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Ultrasonic C-scan Detection for Stainless Steel Spot Welding Based on Wavelet Package Analysis

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Abstract: An ultrasonic test of spot welding for stainless steel is conducted. Based on wavelet packet decomposition, the ultrasonic echo signal has been analyzed deeply in time - frequency domain, which can easily distinguish the nugget from the corona bond. The 2D C-scan images produced by ultrasonic C scan which contribute to quantitatively calculate the nugget diameter for the computer are further analyzed. The spot welding nugget diameter can be automatically obtained by image enhancement, edge detection and equivalent diameter algorithm procedure. The ultrasonic detection values in this paper show good agreement with the metallographic measured values. The mean value of normal distribution curve is 0.006 67, and the standard deviation is 0.087 11. Ultrasonic C-scan test based on wavelet packet signal analysis is of high accuracy and stability.

Key words: stainless steel; spot welding; ultrasonic test; wavelet package analysis; nugget diameter

1 Introduction

With the expansion of resistance spot welding technique and increasing requirements of welding quality, quality assessment has become an important issue in welding quality control[1]. In the field of modern automobile and railway vehicle manufacturing, reliable spot welding is the key to guarantee safety and service life[2,3].

At present, in actual production, most industries mainly use destructive testing, which has low efficiency and wastes materials[4,5]. Therefore, in recent years, many researchers are committed to the research on resistance spot welding ultrasonic nondestructive testing technology[6,7]. Ultrasonic C scan testing technology attracts special attention with advantages, such as visual image, high detection sensitivity, defect location, accurate quantitativeness, and so on[8]. Although Shi *et al*[9] used an immersing ultrasonic C scan to test the nugget diameter, the result is relatively larger than the actual value because of the influence of the corona bond, *i e*, high temperature solid metal around the nugget, where plastic deformation and recrystallization of the metal occur under the action of gravity electrode. Yet, the test error can be adjusted through changing the threshold value. Thornton *et al*[10] used ultrasonic C-scan technology to test resistance spot welding. A high error still existed even though the tested specimen is free of surface indentation. However, whether the nugget diameter included a corona bond in the testing result was not mentioned. At present, ultrasonic nondestructive testing results of nugget diameter mostly include the corona size around the nugget, resulting in the test result generally larger than the real value. Furthermore, the corona bond is the weak zone of spot welds. Its size directly affects the quality of spot welding[11,12]. Therefore, the reliability of ultrasonic nondestructive testing results can be effectively improved by distinguishing the nugget from the corona bond.

In this paper, C scan detection is conducted in the weld nugget zone using a stepping mechanical scanning method and the signal of the ultrasonic A-echo is analyzed in time-frequency domain. The characteristic signal in the spot weld is extracted and further processed using the wavelet packet transform to separate the high-frequency echo signal. Then, the nugget and corona bond can be effectively identified

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Table 1 Chemical composition of SUS304 austenitic stainless steel/wt%

C	Si	Cr	Ni	N	Mn	P	S	Fe
≤0.07	≤1.00	18.00-20.00	8.00-11.00	0.01-0.25	≤2.50	≤0.035	≤0.030	allowance

according to the spectrum characteristic. Quantitatively measuring the spot welding C-scan imaging and the nugget diameter allows for rapid and more reliable assessment of the spot welding quality.

2 Experimental

2.1 Specimen preparation

SUS304 stainless steel (0Cr18Ni9) was used in this study, with the chemical composition and mechanical properties shown in Table 1 and Table 2 respectively. The specification of specimen is shown in Fig.1. The stainless steel surface has been treated with sandpaper before welding to ensure that the surface keeps in the same state. Twelve specimens with different welding quality were respectively welded with different parameters.

