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Characterization of nugget nucleation quality based on the structure-borne acoustic emission signals detected during resistance spot welding process

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ABSTRACT

Acoustic emission signals detected during the resistance spot welding of aluminum alloy were studied in order to assess the characterizations of welding process, the characterizations of the effect of welding parameters to nugget nucleation and the characterizations of the nugget quality by the analysis to acoustic emission signals. The results showed that the physical phases of nugget nucleation can be characterized by the acoustic emission signals detected during the resistance spot welding process. The effects of welding current and current duration to nugget nucleation can be characterized by the characteristic parameters of acoustic emission signals. The characteristic parameters of acoustic emission signals had a better relevance to nugget dimensions and weld strength, which made it possible to measure or predict the weld strength by the characteristic parameters of acoustic emission signals detected during the resistance spot welding process.

1. Introduction

Resistance spot welding (RSW) is widely used in automotive body assembly process. There are thousands of spot welds on an automobile body. The quality of spot welds determines the safety and performance. The factors of quality for spot weld mainly include the nugget dimension and weld strength. The strength of spot weld largely depends on the nugget dimension [1], and monitoring and improving the quality of spot welds are an ongoing process in RSW research [2–5].

The sonic and ultrasonic wave detection technologies are widely used in materials research, safety of engineering structures and quality monitoring of process. But the researches to real-time detection of mechanical vibration signals, including sonic, ultrasonic and acoustic emission in welding process, are mainly concentrated in the area of fusion welding, such as laser welding, arc welding and plasma arc welding [6–9]. The electrical energy provided by welding power is released with different energy forms in RSW process as the resistance heat is generated by the welding current passing through the materials and melting the base materials to form nugget. These energy forms include heat energy, mechanical energy and light energy, etc. Among them, the conversion of electrical energy to mechanical energy is characterized to be elastic wave generated in the welding process, such as sonic wave, ultrasonic wave and acoustic emission, which transmission mediums include workspieces, electrodes and air. The regularity of energy conversion changes along with the RSW process and materials properties. Especially, when the phase transformation or deformation of molten metals has happened, a certain regular elastic wave signals will be released. The characteristics of elastic wave signals will be different under the normal nugget nucleation and the abnormal nugget nucleation. Therefore, the elastic wave signals released during RSW process contain a

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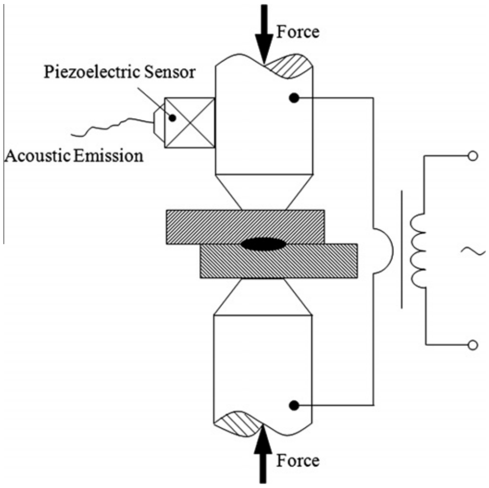

Fig. 1. Diagram of elastic wave signals sensing.

wealth of characteristic information about nugget nucleation and solidification.

The extraction and analysis techniques for characteristic signals of air-borne acoustic signals detected during RSW process were explored by Bu and Luo [10,11]. The characteristic signals containing the information of nugget nucleation can be detached from the noise signals and be used to analyze the quality of spot weld. Primoz and others investigated the estimation of the spot weld strength on the basis of the study of the sonic emission (SE) signals detected during the RSW on zinc coated steels [12], and concluded that the instrumentation required by sonic sound signals detecting is simpler and easier to use.

The SE signals can be detected by a microphone. Because there is no contact between sensor and electrode or workpiece, the air is used as the transmission medium. Therefore, there are some losses for the SE signals detected in RSW. Especially, the microphone is not able to detect the SE signals during solid–solid phase transformation and cracking [12]. Therefore, there has a certain of deficiency to study the nugget quality based on the SE signals.

The acoustic emission (AE) signals can be detected by the piezoelectric sensor mounted on the electrodes or workpiece, which is structure-borne sensing as shown in Fig. 1. Because the electrodes or workpiece are used as transmission medium, the losses of AE signals of nugget nucleation are less. The sensor is sensitive enough to detect the AE signals during solid–solid phase transformation and cracking.

