Effect of Welding Processes on Fatigue Properties of Stainless Steel Welded Joints for Railway Vehicle

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Abstract. The fatigue properties and S-N curves of the 3mm thickness SUS301L-MT and 5mm thickness SUS304 stainless steel sheet lap fillet welded joints made by plasma arc welding, plasma-MIG hybrid welding as well as resistance spot welding are investigated respectively based on the results of fatigue tests. The parameters of curves and the fatigue strength of the lap fillet welded joints are calculated. The influence of the 3 kinds of welding processes on fatigue resistance is discussed. Results show that compared with the fatigue tested results of resistance spot welded joint, the fatigue strength increases by about 73.7% and 39.5%, under the condition of 2×10^6 cycle life, for plasma arc welding and plasma-MIG hybrid welding process respectively.

Introduction

Stainless steel vehicle, because of its good impact energy absorption characteristics, fire protection, lightweight, low maintenance cost and so on, has become one of the important development directions for lightweight railway vehicles [1]. The SUS301L, SUS304 authenticate stainless steel is commonly used for the structural materials of stainless steel carb ody. But owing to the authenticate stainless steel's small heat conductivity and big linear expansion coefficient, the deformation after welding becomes large and the rectification of deformation is difficult. So the welding of stainless steel bodywork structure is mainly used by resistance spot welding process. However, the main problem for the spot wending is the obvious plastic impression on the surface of welding spot area of car body and the poor spot welding's sealing of the structure. Laser welding is regarded to be a good method which is instead of resistance spot welding process for the welding of bodywork side walls, but from the process adaptability point of view, laser welding process doesn't fit the welding for the long lap fillet welds of car body walls.

Plasma arc welding and plasma-MIG hybrid welding are also high energy density welding processes, with the characteristics of energy concentration, strong penetration ability, big depth-to-width ratio of weld, narrow heat-affected zone, high quality weld, low deformation and so on[2]. Its welding process adaptability is more suitable for the welding of long lap fillet welds of the walls. However, compared with the resistance spot welding, the fatigue resistance of plasma arc welded joint and plasma-MIG hybrid welded joint is still lack of experimental data. Therefore, the shear tensile fatigue tests and the fatigue performance analysis were conducted for the lap welded joints of plasma welding, plasma-MIG hybrid welding and resistance spot welding respectively, so as to provide experiment basis for plasma welding and plasma-MIG hybrid welding technology in the application of stainless steel bodywork manufacturing.

Experimental Materials and Methods

Experimental Materials

The thickness 3mm SUS301L-MT and 5mm SUS304 stainless steel sheets are used for the test materials, their chemical composition and mechanical properties are shown in Tab.1. ER308LSi with 1.0 mm diameter is selected as welding wire and its chemical composition and the mechanical properties of its deposited metals are shown in Tab.2. 99.999%Ar and 98%Ar+2%CO2 are used as plasma gas and welding shielded gas respectively.

Table.1 Chemical composition and mechanical properties of stainless steel sheet

stainless steel	chemical composition(mass fraction,%)								mechanical properties		
	C	Si	Mn	P	S	Cr	Ni	N	$R_{p0.2}$/MPa	R_m/MPa	A(%)
SUS301L-MT	≤0.03	≤1.00	≤2.00	≤0.045	≤0.03	16~18	6~8	≤0.20	≥480	≥820	≥25
SUS304	≤0.08	≤1.00	≤2.00	≤0.045	≤0.03	18~20	8~10.5	-	≥205	≥520	≥45

Table.2 Chemical composition and deposited metal mechanical properties of welding wire

welding wire	chemical composition(mass fraction,%)									mechanical properties		
	C	Si	Mn	P	S	Cr	Ni	Cu	Mo	$R_{p0.2}$/MPa	R_m/MPa	A(%)
ER308LSi	≤0.03	0.65~1.00	1.00~2.50	≤0.030	≤0.030	19.50~22.00	9.00~11.00	≤0.75	≤0.75	347~454	598~625	30.7~55

Welding Processes

For the welding of lap fillet welded joints, PTW1500 plasma welding equipment and FANUC Robot M-10iA are used in plasma welding. Standard Super-MIG plasma hybrid welding system, MOTOMAN-HP20D robot and TPS4000 digital MIG welding equipment are used in plasma-MIG hybrid welding. The welding parameters of plasma welding and plasma-MIG hybrid welding are shown in Tab.3.

