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Technical Paper

Online monitoring and evaluation of the weld quality of resistance spot welded titanium alloy

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ABSTRACT

Resistance spot welding is an important branch of the welding subject, and has been widely used in aviation, aerospace, automotive and other industrial areas due to its high efficiency, low cost and small deformation. As the improvement of the product quality, online monitoring of welding quality has become an urgent issue. This paper puts forward an information acquisition and evaluation method based on the online monitoring of the weld quality of spot welded titanium alloys. Through the real-time acquisition and analysis of the welding parameters, the characteristic information of the acquired signal was extracted to achieve the reliable quality assessment of the welding process.

1. Introduction

Resistance spot welding is an important welding technique that has been extensively used in industries due to its high production efficiency and easy realization of automation [1]. The main quality assessment methods of the welding spots are the destructive chisel test and peel test, however, they are time consuming [2,3]. Thus, a development of an online monitoring and evaluation system is urgent. Quality monitoring and evaluation of resistance spot welding has become more and more important and the non-destructive test methods based on the dynamic signals during the welding process have been developed recently [4–6]. The most widely used materials for online quality monitoring of the welding spot are mild steel and aluminum alloy. In 1980, Dickinson established the collection system of dynamic resistance in spot welded mild steel, and pointed out that the dynamic resistance and formation of the nugget are closely related to each other. The dynamic resistance curves are closely related to material type, welding current and electrode pressure [7]. Burmeister used an existing expert system to online assess the weld quality of mild steel based on a fuzzy classification theory and he found a nonlinear relationship between the electrical parameters, the mechanical parameters of the workpiece and quality of the welding spot. Ji et al. [8] studied the electrode displacement in spot welded aluminum alloy, and quality control of spot welding was based on the electrode displacement method. Firstly, ensure that the rise rate of the electrode displacement is equal to the target rate by changing the welding current; then the welding current is unchanged until the electrode displacement reaches the defined value. Hao et al. [9] has done an in-depth research on the quality monitoring of spot welded aluminum alloy. In the monitoring system, they collected the five parameters consisting of welding current, voltage, dynamic resistance, electrode pressure and electrode displacement, and data were then analyzed using statistical methods.

Materials for spot welding monitoring are mild steels and aluminum alloys, however, monitoring of spot welded titanium alloy accounts for a small amount. Titanium and its alloys have been identified as one of the best engineering metals for application in industrial fields [14], such as aviation, medical industry and chemical engineering due to their small density and high strength [15]. This paper aims to investigate the online monitoring and the quality assessment of the spot welding process. A new quality evaluation method of spot welding was proposed. Through the extraction of characteristic parameters of each welding spot, the quality assessment was carried out timely, effectively and accurately. The information management database of the welding spot

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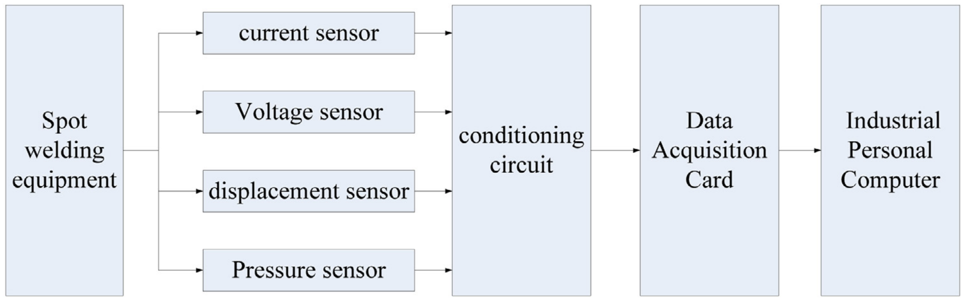

Fig. 1. Flowchart for the online monitoring system.

was established based on LabVIEW, which incorporates the welding characteristic parameters and quality evaluation results into the database.

2. Experimental procedures

2.1. The design of the online monitoring system

Conventional resistance welding process control was based on monitoring the voltage and current, or power and resistance [10,11]. A variety of dynamic signals were measured and different kinds of signal processing technologies were proposed to monitor or control the quality of welding and joining [12,13]. The monitoring system monitors the welding current, welding voltage, electrode pressure and electrode displacement. The outside of the online monitoring system is connected with four sensors for real-time monitoring and collecting signals from the current, voltage, pressure and electrode displacement, then the multiple signals enter into the data acquisition card, finally the collected data was saved to the hard disk and the collected waveforms will be then displayed on the computer screen. Fig. 1 shows the flowchart for the online monitoring system.

It is very important to select the sensors for monitoring the welding process. There is a high requirement of precision and response speed for the pressure sensor and displacement sensor. The pressure sensor of this system is a piezoelectric sensor which is attached to the welding machine. Piezoelectric sensors have the advantages of high sensitivity, high signal-to-noise ratio, simple structure and reliable operation. The sensor was put inside the cylinder to measure the size of the cylinder force. Type of the pressure sensor is German Matuschek SPATZMultimate04. Displacement sensor of this system is a laser displacement sensor which uses the non-contact measurement of displacement, and it has very high measurement accuracy, the displacement sensor measures the downward displacement of the electrode arm. The laser sensor detects the dynamic displacement of the electrodes. The laser sensor is fixed in front of the cylinder and the reflection plate is fixed to the movable block which is connected to the electrode. During welding, the decrease of the movable block was driven by the cylinder, which controls the downward movement of the reflection plate and the upper electrode. Fig. 2 is a schematic diagram of the displacement sensor, Fig. 3 is a photograph of spot welding machine, and Fig. 4 is a photograph of the monitoring system.

