FEATURE ANALYSIS AND EXTRACTION OF INNER DEFECTS FOR SPOT WELD NUGGET OF ALUMINUM ALLOY①

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ABSTRACT The information and data reflecting inner defects in spot welding nugget of aluminum alloy were obtained by edge extracting and tracking to binary image. Based on the K- L transformation, the major and minor axes of defects were calculated, and the distribution of defects in spot welds were described. Based on the above mentioned, a preliminary analysis of defect features was carried out.

Key words spot welding nugget defect K- L transformation feature analysis

1 INTRODUCTION

Spot welding has been widely used in aluminum alloy structures of spacecraft and aircraft due to its characteristics of technology. In order to increase the reliability of relevant structure works, the key is to ensure the quality of products. The kinds and shapes of defects in spot weld nugget of aluminum alloy are complex, furthermore the influence of kind, size and distribution of defects on the quality of spot weld are different. Accordingly, the description, classification and recognition for defect features must be carried out before evaluating the quality of spot weld. At the present time, the assurance for quality of joints are mostly conducted with welding technology and parameter monitoring of spot welding process. However there are few cases in which evaluation of joint quality is carried out with non-destructive testing in postwelding. It was reported that ultrasonic methods[1] and potentiometry[2-4] are used for the quality detection of spot weld. Radiography method was also used in important structures[5, 6], but it is of low efficiency and the assessment criteria are different by profession. It is an effective approach for improving this problem to introduce real-time X-ray image detection[7, 8], but it is very difficult to extract the feature value, which reflect the quality of spot weld from the image. These feature values are the input variables for recognition classifier, and will directly influence the output results. Aimed at such a status, on the basis of the preprocess of spot weld image the analysis and extraction of spot weld defect features were carried out, and typical feature values relevant to the quality of spot weld were obtained in this paper. These results provided scientific basis for further defect classification and quality evaluation.

2 MEASURING FOR DEFECTS

2.1 Experiment method

The binary images of defect in spot weld nugget were obtained by automatic windowing processing, background simulation and correction, as well as automatic binary processing

① Received Sep. 29, 1997; accepted Feb. 8, 1998

(Fig. 1). In order to extract defect features and evaluate quality of spot weld the edge extracting and tracing have to be carried out before the description of defect features, so that the data for the defect measuring could be obtained. The method of edge extraction used is as follows: scanning was taken in the zone of binary image, when the nonzero point was found, the pixel greyscale of 8 neighborhoods of this point will be considered to set the greyscale of this point to zero when the greyscale of surrounding 8 points are all nonzeros. The greyscale of this point was kept original when one or more points are zero in 8 neighborhoods. According to this method whole edge of defects could be obtained after finishing scanning. The results are given in Fig. 2.

Fig. 1 Binary image of defects

Fig. 2 Schematic of edge extraction

2.2 Data encode of eight neighborhoods

After formation of an edge its encoding should be carried out, and a sequential data structure was made up in the light of definitive rule so that the description of defects was facilitated. The common method for forming sequential data structure is edge tracing and the method adopted in the present paper is based on left-hand rule that is as follow[9]. Scanning in the processing domain, when the start point was found set it as I, and set it as current point. According to the definition of 8 neighborhoods and the sequence shown in Fig. 3, find the nonzero pixels of 1~ 8 points, and set it as next point of edge tracing. Record its coordinate, and take it as current point, continually find the next point of edge tracing by this rule, the tracing will be finished until the condition can not be satisfied.

In the course of tracing such a serial of data encode for a defect edge was made up, that is as follows: $\{(0, 0), (x_i, y_i), i = 1, 2, \cdots, N\}$, where (0, 0) shows the end of defect edge tracing for the former defect and the start of edge tracing for next defect as well; it is an identifying coordinate point, and (x_i, y_i) are the coordinates of edge sequence points.