This research analyzed the relationships between the characteristic parameters of structure-borne AE signals and the nugget quality for the study of the RSW.

2. Experiment detail

The materials used in experiment are 2024 aluminum alloy. The alloy plates have a thickness of 2 mm. The specification of samples is 25 mm × 100 mm. Two specimens are welded overlay by 25 mm lengths, as shown in Fig. 2. The resistance spot welding machine used in experiment is YR-A05CM2 AC device with a silicon controlled rectifier welding source. The materials of electrodes are Cu–Cr–Zr alloys, and the electrode tip geometry is circular truncated cone, the electrode diameter of flat tip is 8 mm. Specimens of 2024 aluminum alloy are processed by chemical cleaning and drying before welding experiment.

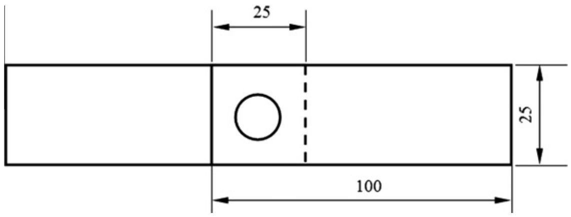

Fig. 2. Specimen specification.

The AE signals in welding process are monitored in real-time, where the piezoelectric sensor is mounted on the wall of electrode as shown in Fig. 1. The frequency bandwidth of the piezoelectric sensor is extended from 22 kHz to 220 kHz. The AE signals are transferred to the computer for further processing and analysis.

3. Results and discussions

3.1. Acoustic emission in resistance spot welding

Table 1 shows two sets of welding process parameters and Fig. 3 shows the nugget formation welded by the process parameters, which structure-borne acoustic emission signals in welding process are shown in Figs. 4 and 5, respectively. It can be found that the stage characteristics presented by the AE signals in welding process are distinguished, including the electrode loading event (arrow 1 in - Fig. 4), nugget nucleation event (arrow 2 in Fig. 4) and electrode unloading event (arrow 3 in Fig. 4). As the cracks are generated at the late of the solid–solid phase transformation, the cracking event is detected, which is indicated by the arrow 4 in Fig. 4 and the crack appearance is shown in the nugget formation of Fig. 3a. The expulsions are induced in welding process as the electrode pressure is increased to 0.28 MPa for the welding of Weld B sample. The expulsion event is indicated as arrow 5 in Fig. 5. The nugget nucleation event of Weld A indicated by arrow 2 presents a nugget nucleation process without expulsion, and the nugget nucleation event of Weld B indicated by arrow 5 presents a nugget nucleation process with expulsion.

The AE signals of further extractions of nugget nucleation event and cracking event are shown in Figs. 6 and 7, respectively. The characteristics of time domain and amplitude of AE signals in Figs. 6 and 7 are different, which

Table 1
Welding parameters.

No.	Welding current (I/A)	Current duration (T/s)	Electrode force (P/MPa)
Weld A	24,000	0.16	0.1
Weld B	24,000	0.16	0.28

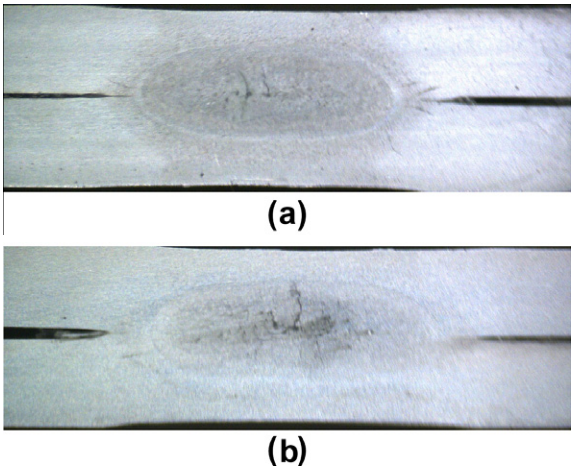

Fig. 3. Nugget formation of (a) Weld A and (b) Weld B in RSW on aluminum alloy.

indicates different energy release in characteristic events. Figs. 6a and 7a present the nugget nucleation events of AE signals. Obviously, the nugget nucleation event with expulsions of Weld B releases more energy than the nugget nucleation event without expulsions of Weld A, which indicates the different characteristics of nugget nucleation. Figs. 6b and 7b present the cracking events of AE signals. Similarly, two kinds of cracking event of AE signals present different characteristics of time domain and amplitude, which indicates the different energy release and the different cracking characteristics. It can be seen that the quality characteristics in nugget nucleation process can be monitored and studied by the analysis to AE signals detected in resistance spot welding.