Monitoring system collected signals from the four sensors. The evaluation results are saved to the database and the waveform files. Its main interface is shown in Fig. 5 where collection interface will open when the "collection" button was clicked, click "Open" to view historical data, click on the "pads" in the main interface to view the stored information in the database. Because the main defects of resistance spot welding process is divided into incomplete fusion and splash defects, thus the monitoring system investigates the two

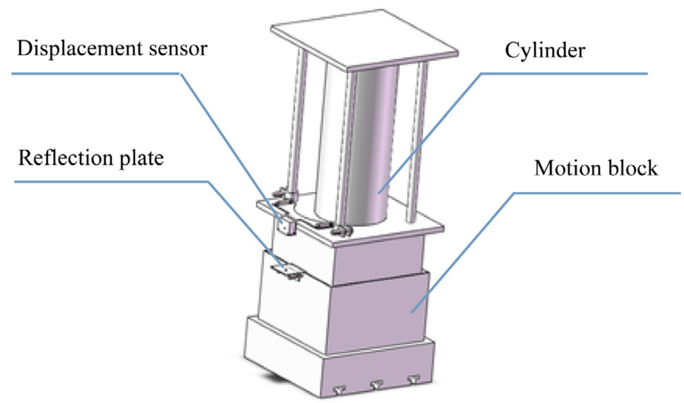

Fig. 2. Schematic diagram of the displacement sensor.

Fig. 3. Spot welding machine.

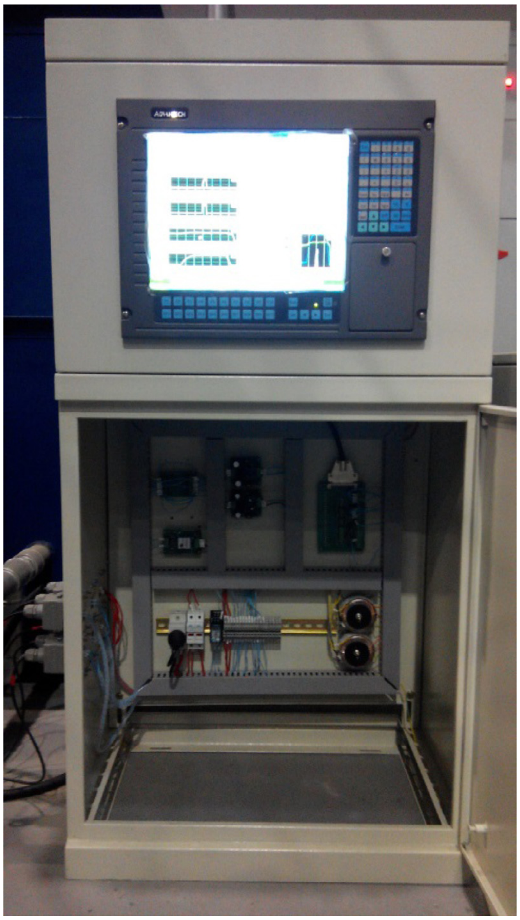

Fig. 4. Monitoring system.

defects. The upper right of the main interface of the "spot welding quality information box" shows the quality information and characteristic value of the welding spot.

Because of the direct current used in the spot welding machine and the low frequency of changing pressure signal and displacement signal during spot welding process, frequency of changing the signals is basically less than 1k, thus, the sampling frequency is set to 10k which can well meet the requirements for sampling. Abscissa shows the number of sampling. The rising signals of pressure were captured until the pressure value is greater than 600 N, the weld waveform was stored automatically, and the weld waveform file was then saved to computer disk. The file name was saved and named after the completion time of each welding spot, finally, the information of the weld quality was saved to the database. Take into consideration of the welding pressure and power-on time, the storage time was set to 2 s, that is, 20k points was collected, so that each stored waveform file consists of the quality information of a single weld spot. During the welding process, the monitoring system collect and record the real-time wave waveform data of the welding spots.

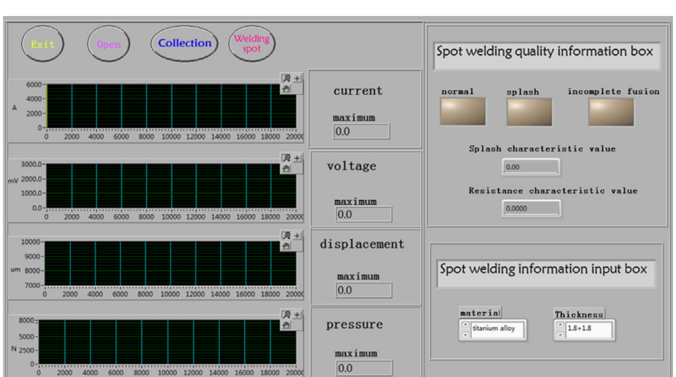

Fig. 5. On-line monitoring system of the main interface.

2.2. Experimental conditions

A 1.8 mm thick TB2 titanium alloy was resistance spot welded in this work. TB2 titanium alloy (Ti-5Mo-5V-8Cr-3Al) is a new type of material belonging to the metastable β type titanium alloy, TB2 alloy has good welding performance, good plasticity and high strength in solid solution aging conditions and. The specimen size is 100 mm × 20 mm with overlapping volume of 20 mm, progressing grinding papers of 800 grit, 1000 grit and 1200 grit was used to remove all the starches in the specimen, and the specimen was then cleaned in acetone solution. Welding parameters are as follows: welding current is 6.5 kA, pressure is 6 kN, and welding time is 120 ms. Minor adjustments of the welding parameters will be made to produce welding spots with defects intentionally.

3. Results and discussions

3.1. Signal characteristics of the welding spot splash

From the characteristic curves of a large number of different welding spots in Fig. 6, it was found that the welding pressure curves and electrode displacement curves of the qualified welding spots are relatively smooth with almost no oscillation. But it was obvious that in the welding spot splash experiments, because of the process of welding electrode of jitter, the electrode displacement signal curve decreased significantly and the pressure signal has experienced a great oscillation. Fig. 6(a) is a pressure wave of a splash welding spot, it is seen that at about 1.2 s, a splash occurred and it is shown as a vigorous agitation on the waveform. And this kind of phenomenon exists only in the wave curve which has a splash on the welding spot, so the pressure curves and displacement curves can be used to analyze the occurrence of a splashed welding spot. As shown in Fig. 6(b), the normal pressure curve starts to rise slowly and then stays stable after a period of time, and the pressure signal has a short-term projection due to the nugget expansion.

