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ADAPTIVE CONTROL METHOD FOR SPOT WELDING BASED ON RESISTANCE PREDICTION

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The interference of different working conditions is inevitable in the process of large-scale spot welding. Under the interference of different working conditions, the welding quality will decrease, and the welding consistency will be reduced. To address this issue, this paper proposes an adaptive control method based on resistance prediction, so as to reduce the impact of interference conditions on the quality of weld joints by maintaining consistent welding power during the welding process. At the same time, to improve the tracking effect of the reference power, a resistance prediction method is introduced. On this basis, to compensate for the heat loss caused by the interference condition, the fuzzy criterion is designed based on the dynamic resistance characteristic quantity, and the welding time is decided. Finally, four common interference conditions are simulated on the testing platform to test the actual effectiveness of the proposed adaptive control method. The experimental results show that the proposed adaptive control method can still achieve a melted nucleus diameter not lower than that of ordinary welding under the conditions of shunting, weldment thinning, conductive gap, and non-conductive gap. This proves to some extent that the control proposed method can effectively reduce the impact of interference conditions on welding quality.

Keywords: resistance spot welding, resistance prediction, reference power control

1 Introduction

Resistance spot welding (RSW) is a manufacturing process widely used in industrial fields, such as automotive manufacturing and aerospace [1-2]. According to statistics from relevant agencies in the United States, there are 4000-6000 connection points formed by spot welding on the steel body of a family sedan [3]. During the welding process with so many welding points, different complex welding conditions may occur, such as too close spot welding spacing, uneven

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thickness of welding parts, and foreign objects between workpieces. These conditions can lead to a decrease in welding quality and an increase in the cost of welding point quality inspection [4-5]. Therefore, studying adaptive control technology for spot welding under complex working conditions to improve welding consistency is of great significance for reducing costs and increasing efficiency in large-scale spot welding.

To achieve adaptive spot welding, many scholars have explored it. Combined with particle swarm optimization (PSO) algorithm, Wang et al. [6] constructed a model for optimizing and identifying electrical structural parameters using measured values of input and output voltage and current. The results showed that both the calculated and measured values are close to 2% of the maximum error, effectively improving the accuracy and energy efficiency of welding control. Yu et al. [7] identified the loudness of spot-welding shunt by studying the relationship between spot welding shunt and dynamic resistance curve, and then designed experiments to obtain a logistic growth model between the strength of shunt effect and welding thermal compensation. Based on this, an adaptive RSW method was designed to compensate for the heat input loss caused by the shunt effect when adjusting the welding time in real-time under constant current control. Experiments have shown that this strategy can improve the quality of welding joints in shunt conditions, but it also reflects the drawback of control hysteresis in this strategy. Yuan et al. [8-9] studied and designed a fuzzy PI adaptive control scheme. This scheme used current closed-loop feedback and fuzzy PI to control the inverter and achieve resistance spot welding in constant current mode. Compared with traditional PID control, this method has the advantages of high control accuracy, fast response, and high welding quality. Yu [10] studied a power tracking welding method to improve the welding quality of high-strength steel, obtaining reference power waveforms from sample welding points and correcting them as reference signals for the tracking strategy. Experiments proved that this strategy can improve welding compatibility, enhance welding effectiveness, and reduce the possibility of spatter.

This article proposes a new adaptive control strategy for spot welding to solve the problem of inconsistent welding quality caused by different welding conditions. The principles of this adaptive strategy are introduced from two aspects: current regulation and time regulation. Then a verification scheme is designed on the resistance spot welding test platform to verify and analyze the welding effect of the adaptive control strategy for resistance spot welding.

2 Adaptive control strategy for spot welding

In the process of spot welding, welding current, welding time and pressure are the three factors that affect welding quality [11]. Under the condition of keeping the electrode pressure constant, a new adaptive control strategy is designed, so that the welding machine can adjust the welding current and welding time in real time according to the welding state during the welding process to achieve spot welding adaptation. This strategy is divided into two parts: current regulation and time regulation. In addition, the use of this adaptive strategy also requires a constant current welding test to obtain a set of high-quality weld joints before welding. Then the welding signal of the group of weld joints is recorded for subsequent adaptive welding reference.