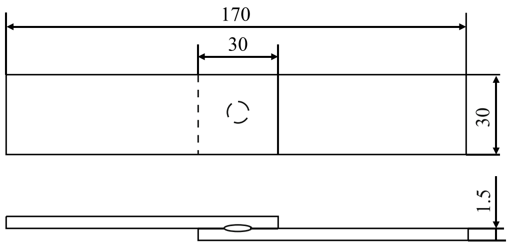


Fig.1 Geometry and dimension of specimen (in mm)

Table 2 Mechanical properties of SUS304 austenitic stainless steel

Yield strength /(N/mm^2)	Tensile strength /(N/mm^2)	Elongation /%	Hardness /HV
≥205	≥520	≥40	≤200

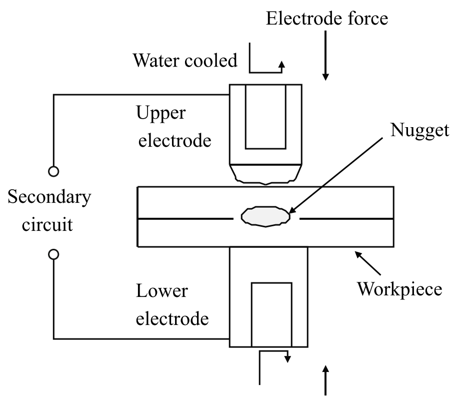


Fig.2 Schematic diagram of resistance spot welds

2.2 Testing device and method

The ultrasonic testing device used in the experiment comprised a 15 MHz ultrasonic focusing probe, an ultrasound card with sampling rate of 100 MHz, a scanning platform and a portable industrial computer.

According to the actual process of resistance spot welding, a spherical electrode was used at one end while a planar electrode (copper platform) at the other end in the preparation of specimens, as shown in Fig.2. This study conducted ultrasonic testing on the side without indentation in order to avoid welding indentation's influence on test results, and used water as the coupling agent. The probe driven by a linear motor scanning platform can scan in the *X*-axis direction parallel to nugget and *Y*-axis direction perpendicular to the nugget. The scanning mode used in this study was S-type complete coverage scanning with step length of 0.08 mm. The probe scanning path is shown in Fig.3.

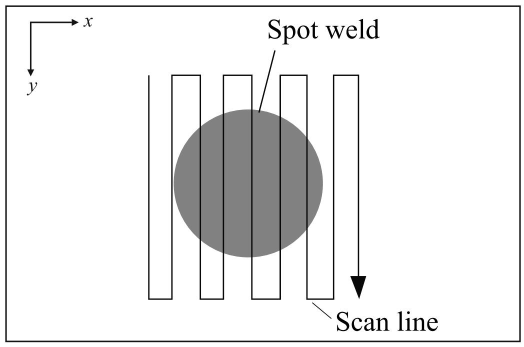


Fig.3 Schematic diagram of the probe scanning path

2.3 Wavelet package analysis

Traditional ultrasonic signal analysis is based on Fourier transform. Fourier transform is a kind of overall transformation, which transfers time-domain signals into frequency domain. During the transformation, time information is lost. So there are serious problems when analyzing non-stationary signals[13]. However, actual ultrasonic signals contain a large number of non-stationary compositions, such as attenuation, scattering, mutation, *etc*, which usually reflect some important signal features. So an analysis method with both time resolution and frequency resolution is needed. Wavelet transform is a time-frequency analysis method, which has strong ability of characterizing local features in time domain and frequency domain[14].

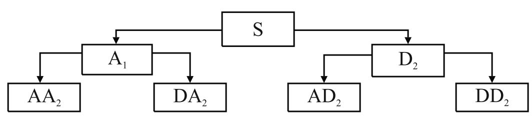


Fig.4 Two-scale wavelet packet decomposition

Wavelet analysis is an effective time-frequency analysis method. However, as its scale function changes in binary, the resolution is low at high frequencies and it is only used for index interval division on the signal spectrum. Wavelet packet transform is a further development of Wavelet analysis. Multi-level decomposition of signal spectrum can subdivide the high frequency part and choose the corresponding frequency band adaptively according to the characteristic, which makes it match the signal spectrum and improves the time-frequency resolution[15].

The two -scale wavelet packet decomposition process is shown in Fig.4. Then,

$$S=AA_2+DA_2+AD_2+DD_2$$

where S indicates the original signal; A represents the low frequency; and D is on behalf of the high frequency. This paper adopted the two-order Daubechies wavelet function. Two scale wavelet packet decomposition of ultrasonic A-echo signal has been applied, as shown in Fig.5.