Weld spatter occurs because of the metal flying, so the mutation occurs in displacement signal, as shown in Fig. 7(a). The normal signal of the qualified welding spots will have a short descend due to the nugget expansion (Fig. 7(b)).

3.2. Signal features of the incomplete fusion welds

It was found that dynamic resistivity of titanium alloys is high and the resistivity decreased significantly during the formation of nugget, thus, dynamic resistance can be used as a good assessment of small defects in the weld nugget.

Dynamic resistance has changed greatly during the spot welding process of titanium alloys. Firstly, dynamic resistance decreases significantly due to the rapid increase of temperature and the rapid sintering of the surface oxide film. Secondly, with increasing welding time, the surface contact resistance becomes small and the dynamic resistance decreases slightly. Finally, after the material has been melted, the smaller resistivity of the liquid metal leads to decrease of the dynamic resistance [16]. Under the condition of welding spot without splash, the more the decrease of the dynamic resistance, the more the liquid metal being melted

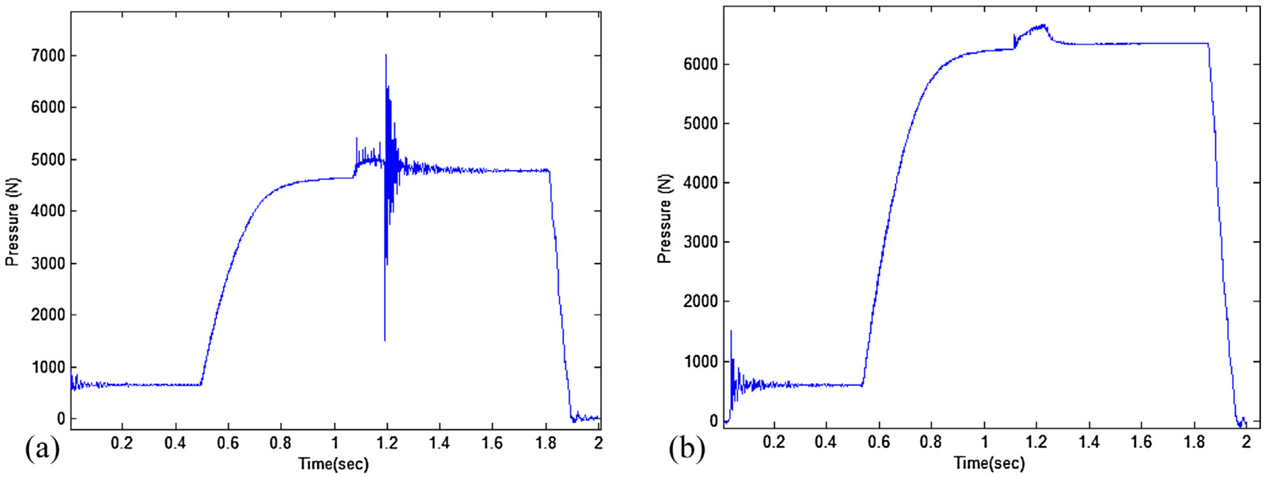

Fig. 6. The pressure signal graph of (a) the splash welding spot and (b) the normal welding spot.

and the larger the nugget diameter. The aforementioned characteristics of dynamic resistance curve will be used to judge whether TB2 titanium alloy has incomplete fusion. The method of evaluating welding spots with incomplete fusion takes into account the relative large resistivity of titanium alloys and the large drop of resistance during the energization process, however, this method cannot be applied to aluminum alloys because aluminum alloys have small resistivity and their resistance drops slightly during the energization process, thus, it difficult to assess the small welding defects for spot welded aluminum alloys.

Fig. 8 shows the waveform curves of dynamic resistance of the normal welding spot and the welding spot with incomplete fusion, respectively. It was also found that the larger nugget diameter corresponds to the large decrease of the dynamic resistance. From Fig. 8(a) and (b), the drop of the dynamic resistance of the welding spot with incomplete fusion is small, however, the dynamic resistance of the normal welding spot has a deceased in a large amplitude, this is because during the growing process of the liquid metal, the dynamic resistance will gradually decline, and the dynamic resistance decreased greatly with the great increase of the liquid metal.

3.3. *Signal extraction method of the splash feature*

In the process of spot welded titanium alloy, influence of splash on the quality of the welding spot is very serious. Through collecting a large amount of data of waveforms of the welding spot, it was found that when the spot splash occurs, the pressure signals have obvious agitation. So extraction of features of the splashed welding spot mainly relies on the pressure signal, the pressure signals of the welding spot was obtained by real-time acquisition and feature extraction.

The specimens are sensitive to pressure signal and pressure signal agitation of the splashed welding spot, so a method of measuring signal agitation was proposed to assess whether the welding spots splash. Splash generally occurs after a period of time when the welding current reaches the maximum. Use the time when welding current is the maximum as a reference to carry out the interception of pressure waveform of the electrode and to draw the linear fitting curve, moreover, the actual pressure curve and its fitting curve were compared to obtain the characteristic value, and this will result in a better, more intuitive evaluation of quality of the welding spot. The specific extraction method is listed as follows:

(1) The first step is to find out the array index value at the moment when the current value reaches the maximum.
(2) The pressure signal was taken at the forward 1600 points and the backward 400 points using the time of the maximum current value as the reference, namely, the pressure signal data has a total of 2000 points corresponding to the pressure signal data at 200 ms, the majority of splash all occurred during this period of time.

