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Study on Welding Process Between the Hexagonal Tube and the Grid Frame Component of MOX Fuel Assembly in CEFR

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Abstract

A series of welding process tests were carried out for the pressure resistance spot welding (RSW) of the hexagonal tube and the grid frame component of MOX fuel assembly in CEFR. With the help of visual inspection, metallographic inspection and tensile test at room temperature, analyzing the influence trend of single welding parameter on the nugget diameter and mechanical properties. A set of optimal welding parameters is obtained by considering the influence of welding current, welding time and electrode pressure on the quality of welding joints. The results show that when the welding current is 3kA, the welding time is 8cyc (1cyc=1/50Hz), and electrode pressure is 350N, the diameter of the soldering core and the tensile force of the welding joints are relatively stable.

Keywords: CEFR; hexagonal tube; grid frame component; pressure resistance spot welding(RSW); welding process

Introduction

With the rapid development of fast reactor in China, the manufacturing technology of fast reactor MOX fuel assembly has also been quickly mastered and applied in China. In the manufacturing process of MOX fuel assembly for fast reactor, the pressure resistance welding process has been successfully applied to the key process of MOX assembly manufacturing abroad. In China, Liu Bo [1] used pressure resistance spot welding equipment to weld 316 (Ti) stainless steel transmutation module simulator containing neptunium. Wang Jian Hong [2] conducted a large number of welding tests on the grid plate frame components and hexagonal tubes of the experimental fast reactor conversion area assembly using a mobile multifunctional welding equipment (the device is equipped with an X-shaped pneumatic pressure resistance welding gun). The device can realize the welding of the grid plate frame components and hexagonal tubes, but its degree of automation is low, and the welding process requires human intervention, which is suitable for the welding of the conversion area assembly without MOX fuel rods.

During the manufacturing process, due to the extremely high radioactivity of MOX fuel assembly, the welding personnel can not carry out welding operations at close range. Therefore, for the welding of grid plate components and hexagonal tubes of fast reactor MOX fuel assembly, ABB full-automatic pressure resistance welding robot is used in all tests in this paper to weld them, which greatly solves the problem of welding in high radiation area. At the same time, online real-time monitoring of welding parameters and stable and accurate control of heat input are realized, It avoids the serious oxidation of air to the weld, improves the automation and production efficiency of the production line, and can meet the requirements of repeated large-scale production.

In this paper, the pressure resistance spot welding process for grid plate components and hexagonal tubes of MOX fuel assembly of China experimental fast reactor was tested. It is found in the test that welding current, welding time and electrode pressure are the main factors affecting nugget diameter, joint microstructure and properties of pressure resistance welding. The influence of these three welding parameters on weld joint quality is analyzed by controlling single variable research method, and the best welding process parameters are obtained through comprehensive analysis and process evaluation.

Materials and Equipments

Experimental materials

The material used for the hexagonal tube of MOX fuel assembly of experimental fast reactor is 1.2mm (20 ± 3)% cold worked cn-1515 austenitic stainless steel, and the material used for grid plate components is 1.2mm solid solution cn-1515 austenitic stainless steel [3-6]. The chemical composition of the material is shown in Tab.1 and Tab.2.

Element	C	Cr	Ni	Mo	Si	Mn	Ti	P	Al	Cu	Fe
Content	0.057	16.33	15.16	2.15	0.47	2.14	0.34	0.004	0.01	0.0005	-

Table 1: Chemical composition of the hexagonal tube (wt.%).

Element	C	Cr	Ni	Mo	Si	Mn	Ti	P	Al	Cu	Fe
Content	0.045	16.23	14.93	2.06	0.45	1.91	0.37	0.0085	0.038	0.0007	-

Table 2: Chemical composition of the grid frame component (wt.%).

Experimental equipment

ABB IRB 6620 spot welding robot is selected as the equipment for welding hexagonal tube and grid plate components according to the structure of MOX fuel assembly, welding process requirements, site design planning, robot characteristics, etc. ABB spot welding robot system is composed of robot system and welding system, as shown in Fig.1.