We, therefore, can make clear from the above discussion that the energy characteristics of AE event in RSW process can be described by the characteristic parameters indicating the characteristics of time domain and amplitude, such as AE count and positive peak of AE event. This paper assesses the nugget quality and the effect of welding parameters to nugget nucleation by the index statistics of AE count and positive peak in nugget nucleation event.

3.2. Characteristic signal related to welding parameters

Fig. 8 shows the variation tendency of characteristic parameters of AE signals detected in RSW process as the welding current is set from 2000 A to 20,000 A, the current duration is set from 0.12 s to 0.20 s and the electrode pressure is 0.1 MPa. Fig. 8a presents the influence of welding current upon the AE count of nugget nucleation event and Fig. 8b presents the influence of welding current upon the positive peak of nugget nucleation event. It can be found that, when the welding current is below about 9000 A–10,000 A and the limited energy is imposed, the AE count and positive peak of nugget nucleation event are very low, which indicates that the energy release is also very low as there is no nugget nucleation in welding process. When the welding current increases above 9000 A–10,000 A, the nugget begins to form in the weld due to the larger energy imposed. At this point, the AE count and positive peak of nugget nucleation event have

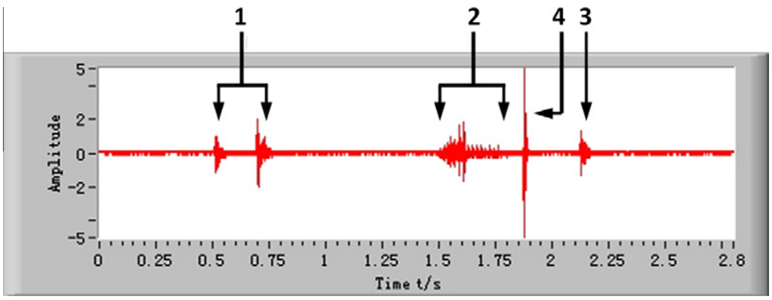

Fig. 4. AE signals of Weld A detected in RSW on aluminum alloy.

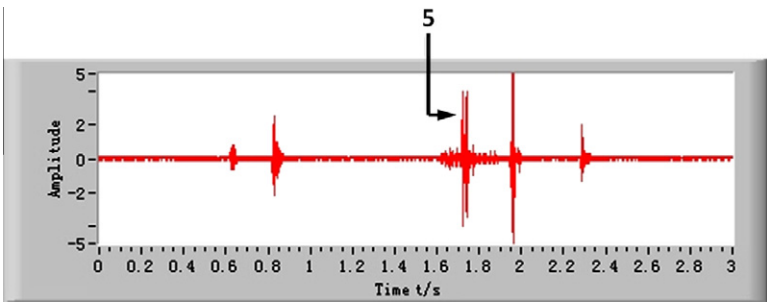

Fig. 5. AE signals of Weld B detected in RSW on aluminum alloy.