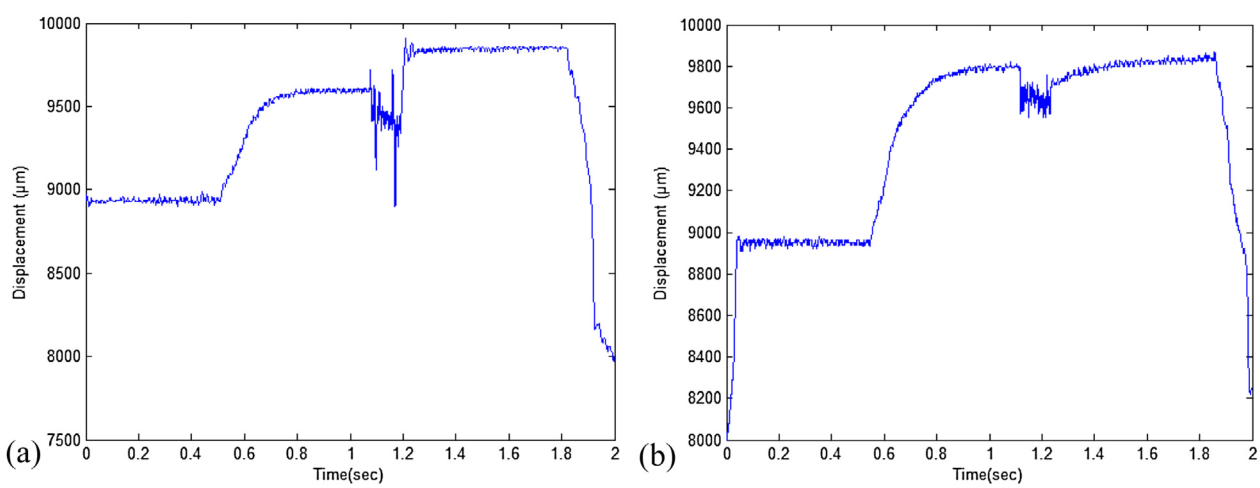

Fig. 7. The displacement signal of (a) the splash welding spot and (b) the normal welding spot.

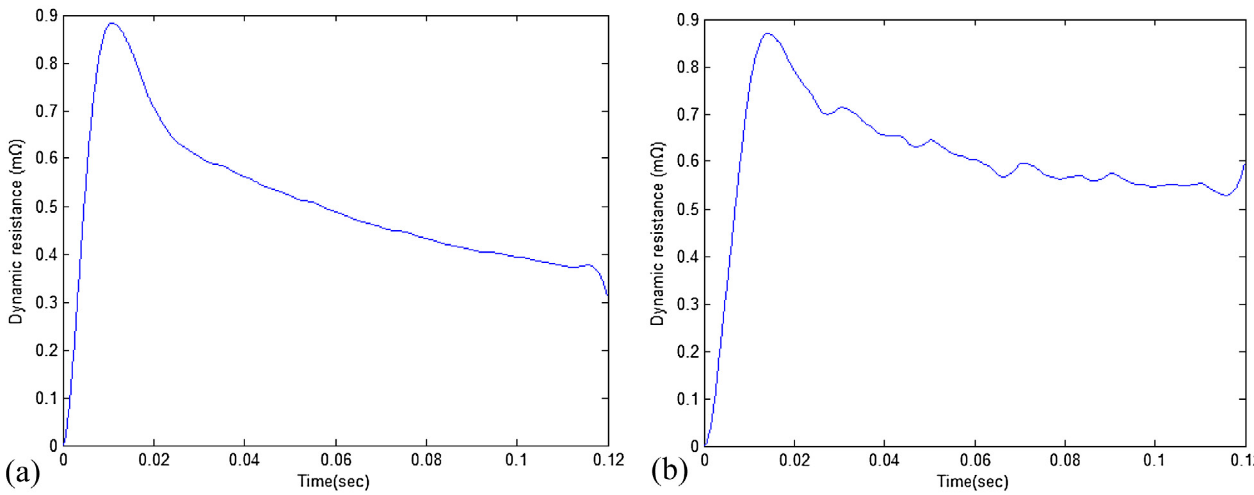

Fig. 8. Signal graphs of dynamic resistance of (a) the normal welding spot and (b) the welding spot with incomplete fusion.

(3) The least square fitting was performed on the pressure waveform curves at the interception of 200 ms and the actual pressure curve and the fitting pressure curve was subtracted to calculate the root mean square values, namely, splash characteristic value.

The least squares fitting method selects a group of date close to linear, the equation after fitting method is shown is follows:

$$y = ax + b \tag{1}$$

In Eq. (1), a and b are calculated by the least square fitting method. The final results of a and b are:

$$\begin{cases} b = \dfrac{\sum x_i y_i - (\sum x_i \sum y_i / n)}{\sum x_i^{\,2} - ((\sum x_i)^2 / n)} \\ a = \bar{y} - b\bar{x} \end{cases} \tag{2}$$

$$\begin{cases} \bar{x} = \sum \dfrac{x_i}{n} \\ \bar{y} = \sum \dfrac{\bar{y}_i}{n} \\ i = 1, 2, \ldots, 1999, 2000 \end{cases} \tag{3}$$

$$Y_i = \bar{y} + \frac{\sum x_i y_i - (\sum x_i \sum y_i / n)}{\sum x_i^{\,2} - ((\sum x_i)^2 / n)} (x_i - \bar{x}) \tag{4}$$

$$Sc = \frac{\sum y_i - \sum Y_i}{n} \tag{5}$$

N represents the fitting points, because interception of the pressure waveform takes 2000 sampling points, thus, $N = 2000$, x_i represents the sampling points, y_i is the actual pressure value of each sampling point, Y_i is the pressure value after linear fitting of each sampling point, Sc is the splash characteristic value.

(4) The threshold of the splash characteristic value was obtained from a large number of experiments and data calculation, if the splash characteristic value is greater than the threshold of the pressure in spot welding process, the pressure fluctuations is great, which will prove the occurrence of splash. Fig. 9 shows the flowchart for evaluating the splashed welding spots.