2.1 Current regulationsStrategy

2.1.1 Current regulation strategy based on resistance prediction

Reference welding power control is an adaptive control strategy that makes the welding power curve track the reference power curve by adjusting the welding current during the welding process. It can effectively cope with some interference conditions [12]. The current regulation strategy proposed in this article is optimized based on this method, and its principle is shown in Fig. 1.

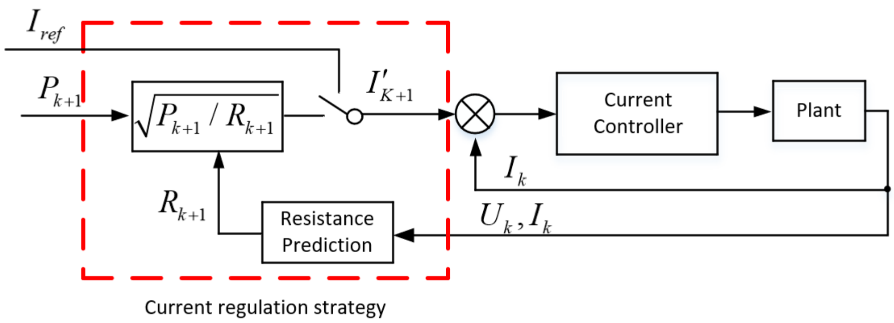

Fig. 1 Schematic diagram of current regulation strategy

According to Fig. 1, the principle of the current adjustment strategy during adaptive welding is as follows: during welding, the welding machine obtains the welding current I_k and electrode voltage $U_k$at the current sampling time, inputting them into the resistance prediction model to predict the welding resistance at the next sampling time. Then the welding current setting value I'_{k+1} at the next sampling time based on the predicted resistance and reference power and executed by the current controller. I'_{k+1} can be calculated as follows:

$$I'_{k+1} = \sqrt{P_{k+1}/R_{k+1}} \tag{1}$$

where $P_{k+1}$is the welding power corresponding to the next sampling time in the reference power curve, and R_{k+1} is the predicted welding resistance at the next sampling time. The reference power curve is obtained in advance through constant current welding, and its time length is limited. If the current adaptive welding requires a longer welding time, subsequent welding cannot continue to use power to calculate the given welding current. Therefore, it is specified that subsequent welding should be carried out at a constant current I_{ref}. I_{ref} is the calculated current value at the end of the reference power curve.

2.1.2 Resistance prediction model

In current regulation strategies, the resistance prediction model is the key. The purpose of using a resistance prediction model is to improve the tracking effect of reference power in actual welding. Combined Eq. (1) with Joule's law, we have:

$$I'_{k+1} = \frac{P_{k+1}}{U_{k+1}} = \sqrt{P_{k+1}/R_{k+1}} \tag{2}$$

where, $U_{k+1}$is the electrode voltage at the next sampling time. In the reference power control, the electrode voltage $U_k$at the current sampling time is used to replace U_{k+1} to calculate I'_{k+1}. As a result, there may be a significant difference between the actual power and the reference power in actual welding.

To improve the effectiveness of power tracking, the resistance prediction model proposed by Kas was introduced [13]. The resistance prediction method proposed by Kas was derived from a simplified thermodynamic model in resistance spot welding. Combined with online parameter estimation, it can predict the welding resistance at the next sampling time. According to Kas's derivation, it has:

$$R_{k+1} = a_1 I_k^2 R_k + a_2 R_k + a_3 \tag{3}$$

where R_k and I_k are the welding resistance and current at the current sampling time, respectively, R_{k+1} is the resistance at the next sampling time, and a_1, a_2 and a_3 are the time-varying parameters. In Eq. (3), R_k and I_k are known, when calculating R_{k+1}, it needs to know a_1, a_2 and a_3. As such, the recursive least squares method with forgetting factor (FFRLS) is used for a_1, a_2 and $a_3$estimation [14-15]. First, the Eq. (3) needs to be written in matrix form:

$$R_{k+1} = X(k)^T a_k \qquad X(k) = \begin{bmatrix} I_k^2 R_k \\ R_k \\ 1 \end{bmatrix}, a_k = \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix} \tag{4}$$

In Eq. (4), $X(k)$is the independent variable parameter matrix and a_k is the coefficient matrix.