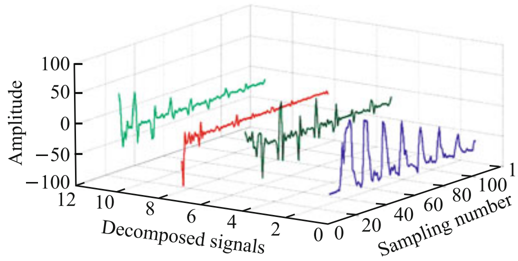


Fig.5 Two-scale decomposed ultrasonic A-echo signal

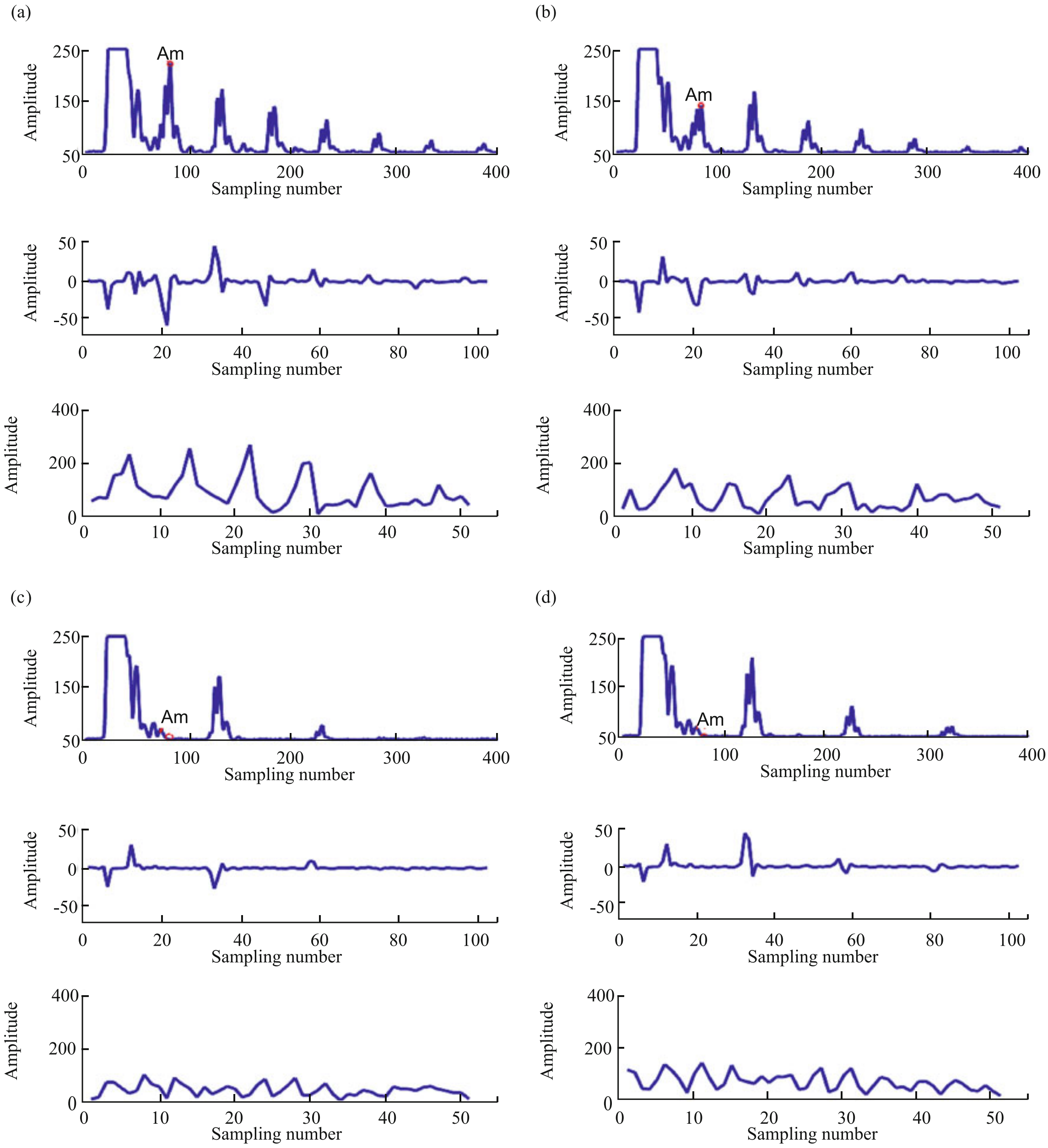


Fig.6 Ultrasonic signal analysis in time-frequency domain in different positions of spot welds: (a) parent metal; (b) near nugget zone; (c)corona bond; (d) nugget