Fatigue Tests

Refer to the standard GB/T1511-1994, the shear tensile fatigue tests are conducted by using MTS810 electric servo-hydraulic material test system for the lap fillet welded joints of plasma welding, plasma-MIG hybrid welding and resistance spot welding respectively. The fatigue test conditions are as follows: constant amplitude sine wave load, ambient air medium, frequency f=20Hz, cycle stress ratio R=0, cycle life setting $N_f=2\times10^6$. The shape and size of fatigue specimen are shown in Fig.1. Electron scanning electron microscope JSM-6360LV is used to analyze the fatigue fracture morphology after fatigue testing.

Table.3 Welding parameters

welding process	Plasma arc current/A	Plasma arc voltage/V	MIG current/A	MIG voltage/V	welding speed/(cm min^{-1})	Plasma gas flow/(L min^{-1})	shield gas flow/(L min^{-1})
plasma arc welding	140	16	—	—	25	0.6	10
plasma-MIG hybrid welding	110	23	200	22.3	120	3	15

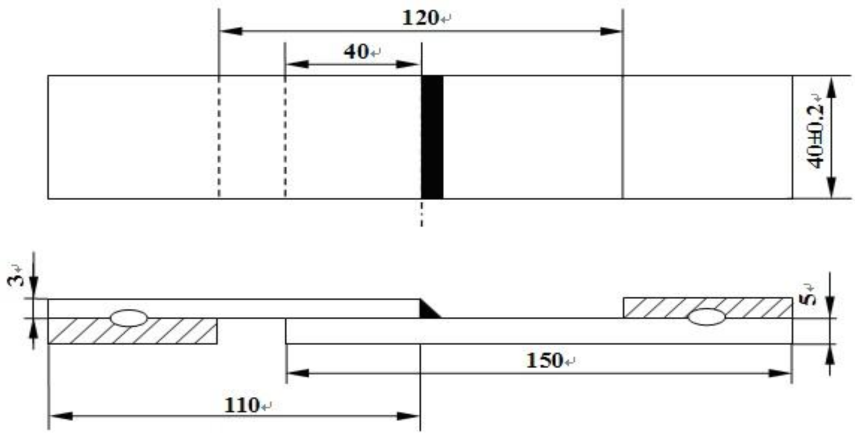


Fig.1 Fatigue specimen of lap fillet welded joint

Experimental Results and Analysis

Fatigue Strength and S-N curve

S-N curve of stainless steel sheet lap fillet welded joints can be expressed as the relationship between nominal load range ΔP and fatigue cycle life N under different cyclic loads [3]. Generally, in the condition of a given cycle load ratio R=Smin/Smax, the nominal load range ΔP and fatigue cycle life N obey the exponential relationship:

$$S^m \cdot N = C \tag{1}$$

In formula (1), *S* is the load range Δ P in the name of the loading change; *N* is fatigue life; mand C are constants.

The logarithm is taken for the both ends of formula (1) and expresses as follows:

$$\lg N = A + B \lg S \tag{2}$$

In formula (2), *A* and *B* are the fitting constants. The corresponding relations of parameters in the formula (1) and formula (2):

$$m = -B \tag{3}$$

$$\mathrm{C} = 10^{\mathrm{A}} \tag{4}$$

According to the fatigue test data in Tab.4 and referring to the formula (2), the S-N curve of each group sample is established and drawn as shown in Fig.2 by means of the principle of least square fitting, where the S-N curve equation for each welding process is as follows:

Plasma welding: $\lg N = 11.88 - 5.79 \lg S$ (5)

Plasma - MIG welding: $\lg N = 10.51 - 4.85 \lg S$ (6)

Resistance spot welding: $\lg N = 9.63 - 4.61 \lg S$ (7)

Calculated by the formula (3), (4) and S-N curve equation (5), (6) and (7), m and C material constant of fatigue specimen, and the fatigue strength of joints in the N = 2×10^6 cycles, the results as shown in Tab.5.