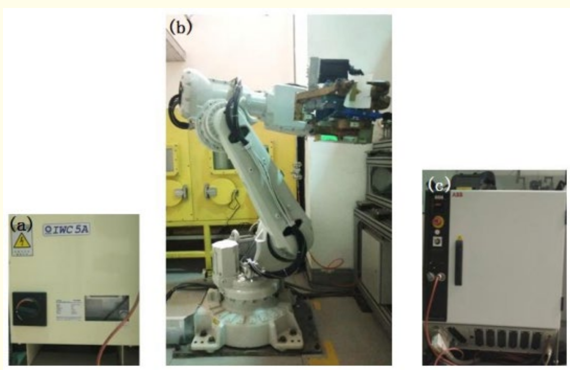

Figure 1: The welding robot system:(a) Welding controller; (b) Spot welding robot;(c) Control cabinet.

The servo spot gun servo robot welding tongs produced by the capacitor industry of Japan Co., Ltd. are selected as the welding tongs. The model of the welding tongs is TMX • TMC. Due to the high hardness of cn-1515 stainless steel, the electrode used in the experiment is required to be high, so the material with high softening temperature and high hardness should be selected as the electrode. Therefore, Zr CR Cu alloy electrode cap is adopted in this experiment, and the design drawing is shown in Fig.2.

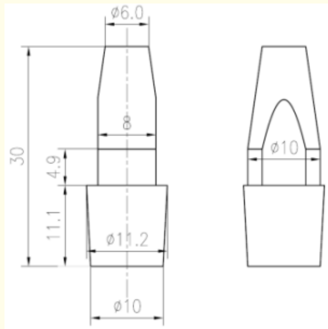

Figure 2: Alloy electrode cap.

Quality Requirements and Experimental Methods

Welding quality requirements

The welding shall be carried out in strict accordance with the technical conditions of components and the requirements in the design drawings. The specific requirements for welding are as follows:

1. Visual inspection. The weld surface shall be smooth, and the weld surface shall smoothly transition with the base metal. Defects such as missing welding, too deep indentation, burn through, serious oxidation color and cracks are not allowed.
2. Metallographic examination. The metallographic examination was carried out according to the inspection methods for welds of pressurized water reactor fuel rods metallographic examination and X-ray radiographic examination (GB/T 11809). The magnification was 100 times, and there were no cracks, inclusions and other defects.
3. Strength test. Prepare representative process samples for tensile and shear tests. 12 welding joints shall bear at least 2538.5n tensile force without damage. The tensile force borne by the prepared representative process samples shall not be less than 211.5N.

Experimental method

Due to the complex structure of hexagonal tube and grid plate and the large number of welding points, the position accuracy of welding points is required to be high, as shown in Fig.3 and Fig. 4. At the same time, considering that the welding parameters of the 12 solder joints are completely consistent, if the technical conditions permit, select a single solder joint for a representative welding test.

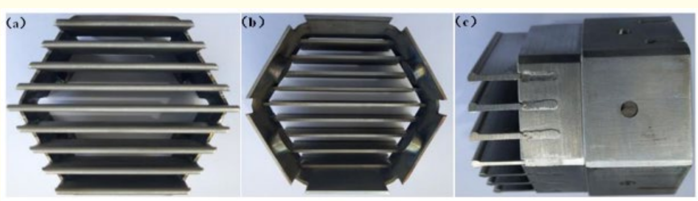

Figure 3: The physical drawing of the grid frame component: (a) The front; (b) The back; (c) The side.

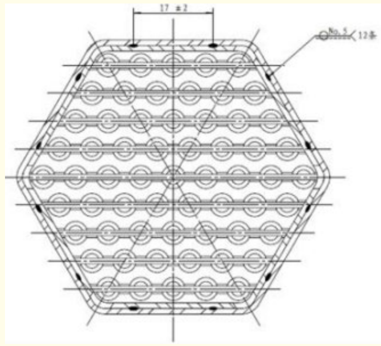

Figure 4: Welding spot location diagram.

The sample with representative process is shown in Fig.5. Before welding, polish the surface of the workpiece with sandpaper, wipe it with acetone or alcohol, and then weld as shown in Fig.6.

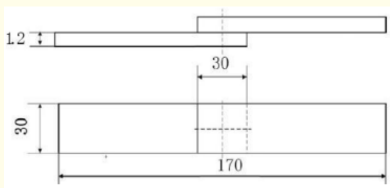

Figure 5: Welding sample diagram.

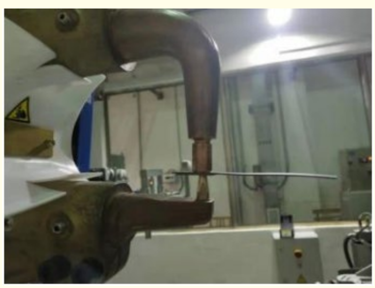

Figure 6: welding object.