Eq. (5)- Eq. (7) are the iterative equations for FFRLS estimation. K_n is the gain matrix. The larger K_n is, the stronger the correction effect is. T_k is the covariance matrix. $a_k$is the iteration parameter matrix and λ is the forgetting factor (λ ∈[0,1]):

$$K_n = \frac{T_{k-1} - X_k}{\lambda + X_n^T T_{k-1} X_k} \tag{5}$$

$$T_k = \frac{1}{\lambda}(T_{k-1} - K_n X_n^T T_{k-1}) \tag{6}$$

$$a_k = a_{k-1} + K(R_k - X_n^T a_{k-1}) \quad (7)$$

To verify the predictive effect of the resistance prediction model, the resistance prediction method is simulated on the Matlab platform. The simulation waveform is shown in Fig. 3. The results show that when the welding current exceeds the unstable period at the initial rise, the error rate of the prediction model converges within ± 0.05. This verifies that the model can accurately predict the welding resistance at the next sampling time [16].

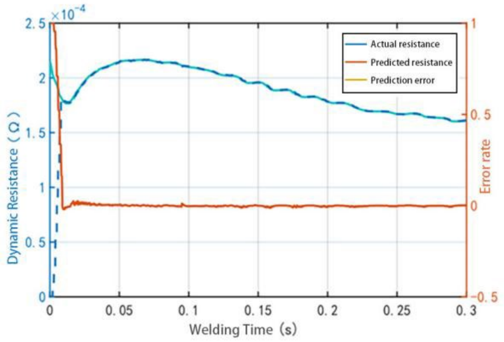

Fig. 2 Simulation results of resistance prediction

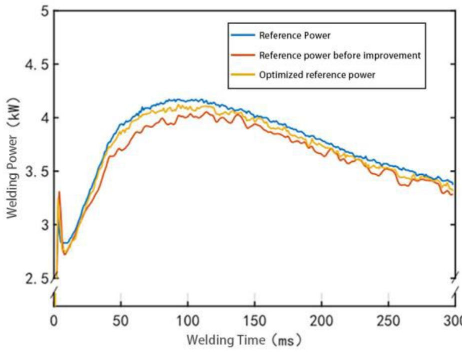

Fig. 3 Improvement effect of reference power control

To verify that the reference power control introduced by the resistance prediction model can better track the reference power curve during the welding process, a set of reference power curves is first obtained using constant current welding. Then, the improved and unimproved reference power control is used for welding, and the signal curves are plotted in the same coordinate for comparison. The results are shown in Fig. 3. The results show that the improved reference power control can make the welding power during the welding process closer to the reference power, and to some extent reduce the control hysteresis.

2.2 Time regulation strategy

Under the interference of complex working conditions, some energy is often lost during the welding process. It is an effective means of energy compensation to extend the welding time appropriately according to the state in the welding process. Due to varying degrees of interference during the welding process, a fixed compensatory time strategy is not suitable, and it is necessary to adaptively adjust the compensatory time duration based on the welding status.

Numerous scholars have confirmed that the characteristic quantity of dynamic resistance is closely related to the state of spot welding. Therefore, in the real-time control process of spot welding, the dynamic resistance characteristic quantity can be used to roughly judge the spot-welding status, and then fuzzy reasoning and more can be used to make decisions on the process parameters during the welding process. The more features used in this process, the more robust and accurate the control strategy will be. However, it will also bring about the disadvantages of design difficulties and reduced versatility. Consequently, considering a compromise, the dynamic resistance drop J and the dynamic resistance peak R_β are selected as inputs to decide the length of the compensatory time by fuzzy reasoning. Among them, the resistance drop amount J is closely related to the quality of the solder joint [17]. The peak R_β of the dynamic resistance curve can reflect the current intensity [7] actually flowing through the solder joint to a certain extent, as shown in Fig. 4.