The method to determine the threshold value is shown as follows:

The first step is to arrange all the data points from the lowest to the highest. Here is an experiment consisting of 30 splash characteristic value of all of the welding spots: 59, 60, 66, 67, 69, 70, 73, 76, 81, 86, 88, 89, 92, 93, 95, 96, 98, 99, 100, 101, 103, 104, 109, 112, 117, 126, 135, 152, 479, 630. The two weld spots 479 and 630 are the splash characteristic value of the splashed spot. Data number is 30, thus, $N = 30$.

The second step is to calculate the upper quartile $Q1$ and the lower quartile $Q3$ using the equations:

$$\begin{aligned} Q1 &= 0.25(N+1)\text{th ordered point} = 7.75\text{th ordered point} \\ &= 73 + 0.75(76 - 73) = 75.25 \end{aligned}$$

$$\begin{aligned} Q3 &= 0.75(N+1)\text{th ordered point} = 23.25\text{th ordered point} \\ &= 109 + 0.25(112 - 109) = 109.75 \end{aligned}$$

The third step is to find out the interquartile range:

$$Q3 - Q1 = 109.75 - 75.25 = 34.5.$$

The fourth step is to find out the "inner fences" of the data set:

$$\text{Lower inner fence} = 75.25 - 1.5 \times 34.5 = 23.5$$

$$\text{Upper inner fence} = 109.75 + 1.5 \times 34.5 = 161.5.$$

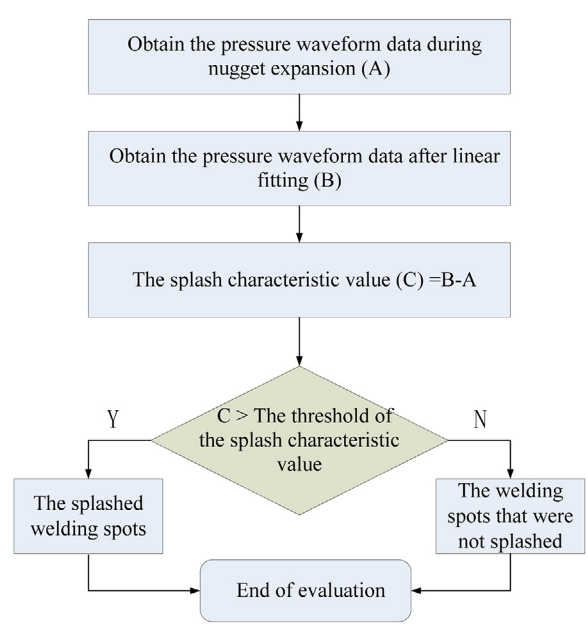

Fig. 9. Flowchart for evaluating the splashed welding spots.

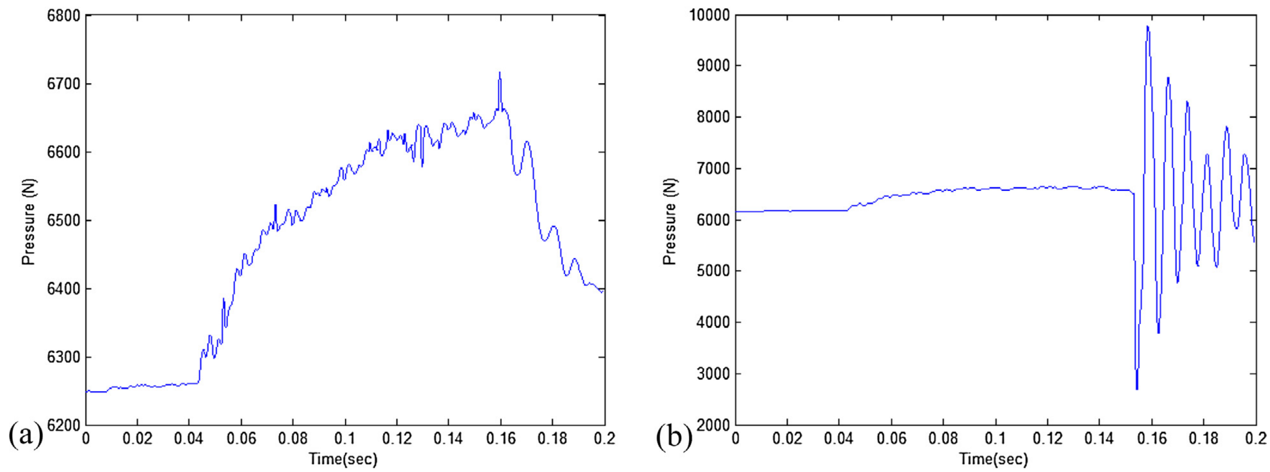

Fig. 10. Pressure waveform graphs of (a) the normal welding spot and (b) the splash welding spot after the interception.

If splash characteristic value of any weld spots lies out of the fences, it will be considered as weld spots that have defects. It was found that the minimum splash characteristic value of the splash spots is 302 and the highest splash characteristic value is 157 for the normal spots splash characteristic value. Thus, result of the threshold of the splash characteristic value is correct.

During the welding process, the splashed welding spot can cause large change of the pressure signal, thus, whether or not the welding spot has the splash defects can be assessed by the degree of pressure agitation. Thus, as shown in Fig. 10, difference between the pressure waveforms of the normal welding spot and splashed welding spot lies in that the pressure waveforms of the splashed welding spot have a short-time agitation. However, the changing trends of the pressure waveforms of the normal welding spot and splashed welding spot is consistent. In the initial stage of energization, the pressure waveforms of the two kinds of welding spots are gradually rising, but at a later stage of energization, splashed pressure waveforms generate agitation. Linear fitting of the pressure waveforms of the two kinds of welding spots are basically identical, however, the degree of differentiation between the characteristic values of the two kinds of welding spot is big after subtracting the fitting data from the original pressure data.