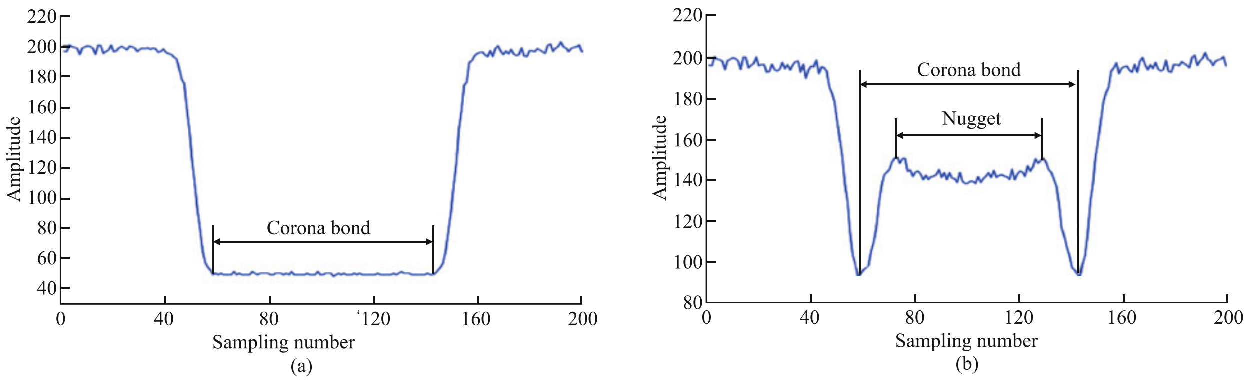


Fig.7 Amplitude curves along the scanning line: (a) the first echo signal amplitude Am; (b) frequency is 16 MHz

3 Signal analyses

For stainless steel resistance spot welding specimens, a time-frequency analysis of ultrasonic signals in different positions of the spot weld has been conducted. The result is shown in Fig.6, including four groups of analysis results in different positions. Each group includes three sketches. The first sketch is the returned original ultrasonic signal in different positions. The second sketch is the high frequency signal (DD_2) extracted after two-scale wavelet packet decomposition of the original signal. The last sketch is the spectrum characteristic curve corresponding to high frequency signal (DD_2). From the diagram we can see that as the probe moves towards nugget, ultrasonic signal amplitude reduces, especially with the obvious change of the first echo signal amplitude Am. Furthermore, it is concluded after large numbers of tests that the amplitude of 16 MHz on DD_2 frequency spectrum characteristic curve varies most obviously. Then, the amplitude Am and 16 MHz amplitude value on DD_2 frequency spectrum characteristic curve of each point along the scan line are extracted for curve plotting respectively, as shown in Fig.7.

As shown in the graph, the amplitude Am has reduced to the minimum value in the corona bond. Since the amplitude of the nugget is the same as that of the corona bond, it is impossible to distinguish the nugget from the corona bond simply from signal analysis in time domain. The overall size is taken as the reference to evaluate the quality of spot welding. The corona bond is the weak zone of spot welds, so it is not reliable to use the overall size to evaluate the quality. Of course, if parameters can be adjusted in welding to make the corona bond very narrow, or the test accuracy requirement is not high, the test error of this method is negligible. However, if the corona bond is very wide or high test accuracy is required, it seems necessary to distinguish the nugget from corona bond. It is shown in Fig.7(b) that the 16 MHz amplitude value also reduces to the minimum value in the corona boundary. Unlike Fig.7(a), a new characteristic area appears within the corona bond zone. The reason of the phenomenon is that the amplitude of the ultrasonic echo signal changes with different status of combination[16]. Fig.7(b) shows that when the ultrasonic probe moves to the boundary of the corona, 16 MHz amplitude value reduces to the minimum, which corresponds to the bottom of the amplitude curve. As the probe continues to move towards the nugget, the amplitude increases gradually. This is because the corona bond is a solid connection in the high temperature state outside the nugget, belonging to a typical weak combination. In this zone, the amplitude shows changing characteristics dependent