After welding, each welding sample shall be visually inspected, and the samples with qualified appearance shall be subject to metallographic inspection and strength test respectively. The prepared metallographic samples were corroded with 5ml HNO_3+15ml HCl corrosive solution, and metallographic analysis was carried out with German Zeiss metallographic microscope. CMT5305 electronic universal tensile testing machine is used to conduct strength test on the welded specimen, and the tensile specimen is shown in Fig.7.

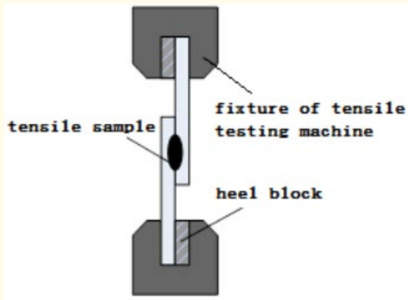

Figure 7: Schematic diagram of tensile test.

The Results and Welding Procedure Qualification

Through a large number of welding tests in the early stage, the approximate range of welding parameters is preliminarily obtained: welding current 2.6~3.2kA, electrode pressure 200N~400N, and welding time 3~10cyc. Within this range of welding parameters, the welded specimen has smooth appearance, small deformation of the two plates, uniform indentation and stable microstructure of the joint. However, there are some problems in metallographic analysis, such as unstable nugget diameter and large fluctuation of tensile shear force. For the above problems, it is necessary to further optimize the range of welding process parameters.

According to the Joule heat formula, the welding current and welding time jointly determine the heat input of welding, and the main role of electrode pressure is to compress the parts to be welded. Therefore, for these three welding parameters, the method of controlling variables is used to further carry out relevant process tests, and the best welding process parameters are obtained according to the analysis of test results.

Influence of welding current

Under the conditions of electrode pressure 350N and welding time 6cyc, a group of process tests were carried out by changing the welding current, and the changes of nugget diameter and room temperature tensile strength under the influence of welding current were analyzed. Specific welding parameters are shown in Tab.3.

No.	***welding current (Ka)***	***Welding time (cyc)***	***Welding pressure (N)***	***Weld appearance inspection***	***Splash condition***
1.	2.6	6	350	good	No
2.	2.8	6	350	good	No
3.	3.0	6	350	good	No
4.	3.2	6	350	good	Splash

Table 3: Welding parameters (welding current is variable).

It is found that the welding current has a direct effect on whether the welding spot produces spatter. When the current is not more than 3kA, there is no spatter during the welding process. When the welding current reaches 3.2kA, spatter will occur. If the current continues to increase, spatter will inevitably occur.

Influence of welding current on nugget diameter

The size of nugget diameter is the most intuitive reflection of the quality of solder joint. The nugget diameter under different current is measured as shown in Fig.8. The heat source of nugget formation comes from the heat generated by the resistance between the two plates after power on. The heat generated is proportional to the square of the welding current. Therefore, the size of the current has a great impact on the nugget formation during the welding process. If the current is too small, it will generate less heat, which is not enough to melt the base metal or the formed welded joint is not reliable enough, and if the current is too large, it is easy to generate splash. It can be seen from Fig.8 that when the current is 2.6kA-3.0kA during welding, the nugget diameter also increases with the increase of the current. When the current increases to 3.0kA, the diameter of the solder joint is the largest. If the current continues to increase to 3.2kA, spatter will occur, causing the molten metal to fly out, greatly reducing the volume of the effective nucleating liquid metal, resulting in the rapid reduction of the nugget diameter.

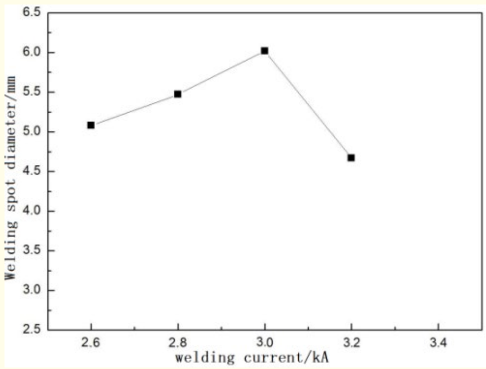

Figure 8: Influence of welding current on nugget diameter.