Fig. 10(a) shows the pressure waveform graph of the normal welding spot after the interception, Fig. 10(b) shows the pressure waveform graph of the splashed welding spot after the interception. It is seen from Fig. 10(a) that during nugget expansion, the waveform showed a trend of rising before 160 milliseconds, Fig. 11 is a linear fitting view of Fig. 10(a). It is seen that the fitting curve of the normal welding spots has a slope of 1706.1 and an intercept of 6300.2. The fitting curve of the splashed welding spots has a slope of 1759.3 and an intercept of 6257.3.

3.4. Signal extraction method of the incomplete fusion feature of the welding spot

In the spot welding process, incomplete fusion is a serious defect. The conventional non-destructive testing method cannot detect the defects of incomplete fusion welding well, thus, a real-time online monitoring method to monitor the incomplete fusion welding defects is needed. The incomplete fusion defect is complex, which includes specification, welding machine, welding material, surface state, etc., in addition, the operator. The large pressure leads to decreased contact resistance between the specimens, or short welding time. In this case, less heat input will not be able to form a molten nugget, which leads to the incomplete fusion defects. Due to the fact that the resistance of the liquid metal is smaller than that of the solid metal, the greater nugget diameter results in more transition of the solid metal into the liquid metal, and these features provides the theoretical basis for the extraction of characteristic signal of the incomplete fusion defects. The specific extraction method is listed as follows:

(1) Through the real-time acquisition of the welding current and welding voltage, the real-time dynamic resistance curve was obtained and the mean value of the dynamic resistance was calculated. The mean value of the dynamic resistance is defined as the dynamic resistance characteristic value.
(2) Draw the least square linear fitting curve of dynamic resistance and calculate its slope, the slope is the dynamic resistance slope characteristic value. It should be noted that the dynamic resistance curve has a decrease trend with increasing time, thus the slope of the fitted curve is a negative value.
(3) Through a lot of experimental analysis, the critical threshold of the dynamic resistance slope was calculated from the dynamic resistance curves. If the dynamic resistance characteristic value of the welding spot in the actual welding process is greater than its critical threshold and the dynamic resistance slope characteristic value is larger than the critical threshold, then this will prove that the incomplete fusion defects has occurred in the welding spot. Fig. 12 shows the flowchart for evaluating the welding spots with incomplete fusion.

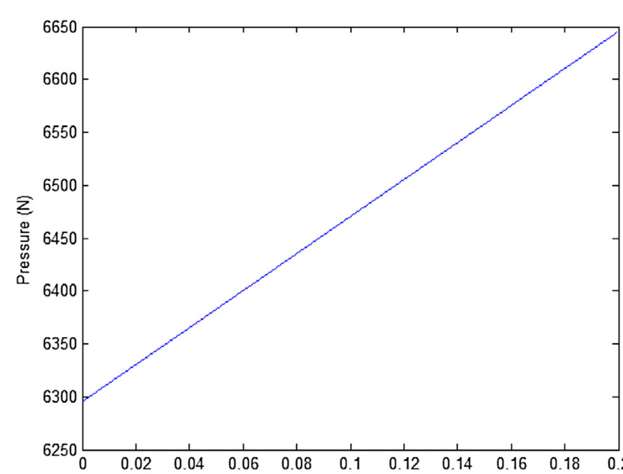

Fig. 11. Pressure waveform graphs after linear fitting of the splash welding point after interception.

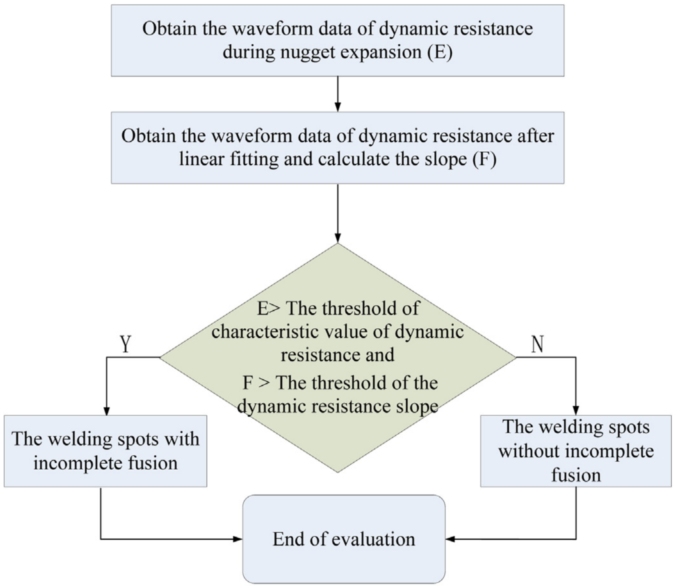

Fig. 12. Flowchart for evaluating the welding spots with incomplete fusion.

Fig. 13 shows the dynamic resistance curve of the normal welding spot and the welding spot with incomplete fusion, respectively. Fig. 14 shows the linear fitting graph of the dynamic resistance of the normal welding spot and incomplete fusion welding spot, respectively. From the above two curves it is seen that dynamic resistance of the normal welding spots is small, the value is 0.5058 mΩ, and the dynamic resistance slope characteristic value is −2.683, this is because dynamic resistance of the welding process decreased greatly, and dynamic resistance of the incomplete fusion of the welding spot is 0.6030 mΩ, which is larger than that of the normal welding spots, and the dynamic resistance slope characteristic value is −0.784. The dynamic resistance slope characteristic value of the normal welding spot is far less than that of the welding spot with incomplete fusion. Thus the smaller dynamic resistance characteristic value of the normal welding spots results in more molten liquid metal and better welding quality.