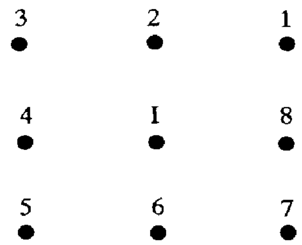

Fig. 3 Definition of 8 neighborhoods

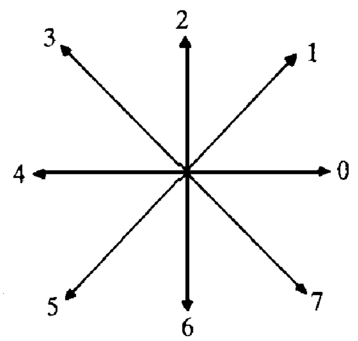

Fig. 4 Definition of Freeman code

2.3 Method of Freeman encode

The method of Freeman encode was further used to reveal the edge information because the method used above for defect encode could not reflect the information clearly. Freeman encode element has directivity and its definition is given in Fig. 4[10]. The information of code element is determined by the coordinate difference of current point and next point of edge. For a defect the Freeman code was made up as follow: A= { 0, a_1, a_2, a_3, …, a_i, …, a_N}, where 0 is identifying unit between defects, a_i is a code element reflecting the relationship between the current point and next point. In the whole course of defect encode the parameters may be obtained as follows:

Gravity coordinates:

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i \tag{1}$$

$$\bar{y} = \frac{1}{N}\sum_{i=1}^{N} y_i \tag{2}$$

Circumference:

$$L = T[n_e + n_0\sqrt{2}] \tag{3}$$

where x_i and y_i are sequence point coordinates of defect edge, T is pixel unit length of 8 neighborhoods, and n_e and n_0 are numbers of code element for odevity respectively.

Integrating the defect edge over X or Y axis, the area represented by the chain code can be calculated as Fig. 5, the integration over X axis can be expressed by formula (4). In this formula, a_{ix} and a_{iy} are unit coordinate lengths of X and Y axes respectively, $a_{ix} \cdot y_{i-1}$ is the area of shaded square and $a_{ix} \cdot a_{iy}/2$ is the area of shaded right triangle in the figure. Because the a_{ix} and a_{iy} are signed (dependent on the direction of integration), the integration is carried out along the closed edge and offsetting against the parts outside of edge, and then the area surrounded by the edge, the area of defect, can be calculated.

$$S = \sum_{i=1}^{N} a_{ix}\left(y_{i-1} + \frac{1}{2}a_{iy}\right) \tag{4}$$

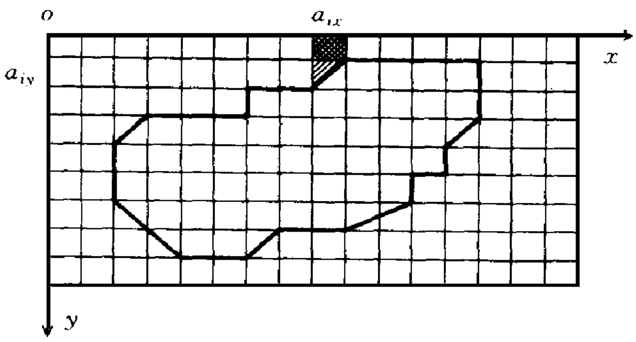

Fig. 5 Schematic of Freeman code property

3 CALCULATION OF MAJOR AND MINOR AXES OF DEFECTS BASED ON K- L TRANSFORMATION

3.1 Method of K- L transformation

There are many kinds of defects in the spot weld nugget, classified by shape they are mainly tree-like or strip crack, elliptical or circle blowhole, or slag inclusion defects. The ratio between major and minor axes of defects, which is a very obvious feature among them, should be considered when their category is distinguished.

Because the location and orientation of defects are random, it is difficult to calculate the major and minor axes by the general method. The K- L transformation was used to calculate the parameters of major and minor axes in present work. The K- L transformation is usually used to the data compression and feature extraction, it is the best correlation transformation[11]. The principle of K- L transformation is simply described as follows:

Set T as a unit orthogonal transformation matrix, $T' = [\Phi_1, \Phi_2, \cdots, \Phi_N]$, where $\Phi_i (i = 1, 2, \cdots, N)$ is N dimension vector and satisfies the orthogonal condition of real value:

$$\Phi_i \Phi_j = \begin{cases} 1 & (i = j) \\ 0 & (i \neq j) \end{cases} \tag{5}$$