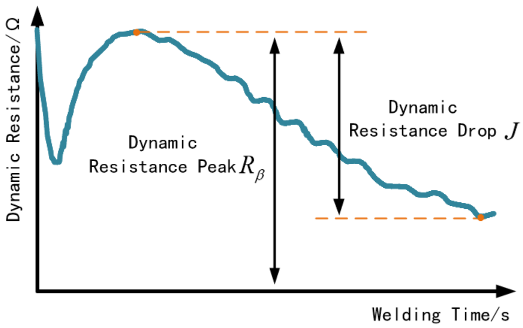

Fig. 4 Schematic diagram of dynamic resistance characteristic quantity

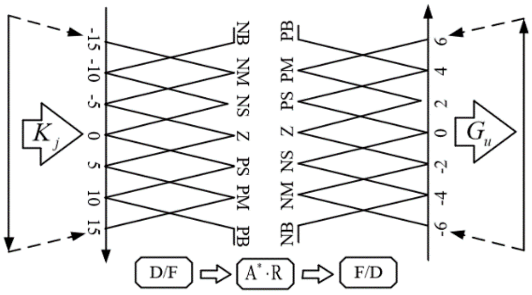

Fig. 5 Fuzzy reasoning

According to existing research and experimental data, a fuzzy criterion of two inputs and single outputs is constructed to realize the reasoning of welding time. When welding, the current regulation strategy is first performed. When the reference group time is reached, the dynamic resistance drop and peak in the current welding process are monitored, and the fuzzy inference process in Fig. 5 is performed as input. According to the fuzzy inference process in Fig. 5, after the fuzzy input of the dynamic resistance drop and dynamic resistance peak R_β, it is mapped to seven fuzzy subsets, PB, PM, PS, Z, NS, NM, and NB, in the fuzzy universe. Combined with the fuzzy control table shown in Table 1, the input fuzzy quantity is used to infer the welding time.

Table 1

Fuzzy inference rules for welding time

R_β \ J	NB	NM	NS	Z	PS	PM	PB
NB	PB	PB	PB	PM	PM	PS	Z
NM	PB	PB	PM	PS	PS	Z	Z
NS	PB	PM	PS	PS	PS	Z	Z
Z	PM	PM	PS	Z	Z	Z	Z
PS	PS	PS	Z	Z	Z	Z	Z
PM	PS	Z	Z	Z	Z	Z	Z
PB	Z	Z	Z	Z	Z	Z	Z

3 Adaptive testing and results

3.1 Resistance spot welding experimental system

The adaptive control of resistance spot welding has high requirements for the performance of spot-welding machines. This article uses a self-developed intermediate frequency inverter resistance spot welding power supply as the core welding system for adaptive spot-welding research. The entire system is shown in Fig. 6. The resistance spot welding system is composed of a self-developed spot welding power supply (with adjustable welding power frequency of 1-5kHz), a serial display screen, an intermediate frequency transformer (with a full wave rectification circuit on the secondary side of the transformer), and an air pressure welding machine head. The maximum power is 25kW, and the maximum welding current is 8kA.

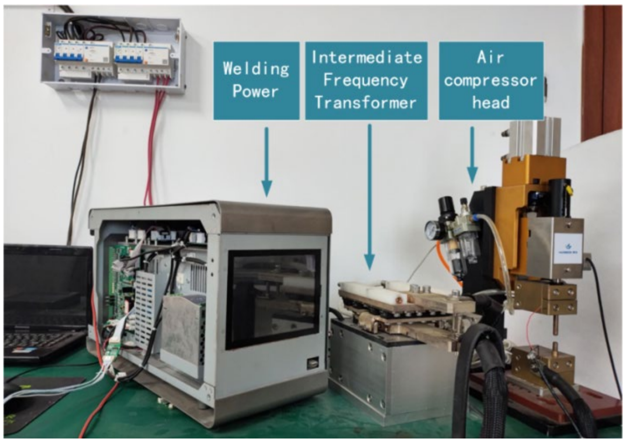

Fig. 6 Resistance spot welding test platform

To be more practical, DP590 high-strength dual phase steel, commonly used in automotive manufacturing, is selected as the welding material for testing. The chemical composition and mechanical properties of DP590 are shown in Tables 2 and 3 [18]. There are two specifications of DP590 steel plates used in the experiment, with dimensions of $100mm \times 50\text{mm} \times 1mm$ and $100mm \times 50\text{mm} \times 0.7mm$.