Threshold setting methods are the same for determining threshold of the dynamic resistance, threshold of dynamic resistance slope and threshold of splash. The 20 dynamic resistance characteristic value of all of the welding spots from one experiment is listed as follows: 0.493, 0.498, 0.505, 0.512, 0.516, 0.524, 0.526, 0.528, 0.528, 0.530, 0.532, 0.533, 0.536, 0.538, 0.541, 0.544, 0.549, 0.554, 0.561, 0.609. The last value 0.609 is the dynamic resistance characteristic value of the welding spot with incomplete fusion and the other values are the dynamic resistance characteristic value of the normal welding spot. The threshold value of dynamic resistance is set to 0.5785.

The dynamic resistance slope characteristic value of all of the weld spots from one experiment is listed as follows: −0.9934, −1.623, −1.685, −1.732, −1.760, −1.821, −1.869, −1.914, −1.952, −1.975, −1.992, −2.057, −2.068, −2.093, −2.117, −2.173, −2.206,

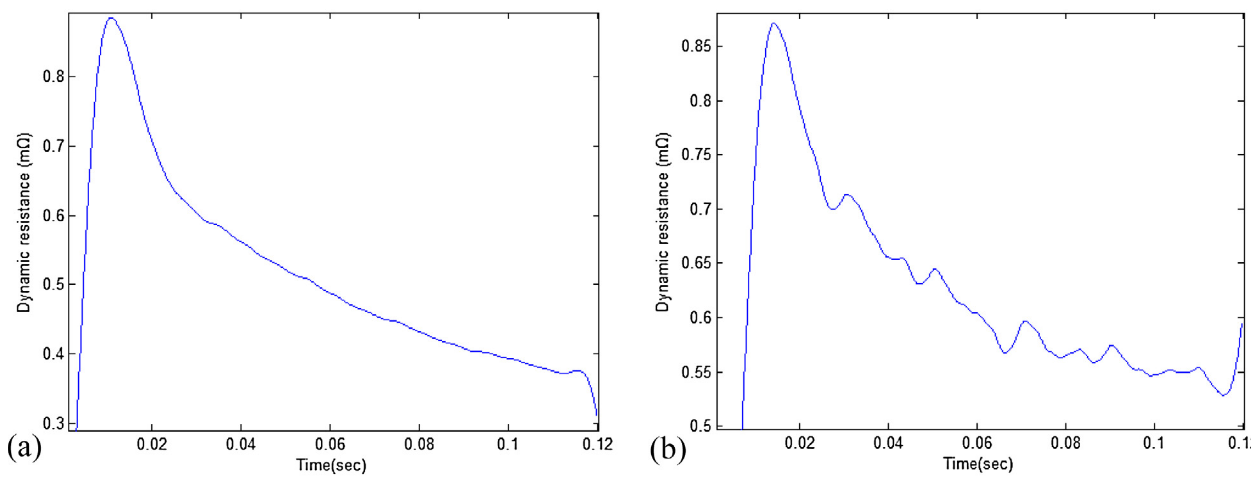

Fig. 13. The enlarged graphs of dynamic resistance of (a) the normal welding spot and (b) the welding spot with incomplete fusion.

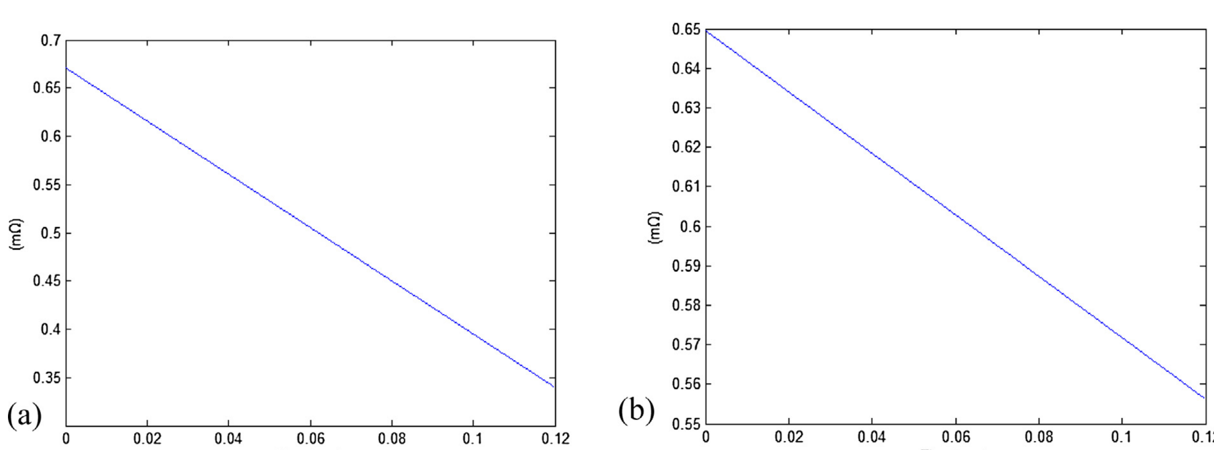

Fig. 14. Linear fitting graph of dynamic resistance of (a) the normal welding spot and (b) incomplete fusion welding spot.

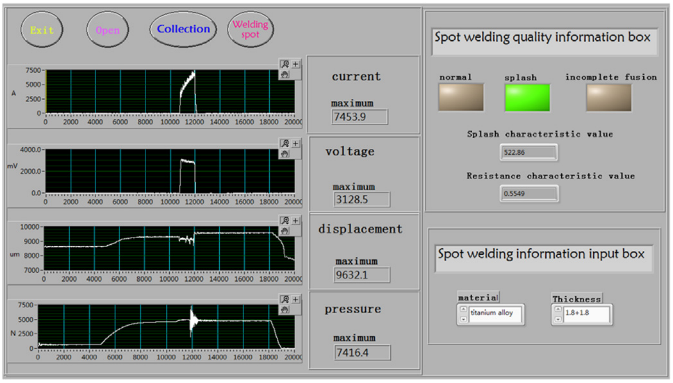

Fig. 15. The main interface of the splashed welding spot.