For a vector $\overline{X}' = [x_1, x_2, \cdots, x_N]$ of a random process the vector $\overline{Y}' = [y_1, y_2, \cdots, y_N]$ can be obtained by the transformation $\overline{Y} = T\overline{X}$. On the condition that T is unit orthogonal transformation, $T'T = 1$ may be obtained, hence the inverted transformation seems to be

$$\begin{aligned}\overline{X} = T'\overline{Y} &= [\Phi_1, \Phi_2, \cdots, \Phi_n]\overline{Y} \\ &= y_1\Phi_1 + y_2\Phi_2 + \cdots + y_N\Phi_N \\ &= \sum_{i=1}^{N} y_i \Phi_i \end{aligned} \tag{6}$$

In order to minimize the difference between inverted transformation data and original data an optimal transformation T should be explored on the basis of mean square deviation and the results derived are as follows:

$$\Sigma_x \Phi_i = \beta_i \Phi_i \tag{7}$$

where Φ_i is the feature vector of autocorrelation function $\sum_x$ and β_i is corresponding feature value.

The process of K- L transformation: for a random vector, its autocorrelation matrix is calculated, then the feature values and feature vectors of autocorrelation matrix are calculated. The feature values and corresponding feature vectors will be arranged by the sequence descendingly, then the feature vector arrange constitutes transformation matrix. The feature values are the variance of each projected component of that random vector, and that is the variance of corresponding component in transformation domain. The autocorrelation function in transformation domain may be expressed by $\sum_y = T \sum_x T'$, and $\sum_y = \mathrm{diag}(\beta_1, \beta_2, \cdots, \beta_N)$ is diagonal matrix, therefore, the components y_i are not correlated after being transformed. When the major and minor axes of defects are calculated the edge point sequence of defects is taken as a set of a two-dimensional random vector, and the equipartition vector and covariance matrix are given by

$$\mu = \begin{vmatrix} \bar{x} \\ \bar{y} \end{vmatrix} \tag{8}$$

$$\Sigma = \begin{vmatrix} x - \bar{x} \\ y - \bar{y} \end{vmatrix} \begin{vmatrix} x - \bar{x} \\ y - \bar{y} \end{vmatrix}^T = \begin{vmatrix} (x - \bar{x})^2 & (x - \bar{x})(y - \bar{y}) \\ (x - \bar{x})(y - \bar{y}) & (y - \bar{y})^2 \end{vmatrix} \tag{9}$$

then, calculate the feature values β_1 and β_2 of covariance matrix and corresponding eigenvector Φ_1 and Φ_2, set $\beta_1 > \beta_2$, map the edge point set to two one-dimensional directions respectively by $y = \Phi_1^T \bar{x}$ and $\bar{y} = \Phi_2^T \bar{x}$, herein the mapping interval in the Φ_1 direction may be taken as the measure of major axes of defects, in the Φ_2 direction as measure of minor axes of defects.

3.2 Determination of distribution for defects position

According to the industry standard for Ministry of Spacecraft Industry Co. QJ 2250-95, the size, distribution and orientations are important criteria for evaluating the quality of spot weld, therefore, their locations and orientation must be determined. It is known from the property of K- L transformation that: Φ_1 is main feature vector, it expresses the orientation of defect in the transformation of two-dimensional vector constituted by the edge point set. The distribution of defects in the nugget are expressed by the included angle θ constituting of vector $\boldsymbol{a}$, which is the link between the center (x_0, y_0) of weld spot and origin of coordinate O, and vector $\boldsymbol{b}$, which is the link between the center of spot weld and the gravity center of defect, and by the distance r between gravity center of defect and spot weld center. Furthermore, it should be considered that the angle θ may be clockwise or counter clockwise. The size of defects is expressed with the area included by the defect edge. The schematic plan of analysis is shown in Fig. 6.