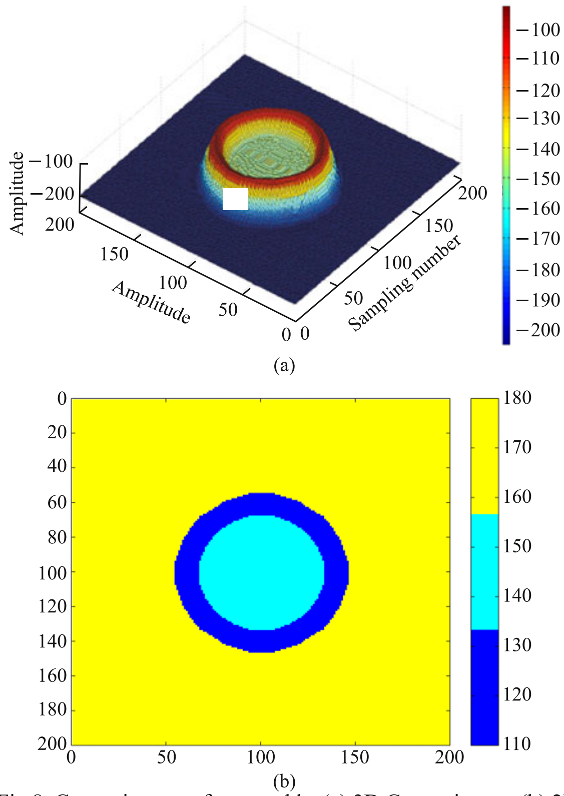


Fig.8 C-scan images of spot welds: (a) 3D C-scan image; (b) 2D C-scan image

on frequency, that is to say, the high frequency signal amplitude increases with the decrease of the space. The space tends to be the least on the nugget boundary, and at this time, the amplitude value Am increases to the peak. However, within the nugget, the amplitude is only relative to acoustic impedance and internal organizational structure of medium itself, having nothing to do with the frequency. Thus, the amplitude trend changes gently. Above all, the new feature region within the corona bond zone in Fig.7(b) corresponds to the real nugget.

In order to reflect spot weld appearance more intuitively and achieve a quantitative measurement of the nugget diameter, the 16 MHz amplitude is treated as the characteristic value to get the 2D and 3D C-scan images of the spot weld respectively. The result is shown in Fig.8. It is found by comparison that the gradational 3D surface is not convenient for computer to calculate nugget diameter quantitatively. Therefore, 2D C-scan images of spot welds are selected for further analysis in this paper.

4 C-scan image processing

In the process of generating a C-scan image, noise exists in echo signal with the influence of many factors, such as detection system resolution, signal-to-noise ratio and discontinuity of materials inspected, *etc*, which finally results in that C-scan image is distorted in some degree. In order to show nugget morphology more realistically and clearly, and to realize the quantitative measurement of the weld nugget diameter, in this paper, C-scan images are processed through computer image enhancement, edge detection and nugget diameter measurement. Finally a real-time, automatic assessment of spot welding quality is completed.

4.1 Image enhancement

Image enhancement is a processing method which selectively highlights interested image features while ignores some needless features through adding some information on the original image or transforming data by certain means so as to improve image quality and strengthen the effect of image recognition. In order to filter out interference noise effectively and protect the nugget edge information well, a variety of filter methods are used to deal with C-scan images in this paper. After a large number of experimental comparisons and analyses, it is found that the processing effect of spot welds C-scan images through the median filtering with nonlinear smooth characteristics is the best. The 2D C-scan image of spot weld (Fig.8(b)) has been processed by median filtering in 7×7 modules, and the output image is shown in Fig.9(a). It filters out the spike noise and makes nugget boundary clearer in C-scan images, and further improves the quality of C-scan images, which lays foundation for subsequent image edge extraction.

4.2 Edge detection

This paper further chooses Roberts-operator, which is sensitive to noise signals, to conduct edge detection on the C-scan images and obtain accurate nugget boundaries. The results are shown in Fig.9(b). In order to conveniently identify and analyze the nugget zone in the image, a morphological image processing method is also used to segment the needed feature information, as shown in Fig.9(c). After segmentation, not only does the nugget feature become prominent in the image, but also greatly reduces the computer calculation, and it provides favorable conditions to get the real-time nugget dimension and quality assessment of spot welding.