Table 2

Chemical composition (mass fraction) of DP590

Steel grade	C	Si	Mn	P	S	Others
DP590	0.055	0.507	1.616	0.010	0.004	0.048

Table 3

Mechanical properties of DP590

Steel grade	Yield strength	Tensile strength	Elongation(%)	n-value
DP590	357MPa	627MPa	24.9	0.16

To test the adaptive welding effect of the adaptive spot-welding control strategy, four common interference conditions (shunt condition, thickness reduction, conductive gap, and non-conductive gap) are selected for welding testing. After welding, destructive tests are conducted to measure the internal melt nuclear, and the adaptive effect is tested by comparing the diameter of the melt nuclear.

3.2 Test results

To test the adaptive effect of this strategy during the welding process, four common dissimilar conditions of shunt, plate thickness reduction, conductive gap and the non-conductive gap, are simulated on the experimental platform. The welding effect of the adaptive strategy is determined by analyzing the melted nucleus diameter under four different working conditions.

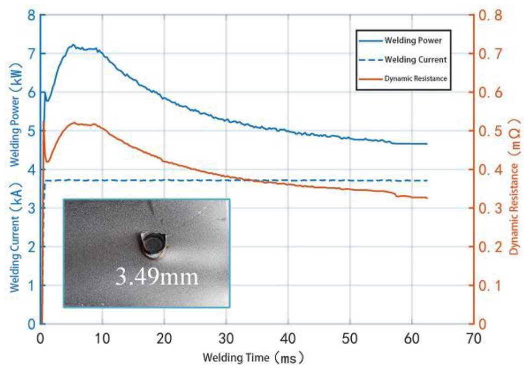

Fig. 7 Welding effect and waveform of reference weld joints

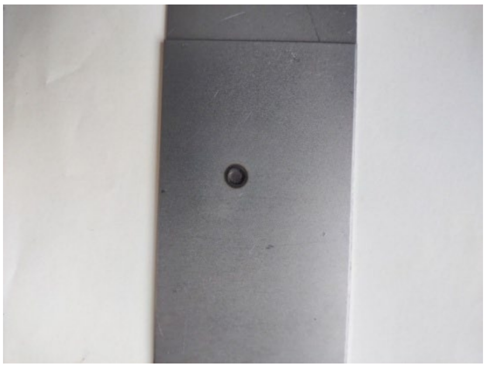

Fig. 8 Sample weld joints

First, multiple welding operations need to be carried out through constant current mode, and a set of excellent welding points without splashing is selected as the reference group. After that, the power curve and resistance curve of the group of welding points during the welding process are recorded as reference signals, as shown in Fig. 7 and Fig. 8. The welding current of this reference group is constant at 3.8kA, and the molt nuclear diameter of the welding joint of this group is measured by destructive tests to be 3.49mm.

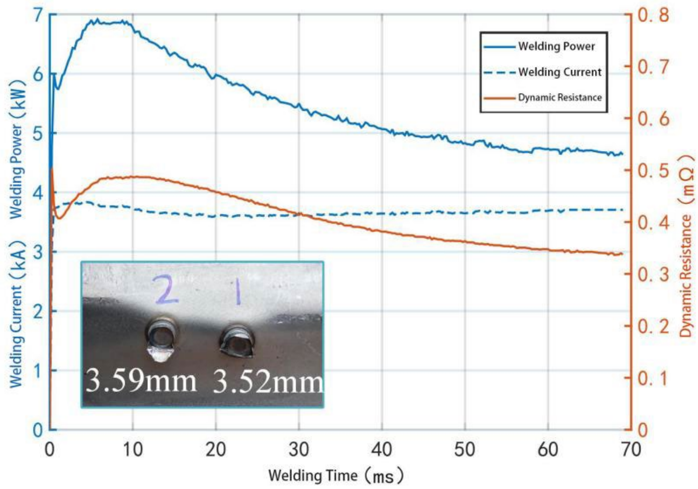

Fig. 9 Welding effect and waveform under shunt condition

Fig. 10 Weld joints in shunt condition (not adaptive)