Figure 9: Residual splash between plates.

Influence of welding current on mechanical properties of welding spot

It can be seen from Fig.10 that the change trend of the maximum tensile shear force of the welded joint is similar to that of the nugget diameter, which increases with the increase of the welding current. When the welding current is too large, spatter occurs, resulting in a sudden drop in the nugget diameter and the tensile shear force of the joint. When the welding current is 3.0kA, the tensile shear force of the joint reaches the maximum value of 4.85kN, and the nugget diameter also reaches the maximum value under this current. It can be found that the nugget diameter is closely related to the maximum tensile shear force of the joint. When the current is small, the heat input of the electrode to the base metal is small, the base metal melts less, and the nugget formed is also small. Therefore, the maximum shear force of the solder joint is small, and the firmness of the solder joint is not high. With the increase of current, the heat input increases, the molten base metal increases, the nugget diameter also increases, and the firmness of the solder joint also increases. However, if the current continues to increase to 3.2kA, the expansion speed of the nugget will be greater than that of the plastic ring, resulting in splashing, resulting in the reduction of molten metal actually participating in the nucleation, the decrease of nugget diameter and the decline of the reliability of the solder joint.

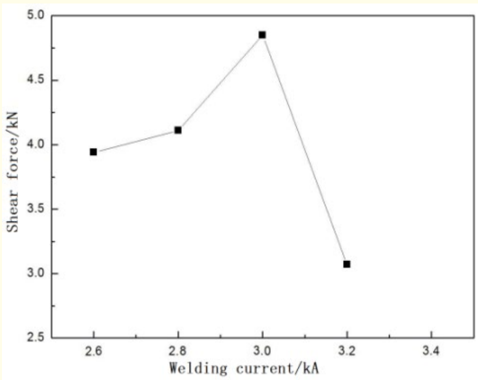

Figure 10: Influence of welding current on shearing force of welding spot.

Influence of electrode pressure

Under the conditions of welding time 6cyc and welding current 3.0kA, the spot welding test was carried out by changing the electrode pressure, and the changes of nugget diameter and room temperature tensile strength under the influence of electrode pressure were analyzed. Detailed welding parameters are shown in Tab.4.

No.	***welding current (kA)***	***Welding time (cyc)***	***Welding pressure (N)***	***Weld appearance inspection***	***Splash condition***
1.	3.0	6	200	good	large splash
2.	3.0	6	300	good	Little splash
3.	3.0	6	350	good	No
4.	3.0	6	400	good	No

Table 4: Welding parameters (electrode pressure is variable).

It is found that the electrode pressure mainly controls the growth of plastic ring and the contact area between plates, thus changing the current density. With the increase of electrode pressure, the contact resistance between plates decreases and the heat produced decreases, which affects the growth of nugget diameter; However, the electrode pressure is too small, and the gap between plates is large, which is easy to produce splash.

Influence of electrode pressure on nugget diameter

It can be seen from Fig.11 that the nugget diameter reaches the maximum value when the electrode pressure is 350N. When the welding current is 3.0kA, the welding time is 6cyc, and the electrode pressure is 200N and 300N, spatter is generated in welding. This is because under this welding current, the heat input is too large, the nugget grows rapidly, and the extrusion of the plastic ring under this electrode pressure is not enough to prevent the outward expansion of the molten metal, resulting in the splashing of the molten metal through the plastic ring. With the increase of electrode pressure, the ability to inhibit the growth of plastic ring is strengthened. At the same time, because the effective contact area between electrode and workpiece is increased during welding, the contact resistance is reduced, the heat input is reduced, and the molten metal is reduced. Therefore, splash is not easy to occur. However, if the pressure continues to increase, the contact resistance will be smaller and the heat will be less, resulting in the decrease of nugget diameter.

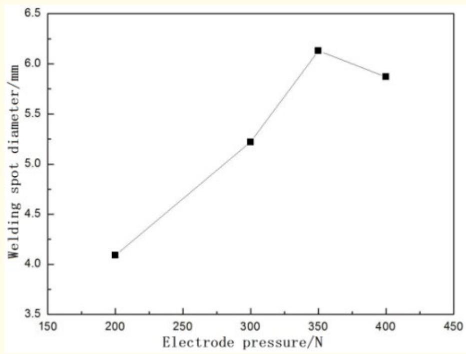

Figure 11: Influence of electrode pressure on nugget diameter.