Table.4 Results of fatigue tests

welding process	No.	△ P /kN	N_f / cycle	crack position
plasma arc welding	1-1	20.47	14409	weld metal
	1-2	17.06	94639	weld metal
	1-3	15.35	91174	weld metal
	1-4	13.64	220653	toe of weld
	1-5	11.94	364491	toe of weld
	1-6	10.23	1099929	toe of weld
plasma-MIG hybrid welding	2-1	20.47	8541	toe of weld
	2-2	17.06	49520	toe of weld
	2-3	13.64	178505	toe of weld
	2-4	10.23	315382	toe of weld
	2-5	8.53	725912	toe of weld
	2-6	7.67	1965982	toe of weld
Resistance spot welding.	3-1	20.47	5129	joint surface
	3-2	17.77	7512	joint surface
	3-3	14.21	10179	joint surface
	3-4	10.66	151405	joint surface
	3-5	7.11	267399	joint surface
	3-6	6.22	1471015	joint surface

Table.5 Parameters of S-N curve

welding process	m	C	Fatigue resistance（2×10^6）ΔP/kN
plasma arc welding	5.79	7.54×10^{11}	9.19
plasma-MIG hybrid welding	4.85	3.24×10^{10}	7.38
resistance spot welding.	4.61	4.35×10^{9}	5.29

It can be seen from Fig.2, the areas expressed in load range ΔP and cycle life N in the S-N curves can be divided into two parts: one is the fatigue fracture area located in the upper part of the S-N curve, the other is in the lower part of the S-N curve, where the fatigue failure not occurs. So it is evident that the fatigue S-N curves will provide a reliable experiment basis for the fatigue assessment and design of welded joints.

From Fig.2 and Tab.5, the fatigue strength ΔP = 9.19 kN and 7.38 kN for plasma arc welded joint and plasma-MIG hybrid welded joint respectively under the condition of 2×10^6 cycles, are higher than that of resistance spot welded joint ΔP = 5.29 kN.

Compared with the resistance spot welding, under the condition of the fatigue life of 2×10^6 cycles, the fatigue strength increases by about 73.7% and 39.5% for plasma arc welding and plasma-MIG hybrid welding respectively.

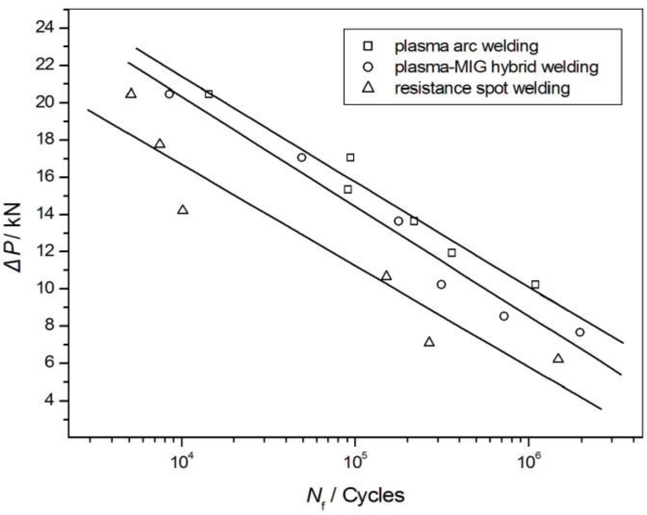


Fig.2 S-N curve of welded joints

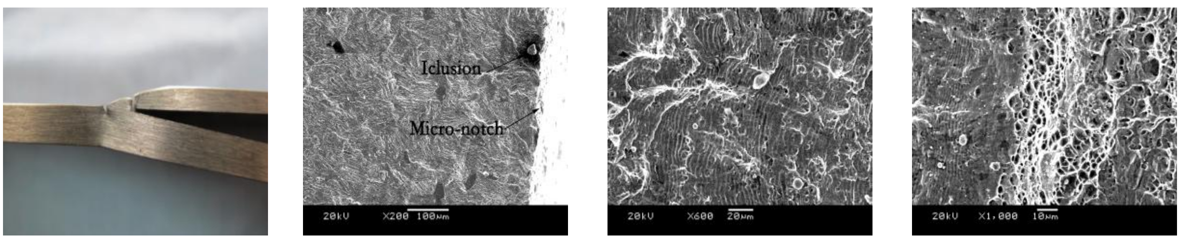
As for stress fatigue, the fatigue mechanism is mainly affected by stress concentration[4]. A large number of tests indicate that the stress concentration of welded joint and welding residual stress are the important factors influencing the fatigue performance of welded joints. Figure 3 show the macro-morphology of lap fillet welded joints for plasma welding and plasma-MIG hybrid welding. Obviously, the shape of weld toe assumes a smooth transition for plasma welding process, but for plasma-MIG hybrid welding process, the transitional angle between the weld and the parent metal in the area of weld toe is small, so as to produce a larger stress concentration. Therefore, the stress concentration of weld toe area is the main cause of which the fatigue strength of lap fillet welded joint for plasma-MIG hybrid welding is lower than that for plasma arc welding. Through further optimization of plasma-MIG hybrid welding process, to improve the weld toe shape, reduce the stress concentration, the fatigue performance can be improved.