Fig. 11 Weld joints in shunt condition (adaptive)

Under the shunt condition, due to the close distance between the weld joints, part of the current will be diverted by the adjacent weld joints during subsequent welding, resulting in a smaller actual welding current and a decrease in the obtained heat, and affecting the final welding quality. Using an adaptive welding strategy, two 1mm thick DP590 steel plates are sequentially welded at close range. The welding signal waveform and effect of the second welding point during the welding process are shown in Fig. 9. From post-weld destructive tests, the effective melt nucleus diameters for the two joints were 3.52 mm and 3.59 mm, respectively.

Figs. 10 and 11 are continuous spot welding tests under shunt condition. Fig. 10 does not use the adaptive strategy. It can be clearly observed that compared with the sample weld joints, the weld melt nuclear under the shunt condition is small, and that between the weld joints is significantly different. Fig. 11 applies the adaptive strategy, and the obtained melted nucleus diameter is not less than the reference weld joints, and the melted nucleus diameter is not affected by the shunt condition under continuous spot welding. From the experimental results, it can be concluded that the adaptive strategy can effectively reduce the influence of shunt condition on the quality of the solder joint.

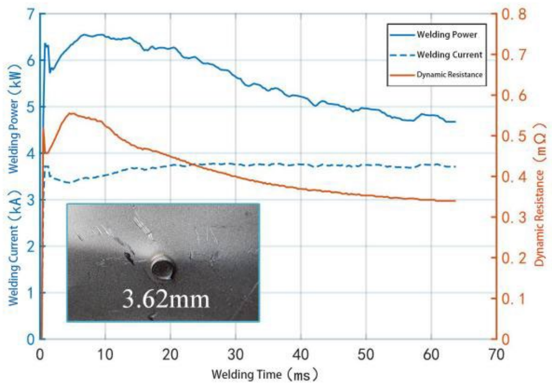

Fig. 12 Welding effect and waveform under reduced plate thickness conditions

Fig. 13 Under conductive gap working condition (without adaptation)

When the thickness of the weldment changes during spot welding, the fixed parameter welding method can cause the welding to deviate from the optimal zone, thereby reducing the quality of the solder joint. To simulate this, adaptive welding tests are performed using1mm and 0.7mm thick DP590 steel plates. After using adaptive control, the melted nucleus diameter of the resulting solder joint is measured to be 3.62mm. The welding waveform during the welding process is shown in Fig. 12.Fig. 13 shows the welding results without adaptive strategy under the condition of reduced plate thickness. Its melted nucleus diameter is significantly smaller than that of the sample solder joint, which greatly affects the welding quality. Obviously, the control strategy proposed in the text strengthens the strength of the welding points in this case.

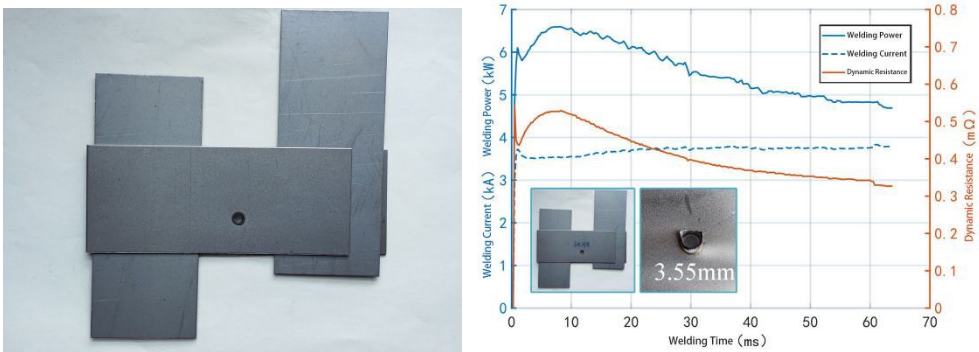

Fig. 14 Welding effect (left) and waveform (right) under conductive gap condition