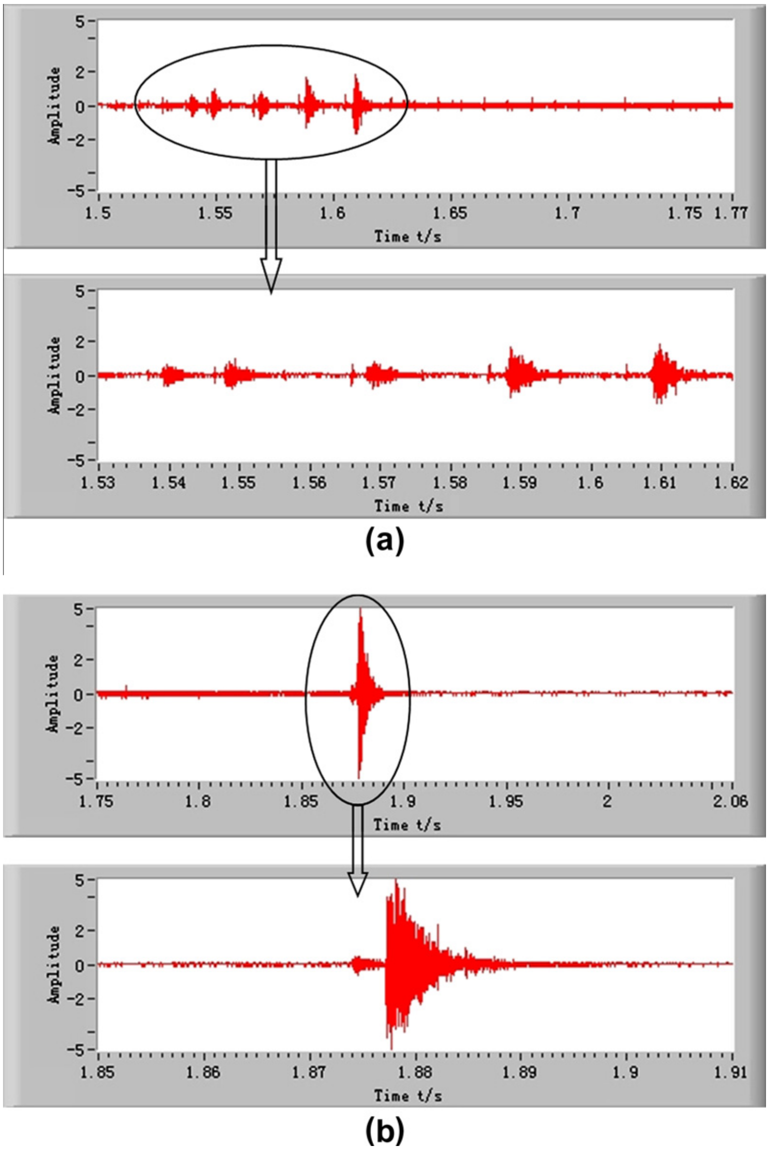

Fig. 6. AE signals of characteristic event in resistance spot welding on Weld A, (a) AE signals of nugget nucleation event and (b) AE signals of crack event.

a high level, which indicates that the energy release grows significantly as there is nugget nucleation in welding process and which is distinguished from the AE energy release with no nugget nucleation.

Fig. 9 shows the variation tendency of characteristic parameters of AE signals detected in RSW process as the current duration is set from 0.02 ms to 0.16 ms, the welding current is set from 10,000 A to 24,000 A and the electrode pressure is 0.1 MPa. Fig. 9a presents the influence of the current duration upon the AE count of nugget nucleation event and Fig. 9b presents the influence of the current duration upon the positive peak of nugget nucleation event. It can be found that, when the welding current is 10,000 A and the current duration is below 0.08 s, there is no nugget nucleation in welding process due to the limited welding energy imposed. At this point, the AE count and positive peak of nugget nucleation event are very low, which indicates that the energy release is also very low as there is no nugget nucleation in welding process. When the current duration increases above 0.08 s, the nugget begins to form in the weld. At this point, the AE count and positive peak of nugget nucleation event increase significantly, which indicates that the nugget nucleation is characterized with higher AE energy release. According to this regularity, the curves of AE count and positive peak variation of nugget nucleation event demonstrate the level of AE energy release in welding process. As the welding current is 12,000 A, the threshold value of the current duration is 0.04 s when the nugget begins to form. As the welding current is increased to 18,000 A or 24,000 A, the nugget nucleation begins to form earlier.

