joints with different thickness have fatigue fracture, and the thin plate is completely broken.

  (3) The weld edge of the loading end of the outer plate of the non-uniform thickness laser lap joint produces large stress concentration. The weld edge of the loading end of the inner and outer plates of the joint with large thickness difference produces serious stress concentration. This stress distribution leads to fatigue fracture of the lap outer plate, while the inner and outer plates with large thickness difference produce fracture.

  (4) The safety fatigue limits of the three non-penetrated lap welding structures with different plate combinations and weld structures are close, while the safety fatigue limits of the reference specimen with complete lap penetration are relatively high. The fatigue stress of the specimen with complete lap penetration is relatively high in the simulation analysis, which further proves that the stress state and microstructure of the non-penetrated outer plate are not conducive to fatigue fracture resistance.

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