The conductive gap working condition is generally caused by the uneven surface of the weldment, resulting in an empty drum in the left area to be welded. At this time, not only the area to be welded is fully in contact under the action of electrode pressure, but there are also close contact points around. This case will make the heat dispersed during welding and cause the welding effect deteriorating. The conductive gap condition is simulated by clamping two parallel steel plates between two 1mm welding pieces. The welding effect and waveform under adaptive strategy welding are shown in Fig. 14, and the final measured melted nucleus diameter is 3.55mm. The measurement results show that the welding points quality is still better than the reference welding points.

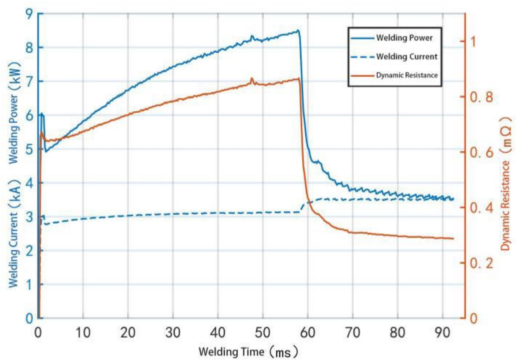

Fig. 15 Welding waveform under non-conductive gap condition

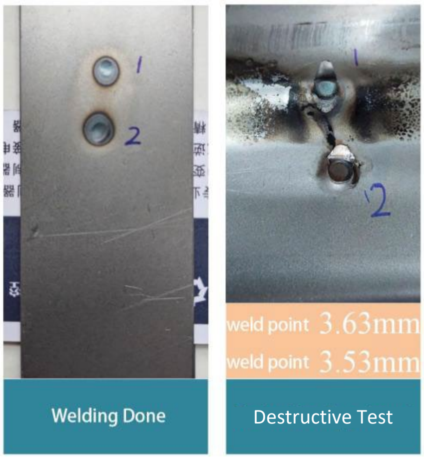

Fig. 16 Welding effect under non-conductive gap working condition

Under the non-conductive gap condition, because the joint surface of the weldment has a non-conductive large area of foreign object barrier, and the welding joint to be welded just falls in the barrier area, a good conductive path cannot be formed between the weldments. The current can only flow through the nearby solder joint or contact surface. The non-conductive gap condition is a relatively harsh situation. When encountering this condition in the constant current mode, the welding effect will become poor or even unable to form weld joints. To simulate this condition, a paper business card was sandwiched between 1mm welding pieces for testing. The waveform during the adaptive welding process is shown in Fig. 15, and the effect after welding is shown in Fig. 16. The final measured diameter of the melted nucleus diameter in the non-conductive area is 3.53mm. The quality of welding points is still better than standard welding points.

In summary, under the four simulated interference conditions, the melted nucleus diameter of the welding points obtained through adaptive control is larger than the reference solder joint, so the welding quality is improved. Experimental results show that the control strategy provided in this article can effectively expand the melted nucleus diameter under various interference ring conditions, thereby improving the welding quality of the welding points.

4 Conclusion

Aiming at the different interferences in the process of large-scale spot welding, an adaptive control strategy of spot welding is designed by combining the current regulation strategy optimized by the resistance prediction model and the time adjustment strategy combining the dynamic resistance characteristic quantity. In the experiment, this article selected four common interferences: current shunting, weldment thinning, conductive gap and non-conductive gap as experimental conditions. The quality of welding points is judged by the diameter of the melted nucleus diameter. The experimental results show that the control strategy proposed in the article has certain advantages and provides a new solution to the anti-interference problem in the spot welding process.

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