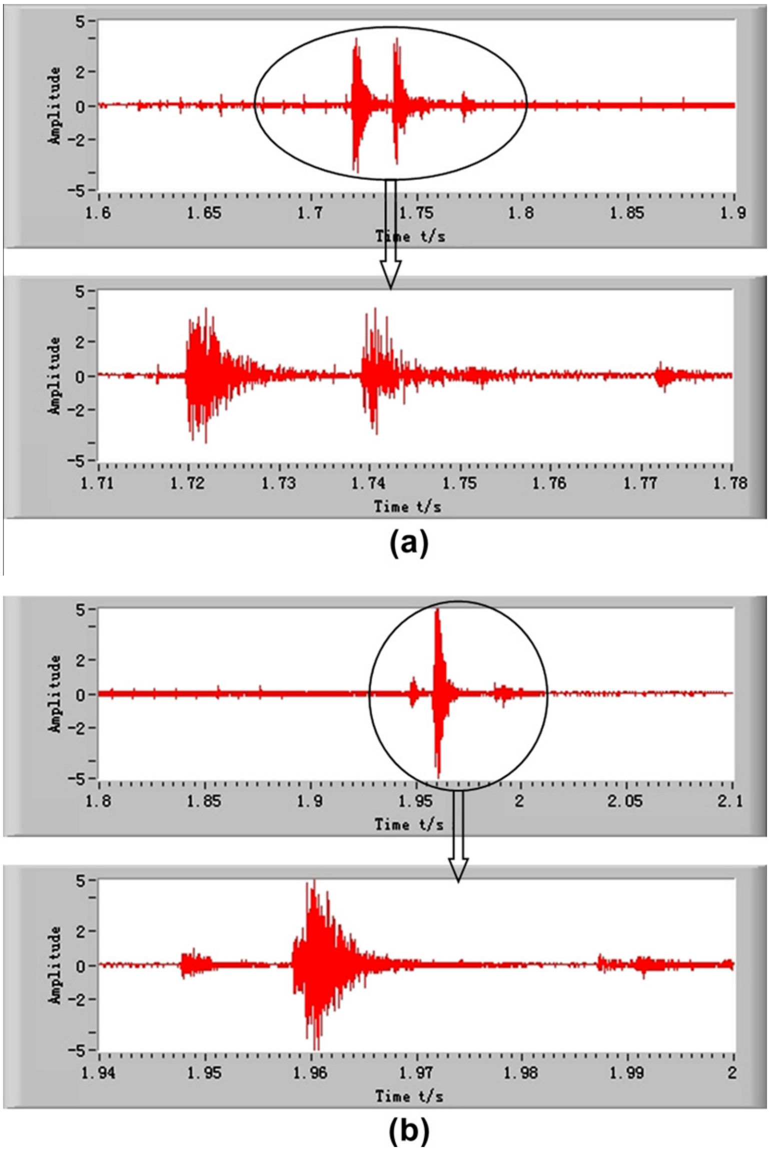

Fig. 7. AE signals of characteristic event in resistance spot welding on Weld B, (a) AE signals of nugget nucleation event and (b) AE signals of crack event.

Above regularity suggests that the effect of welding current and current duration variation to nugget nucleation can be characterized by the characteristic parameters of AE signals detected in resistance spot welding process.

3.3. Characteristic signal related to nugget quality

The above relationships between welding parameters and characteristics of AE signals show that, when there is a certain kind of change for the quality of RSW nugget during welding process, the AE energy released in welding process will change accordingly. Fig. 10 shows the relationships between the nugget diameter and the characteristic parameters of AE signals for corresponding nugget nucleation process under different welding processes. Fig. 10a shows the relationship between the nugget diameter and AE count, and Fig. 10b shows the relationship between the nugget diameter and positive peak of nugget nucleation event. Fig. 11 shows the relationships between the nugget penetration and the characteristic parameters of AE signals for corresponding nugget nucleation process under different welding processes. Fig. 11a shows the relationship between the nugget penetration and AE count, and Fig. 11b shows the relationship between the nugget penetration and positive peak of nugget nucleation event.

It can be found that, when the welding process change induces nugget dimension change in welding, the AE energy released in welding process will show corresponding diversification. The welding process produces larger nugget, the AE energy released in welding process is higher. This phenomenon is characterized as that the AE count and the positive peak of nugget nucleation event present