4.3 Nugget diameter evaluation—Equivalent diameter method

The spot welding quality is characterized by the strength of spot welds, which mainly depends on the dimension of the nugget, especially the nugget diameter[17]. This paper adopts an equivalent diameter method, namely, calculating the average nugget diameter to assess the spot welding quality.

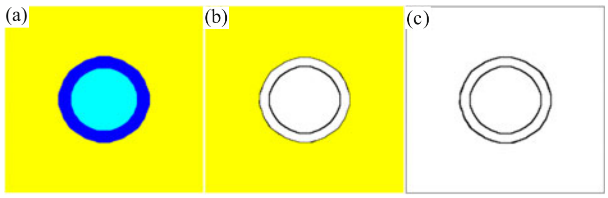


Fig.9 C-scan image processing: (a) median filtering; (b) edge detection; (c) edge segmentation

The procedure of calculation is accomplished by a computer program that picks up N points on the nugget boundary (inner circle in Fig.9(c)) and takes two arbitrary points of the N points as a straight line. The midperpendiculars of two arbitrary straight lines intersect at one point, and the mean value coordinates of all midperpendicular intersection points are taken to be the center of the nugget. The average distance from the center to the N boundary point is the nugget diameter.

5 Test results analysis

The nugget diameters of twelve spot welding specimens with different weld quality are obtained after ultrasonic test through C-scan images processing. In order to evaluate the testing accuracy, after ultrasonic test, the specimens are split along the combining surface of the upper and lower plates to get the nugget cross section's metallograph, as shown in Fig.10. Then,

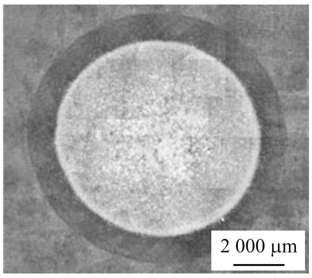
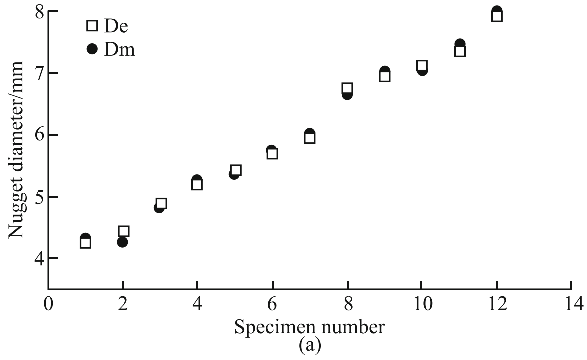


Fig.10 Nugget cross section's metallograph



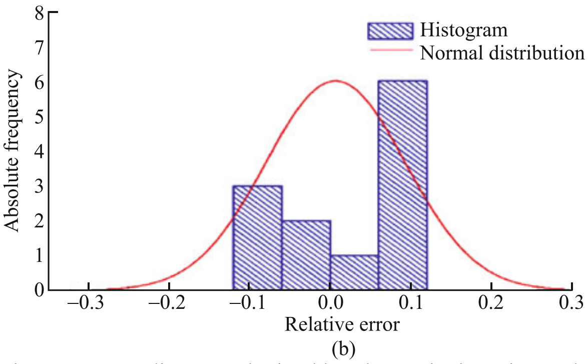


Fig.11 Nugget diameter obtained by ultrasonic detection and actual measurement: (a) comparison diagram; (b) error

the ultrasonic detection values of the nugget diameter are compared with the metallographically measured values. The results are shown in Fig.11(a). De refers to the ultrasonic testing value while Dm refers to the metallographically measured value. Obviously, actual measured value fits the testing value very well. Fig.11(b) is the statistical chart of error statistics. The mean value of normal distribution curve is 0.006 67, and the standard deviation is 0.087 11. The mean value of relative error and variance are small, which shows that under the condition in this test, the precision and stability of ultrasonic C-scan detection based on wavelet packet analysis in time-frequency domain are reliable.