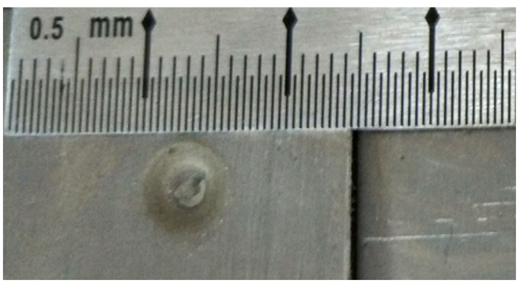

Fig. 16. Photograph of one splashed welding spot.

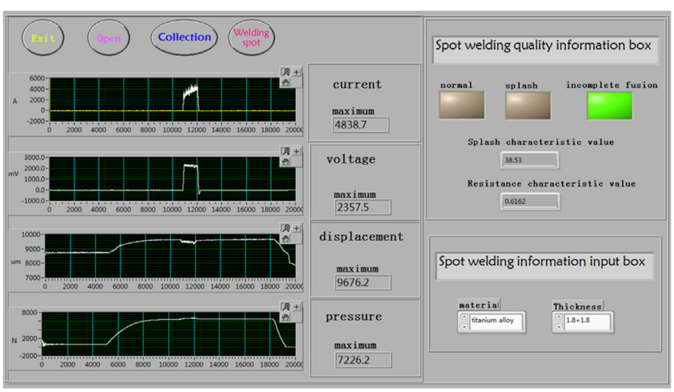

Fig. 17. The main interface of the welding spot with incomplete fusion.

−2.223, −2.305, −2.346. −0.9934 is the dynamic resistance slope characteristic value of the welding spot with incomplete fusion. The threshold value of the dynamic resistance slope is −1.286.

Table 1
Results of the validation tests.

Number of tests	Number of spots	Evaluation result	Tensile test result
1	100	2 splash	2 splash
2	100	21 splash and 9 incomplete fusion welding spot	21 splash and 9 incomplete fusion welding spot

3.5. Application examples

After the establishment of the on-line monitoring system of the weld quality of titanium alloy, critical threshold of welding defects were obtained through the experimental analysis, the on-line monitoring system of the weld quality did real-time acquisition of the welding spot information and quality evaluation of the welding spot.

Fig. 15 shows the waveform diagram and the evaluation results of the splashed welding spot, it is seen that the pressure signal has an agitation and displacement pressure signal has a mutation. It is seen from Fig. 15 that the right side of the splash characteristic value is 522.86. It is seen from “Spot welding quality information box” of the upper right side (Fig. 15) that when the indicator light of “splash” button turns bright green, the weld spots are being splashed. Fig. 16 shows the photograph of one splashed welding spot.

Fig. 17 shows the main interface of incomplete fusion welding spot and the evaluation results, the dynamic resistance characteristic value is 0.6162 and the dynamic resistance slope characteristic value is −0.953; the average dynamic resistance slope characteristic value of the qualified welds characteristic value is 0.5242 and the average dynamic resistance slope characteristic value is −2.074. Therefore the dynamic resistance characteristic value of the welding spot with incomplete fusion is greater than that of the normal welds, the dynamic resistance slope characteristic value of the welding spot with incomplete fusion is smaller than that of the normal welds. The photographs of the nugget after tensile test are shown in Fig. 18, the qualified welding spot has a nugget size of 6.88 mm, and the welding spot with incomplete fusion has a nugget size of 5.12 mm, the qualified weld nugget size of titanium alloy (1.8 mm + 1.8 mm) should be at least 6 mm.

Two validation tests were carried out and the results are shown in Table 1. In the first test, spot welding of titanium alloys was performed under the standard welding parameters used in Section 2.2. The online monitoring system found two flashed welding spots and tensile test results also proved that there are tiny splash defects in the two welding spots. The second test is to fine-tune the standard process parameters. Both the first and second test has shown that the online monitoring results are in excellent agreement with the practical application.

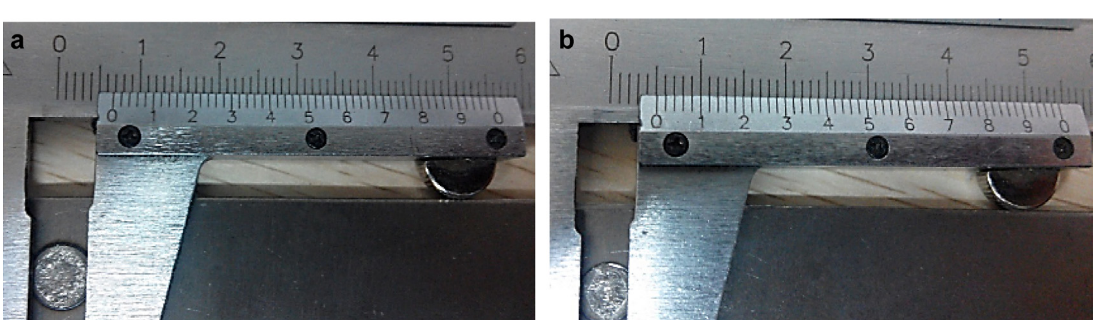

Fig. 18. Photographs of measuring the nugget size of (a) the qualified welding spot and (b) the weld spot with incomplete fusion.

4. Conclusions

(1) A highly accurate online monitoring system of spot welded TB2 titanium alloy was established involving the acquisition of welding current, welding voltage, electrode pressure and electrode displacement signals, which provides information for quality assessment of resistance spot welding. The defects detected by the online monitoring system include splash and incomplete fusion of the welding spots.
(2) The data gap is bigger subtracting the pressure data of the splashed welding spots after linear fitting from the original pressure data due to the fact that the pressure waveform data of splashed welding spot is more discrete.
(3) The decrease of the dynamic resistance of the welding spot with incomplete fusion is relatively small compared to that of the normal welding spots. The dynamic resistance slope of the welding spots with incomplete fusion is small after linear fitting.
(4) The online monitoring results of the weld quality show agreement with the validation test results.

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