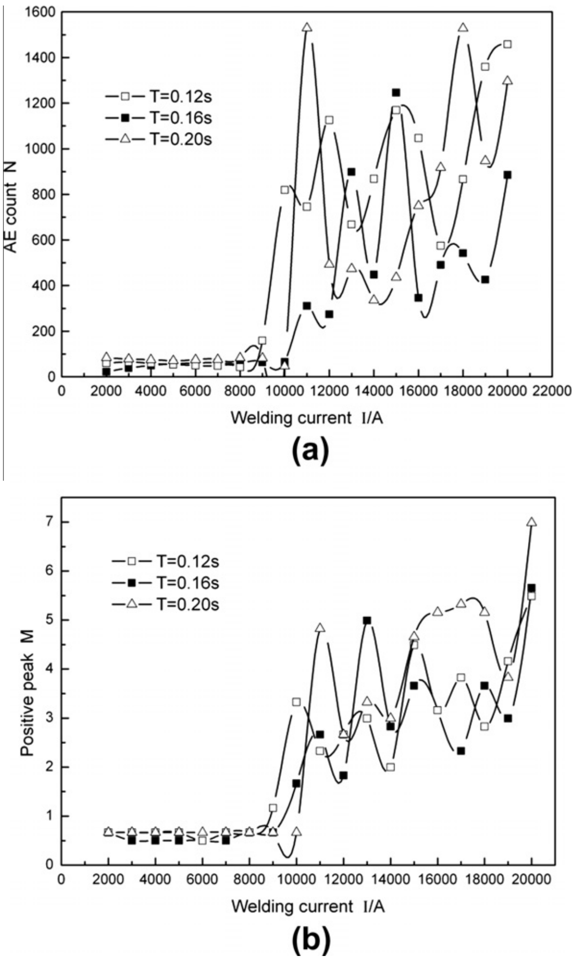

Fig. 8. The influence of welding current upon (a) AE count and (b) positive peak of characteristic parameters of AE in nugget nucleation event.

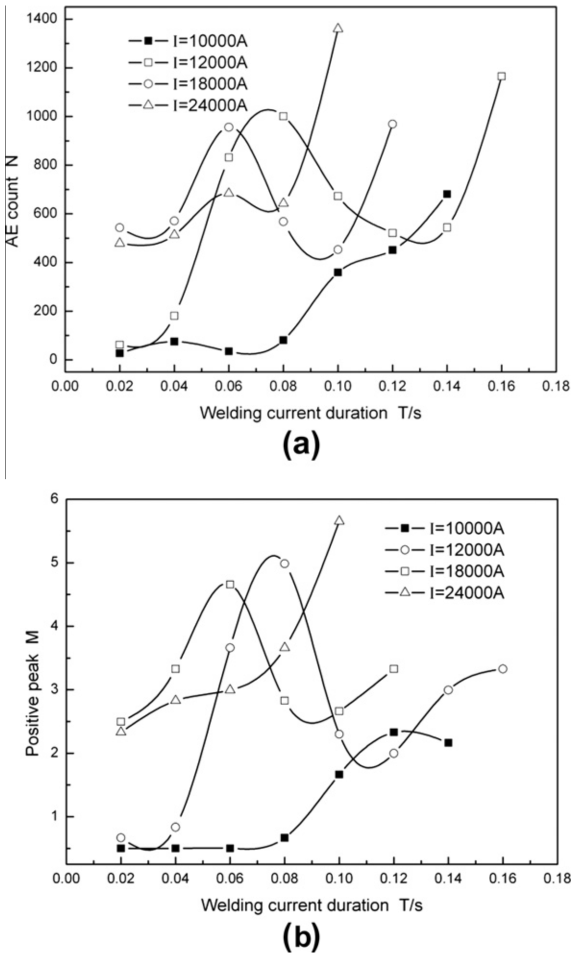

Fig. 9. The influence of current duration upon (a) AE count and (b) positive peak of characteristic parameters of AE in nugget nucleation event.

an upward trend with the increasing of nugget diameter and penetration in welding process. Therefore, the characteristic parameters of AE signals and the nugget dimension have a better relevance.

In general, the nugget dimension can determine to a large extent the spot weld strength. In Figs. 10 and 11, the relationships of the nugget dimension and the characteristic parameters of AE signals present a nearly positive correlation. However, the spot weld strength does not depend entirely on the nugget dimension due to the microstructure, expulsions and defects. Because of the above factors, the relationships of tensile-shear strength of weld and characteristic parameters of AE signals present a nonlinear correlation. Fig. 12 shows the relationships of the tensile-shear strength of weld and the AE characteristic parameters, including the AE count (Fig. 12a) and the positive peak (Fig. 12b) of AE signals. It can be found that the data in Fig. 12a can be fitted using the following logarithm equation

$$y = \ln(a + bx) \tag{1}$$

where the parameters a and b can be calculated separately by fitting method. The data in Fig. 12b can be fitted using the following polynomial equation

$$y = A + Bx + Cx^2 \tag{2}$$

where the parameters A, B and C can also be calculated separately by fitting method. The positive peak of AE nugget nucleation event is susceptible to the expulsion effect. When the expulsion happens in welding processes, the positive peak will significantly increase as the energy released with expulsion grows. The expulsion induces a certain losses of molten metal in nugget during melting, which will restrain the nugget nucleation dimension and reduce the tensile-shear strength of weld. Therefore, the relationships of the positive peaks of the expulsion welds shown in Fig. 12b and the tensile-shear strength of welds are deviated from the fitted curve of polynomial function described in Fig. 12b.