Influence of electrode pressure on mechanical properties of welding spot

Fig.12 shows the effect of electrode pressure on tensile shear force of solder joint. It can be seen from the figure that the influence trend of the electrode pressure on the tensile shear force of the solder joint is basically the same as that of the electrode pressure on the nugget diameter. When the electrode pressure is small, the plastic ring is not enough to bind the molten metal and splash. Therefore, the tensile shear force of the solder joint is relatively small, and shrinkage and cracks as shown in Fig.13 are easy to occur under low pressure, which is easy to lead to the decline of the performance of the welded joint. When the electrode pressure is 350N, there is no spatter during welding, and the maximum tensile shear force of the joint reaches the maximum value. However, when the electrode pressure continues to increase, the effective contact area between the electrode and the workpiece increases, the resistance between the two electrodes decreases, and the heat input decreases, so the maximum tensile shear force of the joint shows a downward trend.

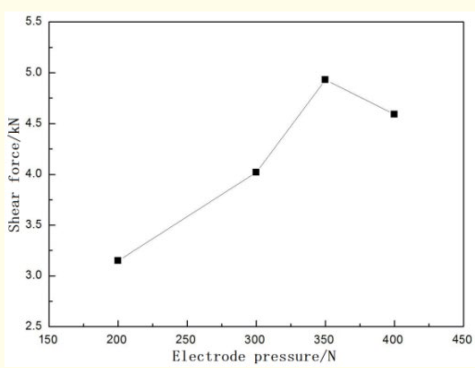

Figure 12: Influence of electrode pressure on shearing force of welding spot.

Figure 13: Welding defects: (a) shrinkage cavity; (b) surface crack; (c) thermal crack.

Influence of welding time

Under the condition of welding current of 3.0kA and welding pressure of 350N, the spot welding test was carried out by changing the welding time, and the changes of nugget diameter and room temperature tensile strength under the influence of welding time were analyzed. Detailed welding parameters are shown in Tab.5.

No.	*welding current (kA)*	*Welding time (cyc)*	*Welding pressure (N)*	*Weld appearance inspection*	*Splash condition*
1.	3.0	3	350	good	No
2.	3.0	4	350	good	No
3.	3.0	6	350	good	No
4.	3.0	8	350	good	No
5.	3.0	10	350	good	Splash

Table 5: Welding parameters (welding time is variable).

It is found that with the increase of welding time, the heat input during welding also increases, which promotes the growth of nugget. However, if the welding time is too long and the heat input is too large, spatter will be caused.

Influence of welding time on nugget diameter

It can be seen from Fig.14 that within 3~8cyc, the nugget diameter increases with the increase of welding time. When the welding time is too long, spatter occurs, resulting in the decrease of nugget diameter. The effect of welding time is the same as that of welding current, but the degree of influence is weak. The longer the welding time is, the more heat will be generated. It can be seen from the figure that when the welding time is 3~8cyc, the nugget diameter shows a gradual and stable increase. When the welding time is 8cyc, the nugget diameter reaches the maximum value, which is 6.19mm. As the welding time reaches 10cyc, the excessive heat input will produce spatter, resulting in the decrease of nugget diameter.

Influence of welding time on nugget diameter

It can be seen from Fig.15 that the maximum shear force of welded joints basically shows a trend of increasing first and then decreasing with the welding time. At 8cyc, the maximum tensile shear force of the welded joint reaches the maximum value of 5.23kN; At 10cyc, the tensile shear force of the joint decreased due to splash.

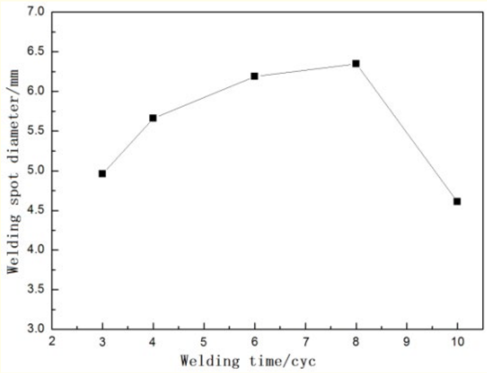

Figure 14: Influence of welding time on nugget diameter.