(a) plasma arc welding (b) plasma-MIG welding

Fig.3 Macro morphology of welded joints

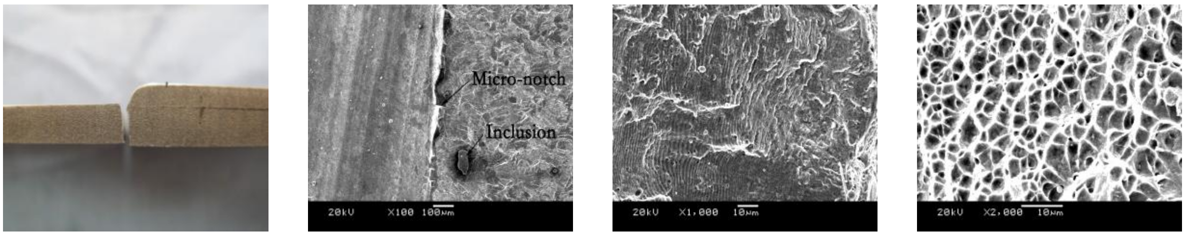
Fatigue Fracture

The shear tensile fatigue fracture and fracture morphology characteristics are shown in Fig.4 and Fig.5 for the lap fillet welded joints of plasma arc welding and plasma-MIG hybrid welding respectively.



(a) rupture location (b) crack initiation (c) crack propagation (d) final fracture

Fig.4 Fatigue fracture position and morphology of plasma arc welded specimen



(a) rupture location (b) crack initiation (c) crack propagation (d) final fracture

Fig.5 Fatigue fracture position and morphology of plasma arc welded specimen

It shows in Fig.3, Fig.4 and Fig.5, that under the effect of axial shear tensile fatigue loading, the fatigue crack of plasma welding joint under higher load stress generally originates in the weld root of stress concentration, in which the micronotch and inclusions exist, and propagates along the weld metal until final rupture. But when loading stress is lower, the crack initiates in the position of weld toe, then extends to fracture in the direction of the parent metal thickness. For plasma-MIG hybrid welded joints, the fatigue crack of all specimens begins in the weld toe, and extends in the direction of the parent metal thickness until completely broken. Two kinds of fatigue fractures show ductile fracture characteristics. In the crack propagation area, it is obvious that the micro morphology of fracture for the two kinds of joints appears fatigue stripes and their banding spacing is similar which shows the same crack propagation rate. In the instantaneous fracture zone, there are a large number of dimples which indicate the fracture mode is ductile fracture.

Summary

Compared with resistance spot welding, the shear tensile fatigue strength of lap fillet joint by plasma arc welding under the condition of 2×10^6 cycling life increases by 73.7%, and for Plasma-MIG hybrid welding, the joint’s fatigue strength also increases by 39.5%.

The fatigue crack of plasma arc welded joint starts at lap fillet weld root, and propagates in the weld until fracture, and also for some joints the crack initiates at the weld toe, and extends to fracture along the direction of the parent metal thickness. But for plasma-MIG hybrid welding, the fatigue crack of all the joints initiates in weld toe area with stress concentration, and then propagates in the direction of the parent metal thickness until complete fracture.

In the fatigue crack propagation regions of the two kinds of joints, there are evident fatigue strips on the fracture surface, and it is not too big for the difference of the strip spacing. In the instantaneous fracture zone, a large number of dimples exist, which means the fracture is the ductile fracture.

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