It is clear that these functions can be used to measure and predict the quality of spot weld such as tensile-shear strength of weld on the basis of statistical analysis and fitting analysis to large amounts of experimental data. Therefore, the characteristic parameters including AE count and positive peak of AE nugget nucleation event in welding are adequate for the assessment of tensile-shear strength of weld. Of course, it can be found from the above discussion

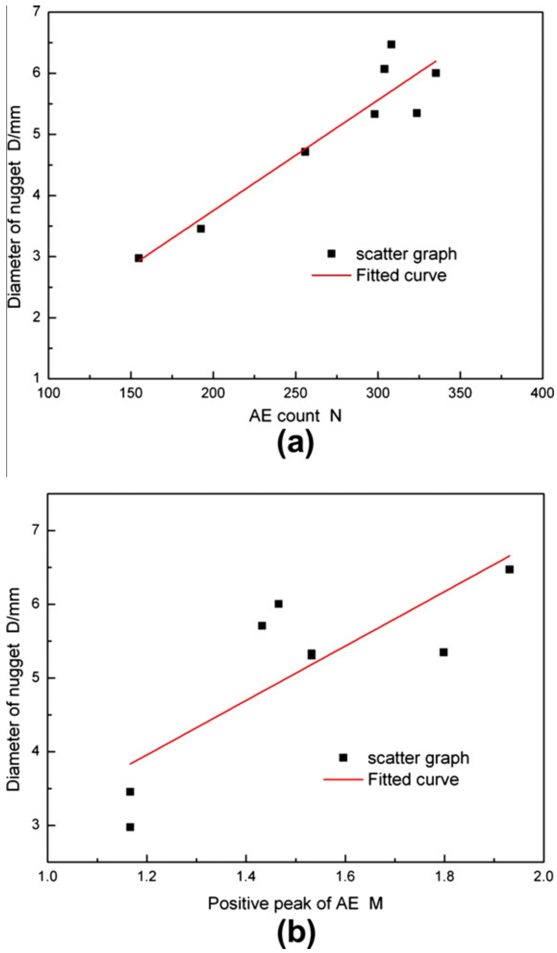

Fig. 10. Relationships between the nugget diameter and characteristic parameters of AE signals, (a) AE count and (b) positive peak.

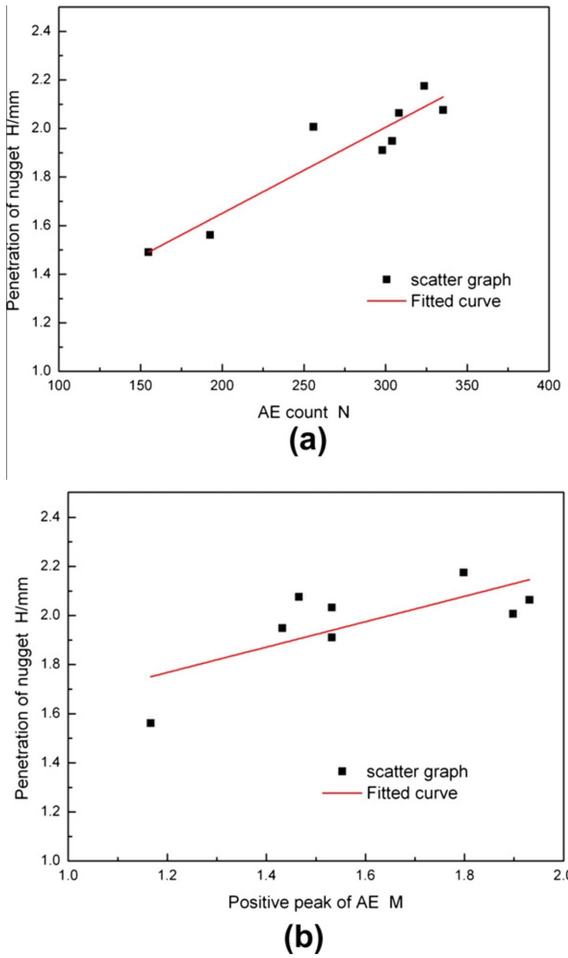

Fig. 11. Relationships between the nugget penetration and characteristic parameters of AE signals, (a) AE count and (b) positive peak.

that the AE count of AE nugget nucleation event used to assess the tensile-shear strength of weld is relatively stable, and which assessment by positive peak of AE nugget nucleation event is more sensitive to the expulsion.