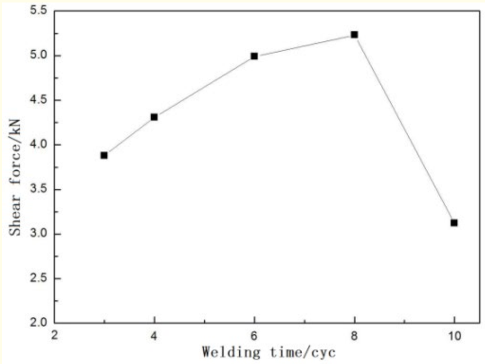

Figure 15: Influence of welding time on shearing force of welding spot.

Comprehensively considering the influence of welding current, welding time and electrode pressure on the nugget diameter and mechanical properties of the solder joint, it is concluded that when the welding current is 3kA, the welding time is 8cyc, and the electrode pressure is 350N, the nugget diameter and joint tensile shear force of the solder joint are relatively stable, and the quality of the solder joint is better. Therefore, this group of parameters is selected as the best welding process parameters.

Welding procedure qualification

In order to verify and evaluate the stability of the whole set of equipment system and the best welding process parameters, the process qualification is also carried out. All personnel in the assessment process have corresponding qualifications; All process equipment is in good condition and meets the requirements of process evaluation; All measuring instruments are within the calibration period. The welding process parameters to be evaluated are shown in Tab.6.

Sample preparation and testing

A total of 6 qualification samples are prepared for process qualification. The welding process parameters in Tab.6 are used to complete the welding. After the welding, random samples are taken for tensile shear test and metallographic inspection, and one sample is retained.

Welding Current	Electrode Pressure	Welding Time
3kA	350N	8cyc

Table 6: Welding parameters to be evaluated.

Welding procedure qualification results

After welding, tensile and shear tests were carried out for GP-01 and GP-06, metallographic examinations were carried out for GP-02, GP-04 and GP-05, and the retained samples were GP-03. Tab.7 shows the process evaluation results.

During the process of procedure qualification, observe that no spatter occurs on all samples during welding. After welding, all samples were visually inspected: the weld surface was smooth, the weld surface and the base metal were smoothly transferred, and no defects such as too deep indentation, burn through, serious oxidation color and surface cracks were found. Destructive inspection shall be carried out on the basis that the above inspection is qualified. Through metallographic examination for GP-02, GP-04 and GP-05 samples, the nugget diameter is relatively stable and no defects are found. The qualification rate is 100%. The tensile shear force of the tensile shear specimen after the tensile shear test is 5.11kN and 5.16kN respectively, which are far greater than the technical index requirements.

No.	Sample No.	Inspection items	Splash condition	Welding defects	Welding spot diameter (mm)	Shear force (kN)
1.	GP-01	VI, TST	No	No	-	5.11
2.	GP-06	VI, TST	No	No	-	5.16
3.	GP-02	VI, MO	No	No	6.11	-
4.	GP-04	VI, MO	No	No	6.09	-
5.	GP-05	VI, MO	No	No	6.13	-
6	GP-03	VI, Retained	No	No	-	-

(*Remarks*: VI-visual inspection; TST-tension shear test; MO-metallographic inspection).

Table 7: Assessment results.

All samples shall be welded according to the welding parameters in Tab.6. After welding, all samples shall pass the visual inspection, metallographic inspection and tensile shear test. To sum up, the evaluated welding parameters are stable and reliable, and can meet the welding process requirements of hex tube and grid plate components of experimental fast reactor MOX fuel assembly.

Conclusions

1. With the increase of welding current, the nugget diameter and the maximum tensile shear force of the joint show an upward trend. When the welding current is too large, it is easy to produce spatter, resulting in the decline of the performance of the welded joint.
2. The larger the electrode pressure, the larger the contact area, the smaller the current density, the less the heat input, and the smaller the nugget diameter. At 200N and 300N, the electrode pressure is too small, resulting in spatter, resulting in small nugget diameter and tensile shear force of welding joint. At 350N, the nugget diameter and maximum shear force reach the maximum value, but when the electrode pressure reaches 400N, there is a downward trend.
3. With the increase of welding time, the nugget diameter and the maximum tensile shear force also increase. When the welding time reaches 10cyc, the welding spatter, nugget diameter and joint performance decrease.
4. When the welding current is 3kA, the welding time is 8cyc, and the electrode pressure is 350N, the nugget diameter and the tensile shear force of the joint are relatively stable, and the quality of the joint is good, which can meet the technical requirements and the actual production requirements.

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