Set vector $\boldsymbol{a} = x_a \cdot \boldsymbol{i} + y_a \cdot \boldsymbol{j}$, and vector $\boldsymbol{b} = x_b \cdot \boldsymbol{i} + y_b \cdot \boldsymbol{j}$, then the included angle between $\boldsymbol{a}$ and $\boldsymbol{b}$ is

$$\theta = \arccos\left(\frac{x_a x_b + y_a y_b}{\sqrt{x_a^2 + y_a^2}\sqrt{x_b^2 + y_b^2}}\right) \tag{10}$$

$$r = \sqrt{(\bar{x} - x_0)^2 + (\bar{y} - y_0)^2} \tag{11}$$

Then take the gravity center coordinate of defects $(\bar{x}, \bar{y})$ into the equation $y = (y_0/x_0) \cdot x$ which is for the link between spot weld center and origin of coordinate, as shown in Fig. 6: if $y > y_0$, take θ as counter clockwise and can be described as "DOWN", otherwise be described as "UP". So we can describe the location of defects in the nugget, and the calculated results are shown in Fig. 7. They are basically the same as those of real measurements, the distribution parameters in Table 1.

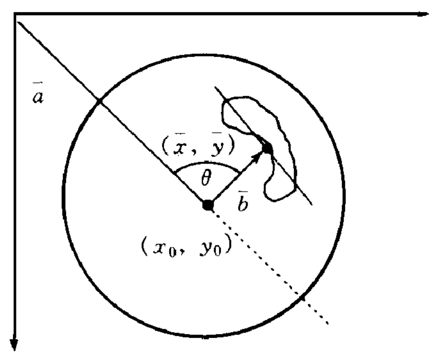

Fig. 6 Calculation method of feature vector

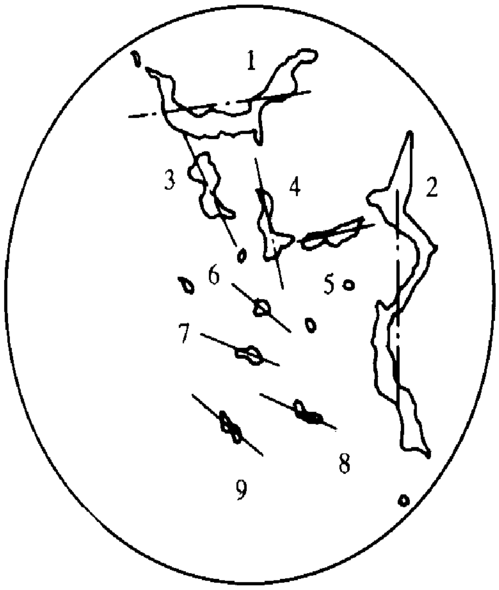

Fig. 7 Schematic of defects distribution

Table 1 Parameters list of defects distribution

No.	Major axis	Minor axis	Circumference
1	59.10	27.89	191
2	113.81	28.68	312
3	26.12	12.82	84
4	22.86	14.01	71
5	27.66	6.59	64
6	8.80	7.20	25
7	11.34	4.67	27
8	12.44	5.02	31
9	11.40	4.63	28

No.	Area	Angle of θ	Position	Distance
1	469	39.9	up	65.64
2	753	137.3	up	61.39
3	148	23.4	up	40.34
4	110	68.3	up	24.84
5	109	105.7	up	39.42
6	46	175.6	down	6.38
7	29	130.9	down	20.83
8	30	161.5	down	48.11
9	29	122.6	down	45.85

4 PRIMARY RESEARCH ON CATEGORY OF DEFECT FEATURES

The shape of different defects category in nugget is variant, generally the crack is slender and curved, the slag inclusion or blowhole is ellipse-like or circular. According to the general pattern features, the feature values-shape coefficient R and ratio of major and minor axes L, which express the difference of shape, was calculated. The shape coefficient is defined as $R = 4\pi S/l^2$, where S is area of defect and l is circumference of defect.

The ratio of major and minor axis is $L = c/w$, where c is length of major axis, and w is length of minor axis.

Admittedly, the shape coefficient R is much smaller than R of ellipse-like(R of perfect circle equals 1) for the crack but the ratio L of major and minor axes is larger. The parameters used for calculating the two feature values have been obtained above.

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(Edited by Peng Chaoqun)