4. Conclusions

(1) The physical phases of nugget nucleation in resistance spot welding process can be characterized by the structure-borne AE signals. The expulsion event and cracking event in resistance spot welding can be distinguished by the characteristic parameters such as AE count and positive peak of AE signals detected in welding process.

(2) The effect of welding current and current duration variation to nugget nucleation can be characterized by the characteristic parameters of AE signals detected in resistance spot welding process. The energy release grows significantly as there is nugget nucleation in welding process, but the energy release is very low as there is no nugget nucleation in welding process, which can be characterized by the characteristic parameters of AE signals detected in resistance spot welding process. That is the characteristic parameters such as AE count and positive peak of AE nugget nucleation as there is nugget nucleation are higher than that as there is no nugget nucleation in welding process.

(3) The characteristic parameters of AE signals show a better relevance to the nugget dimension and tensile-shear strength of weld. Preliminary results indicate that, as the nugget diameter and penetration increase in welding process, the AE count and positive peak of AE nugget nucleation event detected in welding process will increase. The relationship of tensile-shear strength of weld and AE count is more in line with the logarithm equation, and the relationship of tensile-shear strength of weld and positive peak of AE signals is more in line with the polynomial equation. The positive peak of AE nugget nucleation event is susceptible to the expulsion effect, which will cause the relationship of the positive peaks of the expulsion welds and the tensile-shear strength of welds to deviate from the

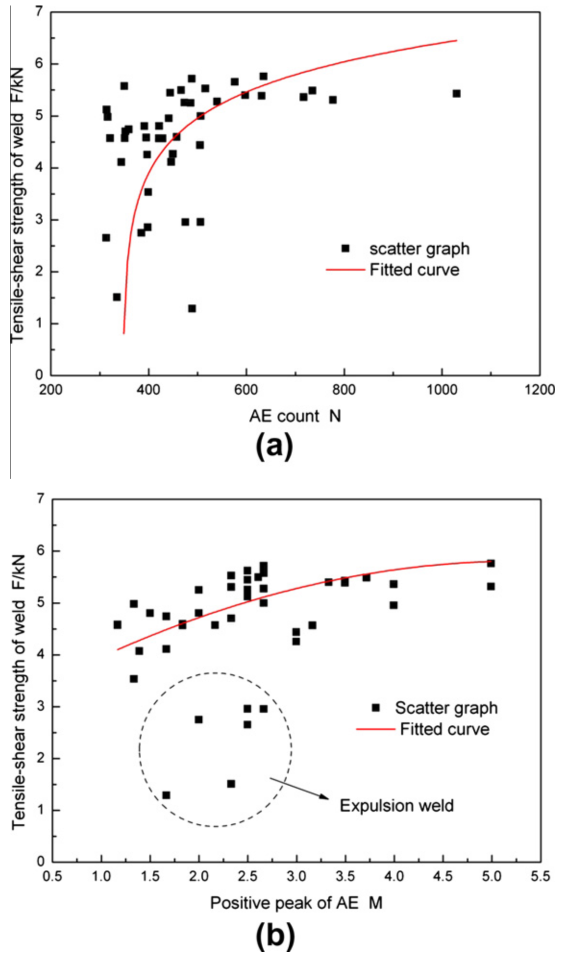

Fig. 12. Relationships between the tensile-shear strength of weld and characteristic parameters of AE signals, (a) AE count and (b) positive peak.

relationship of polynomial function. These functions can be used as one of the methods for assessment of the tensile-shear strength of weld. The AE count of AE nugget nucleation event used to assess the tensile-shear strength of weld is relatively stable, and which assessment by positive peak of AE nugget nucleation event is more sensitive to the expulsion.

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