6 Conclusions

a) The ultrasonic echo signal can be analyzed deeply in time - frequency domain using the method of wavelet packet decomposition. The nugget can be easily distinguished from the corona bond by extracting high-frequency signals at different positions of spot welds.

b) Spot welding specimen is tested by ultrasonic C scan through extracting time and frequency domain characteristic signals. The 2D C-scan images convenient for the computer to quantitatively calculate the nugget diameter are further analyzed.

c) Image enhancement and edge detection processing on 2D C-scan images can provide clear nugget boundary morphology. Not only does nugget feature become prominent in the image, but also the computation amount of data is greatly reduced. The diameter of spot welding nugget can be automatically obtained through an equivalent diameter algorithm procedure.

d) The ultrasonic detection value of the nugget diameter has a good agreement with the metallographically measured values. The mean and variance relative error of normal distribution are very small. Ultrasonic C-scan test based on wavelet packet signal analysis is of high accuracy and stability.

References

[1] Nied H. The Finite Element Modeling of the Resistance Spot Welding Process[J]. *Weld. J.*, 1984, 63(4): 123-132
[2] Jou M. Real Time Monitoring Weld Quality of Resistance Spot Welding for the Fabrication of Sheet Metal Assemblies[J]. *Journal of Materials Processing Technology*, 2003, 132(1): 102-113
[3] Aslanlar S. The Effect of Nucleus Size on Mechanical Properties in Electrical Resistance Spot Welding of Sheets Used in Automotive Industry[J]. *Materials & Design*, 2006, 27(2): 125-131
[4] Aslanlar S, Ogur A, Ozsarac U, *et al.* Effect of Welding Current on Mechanical Properties of Galvanized Chromided Steel Sheets in Electrical Resistance Spot Welding[J]. *Materials & Design*, 2007, 28(1): 2-7
[5] Bayraktar E, Kaplan D, Buirette C, *et al.* Application of Impact Tensile Testing to Welded Thin Sheets[J]. *Journal of Materials Processing Technology*, 2004, 145(1): 27-39
[6] Ditchburn R J, Burke S K, Scala C M. NDT of Welds: State of the Art [J]. *NDT & E International*, 1996, 29(2): 111-117
[7] Mansour T M. Ultrasonic Inspection of Spot Welds in Thin-Gage Steel[J]. *Materials Evaluation*, 1988, 46(5): 650-658
[8] Maev R G, Ptchelintsev A, Denissov A A. Ultrasonic Imaging with 2D Matrix Transducers[J]. Acoustical Imaging, 2002, 25: 157-162
[9] Shi L F, Zheng X M, Shi Y W. Ultrasonic C-Scan Testing for Determining the Spot Size of the Resistance Spot Welding in Aluminum Alloy[J]. *Nondestructive Testing*, 2004, 26(1): 34-36 (in Chinese)
[10] Thornton M, Han L, Shergold M. Progress in NDT of Resistance Spot Welding of Aluminium Using Ultrasonic C-Scan[J] . *NDT & E International*, 2012, 48:30-38
[11] Neves J, Loureiro A. Fracture Toughness of Welds-Effect of Brittle Zones and Strength Mismatch[J]. *Journal of Materials Processing Technology*, 2004, 153: 537-543
[12] Nguyen T N, Wahab M A. The Effect of Weld Geometry and Residual Stresses on the Fatigue of Welded Joints Under Combined Loading[J]. *Journal of Materials Processing Technology*, 1998, 77(1): 201-208
[13] Strang G. Wavelet Transforms Versus Fourier Transforms[J]. *Bulletin of the American Mathematical Society*, 1993, 28(2): 288-305
[14] Daubechies I. The Wavelet Transform, Time-Frequency Localization and Signal Analysis[J]. *IEEE Transactions on Information Theory*, 1990, 36(5): 961 - 1 005
[15] Kaya K, Bilgutay N M, Murthy R. Flaw Detection in Stainless Steel Samples Using Wavelet Decomposition[J]. *IEEE Ultrasonics Symposium*, 1994, 2: 1 271 - 1 274
[16] Luan Y L, Feng J C, Gang T. Ultrasonic Evaluation of TiAl and 40Cr Diffusion Bonding Quality Based on Time-Scale Characteristics Extraction[J]. *NDT & E International*, 2011, 44(8): 789-796
[17] Chao Y J. Failure Mode of Spot Welds: Interfacial Versus Pullout[J]. *Science & Technology of Welding & Joining*, 2003, 8(2): 133-137