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Diagnostics of aluminum alloys with friction stir welded joints based on multivariate analysis of acoustic emission signals

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Abstract. The acoustic emission method was applied to study aluminum-magnesium alloys produced by friction stir welding. Alloy specimens were tested under static tension with simultaneous recording of acoustic emission, applied load, and elongation. The recorded acoustic emission signals were processed using projection methods of multivariate data analysis; the informative features used were the coefficients of wavelet discrete decomposition which characterize the low-frequency form of the signal. It is shown that the proposed approach allows the partition of signals formed on different stages of plastic deformation and fracture. Strong differences in acoustic emission signals were revealed and described to be due to the formation of highly defect structure in the weld zones in different welding modes. The obtained results can be useful for acoustic emission diagnostics of welded joints in structures of metal alloys exposed to external loads.

1. Introduction

Aluminum alloys are popular structural materials for aircraft and automotive applications. Often the manufacturing of various aluminum alloy components implies the use of welding technologies. The manufactured components exhibit highly inhomogeneous structure in weld zones that contain a great number of various defects [1, 2]. The action of external mechanical fields arising in operating components gives rise to the generation of cracks near these defects and thus causes premature fracture. This imposes stricter requirements on the diagnostics of structure and strength properties. Along with such conventional diagnostic methods as eddy current, X-ray and ultrasonic methods [3], the acoustic emission method has certain advantages [4]. This method is based on the identification of acoustic emission characteristics at local rearrangement of internal structure during material deformation.

The measured acoustic emission characteristics are determined by physical emission sources whose action depends on particular mechanisms of plastic deformation and fracture. In the case of materials with highly inhomogeneous structure, the detected acoustic emission signals are simultaneously contributed to from different competing sources and mechanisms [5, 6]. This makes difficult to reveal deformation processes and accompanying structural changes in the material, thus reducing the reliability and efficiency of acoustic emission diagnostics.

The above drawbacks are eliminated by applying different mathematical processing methods of energy and frequency characteristics of acoustic emission signals. In this paper, in order to find the relationship between the physical processes occurring in the loaded material and detected signals, we put forward an approach that uses projection methods of multivariate data analysis in combination with the apparatus of wavelet decomposition. Specimens for investigation are made of aluminum-magnesium alloys and contain welded joints produced in different technological modes.



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2. Materials and experimental procedure

The material for investigation was aluminum-magnesium alloy AlMg5M. An effective technique for joining structural elements made of this alloy is friction stir welding (FSW) [7], which was used in this paper to produce welded joints. FSW gives rise to high temperature and strain gradients that make the structure highly inhomogeneous and lead to the formation of various defects (voids, microcracks, foreign inclusions, etc.) in the weld zone.

The possibilities of the proposed approach were studied by using different welding modes. In the main mode that provided a permanent joint the tool rotation speed was 560 rpm, the downwards force applied to the joined elements was 2600 kg, and the travel speed of the rotating tool was 500 mm/min (mode 1). In the modes with deviations to form a defect structure in welded joints the welding parameters were respectively 560 rpm, 2600 kg, 700 mm/min(mode 2) and 560 rpm, 2100 kg, 500 mm/min (mode 3).The technological mode parameters are given in the table 1.

Table 1. Technological parameters.			
Welding mode	Tool rotation speed, rpm	Downwards force applied to joined elements, kg	Tool travel speed, mm/min
1	560	2600	500
2	560	2600	700
3	560	2100	500

The specimens were shaped as standard specimens for static tension tests, with a length of 160 mm, thickness of 5 mm, and gage part measured 50 x 15 mm. The welded joint was located in the middle of the gage part. The weld microstructure was examined by analyzing metallographic sections cut across the welded joint. A typical micrograph of the weld cross section at a depth of 2 mm from the weld face is shown in figure 1 by the example of a specimen produced in mode 2. Figure 1 clearly demonstrates large void defects penetrating though the weld thickness. The voids are the sources of increased concentration of elastic stresses that arise under specimen loading and relax through microcracking. On the stages of high plastic deformation and fracture it is the crack increments in the weld zone that are the main sources of acoustic emission signals.



Figure 1. Microstructure of weld cross section.

The tensile testing of specimens was carried out on a mechanical testing machine at a constant strain rate. The applied load value and the strain magnitude were determined during loading and then used to calculate strain hardening curves in the "stress σ – strain ϵ " coordinates. The deformation behavior features were quantitatively described by calculating the strain hardening coefficients K:

$$\mathbf{K} = \mathbf{d}\boldsymbol{\sigma}/\mathbf{d}\boldsymbol{\varepsilon} \tag{1}$$

that characterize the slope of different portions of the loading curve. The shape of this curve allowed clear definition of several stages in the plastic deformation domain of all studied specimens which corresponded to portions with different values of the coefficient K. For mode 1 these values were K=9.3x10³ kN/m² (stage A), K =2.3x10³ kN/m² (stage B), and K =0.63x10³ kN/m² (stage C). According to metallographic analysis, a system of microcracks is initiated on stage C. The plastic deformation stages A, Band Cwere followed by a rapid fracture stage D characterized by rapid propagation of main cracks.

The major characteristics for describing acoustic emission were the values of acoustic emission voltage. The detected signals were recorded using an automatic recording system at a sampling frequency

of 2.5 MHz simultaneously with the measurement of mechanical values. The measured acoustic emission was characterized by a continuous spectrum and abrupt signal amplitude change in transition from one loading stage to another.

3. Analysis method of acoustic emission characteristics

Conventional analysis methods of acoustic emission signals are based on acoustic emission pulse count and determination of the amplitude or frequency spectra [8–10]. They fail to reveal the quantitative relation between current deformation processes and the characteristics of the acoustic emission signal induced by these processes. In view of the above said, we used an approach based on the processing of detected signals by multivariate data analysis methods [11]. This approach is implemented using an algorithm depicted in figure 2 which includes the following stages.

On the first stage, the strain interval from the starting point of loading ($\varepsilon = 0$) to specimen separation into two parts was divided into intervals equal to a loading step in experiment. Each of these intervals corresponded to its own reference block of a signal extracted from the entire detected signal and corresponding to a certain portion in the strain hardening curve. A set of characteristics of each block forms a so-called feature vector that describes initial experimental data. For a successful application of multivariate analysis methods, the choice of the feature vector is crucial.

The features that would adequately describe the frequency characteristics of an acoustic emission signal were extracted from the signal using various processing techniques, first of all, the ones based on the Fourier transform, Hilbert–Huang transform, and wavelet transform [12–14]. It should be taken into account that the detected signals reflect not only acoustic emission processes but also various distortions arising due to the propagation of elastic vibrations in the specimen and due to high-frequency resonance vibrations of the piezoelectric detector, noises of the experimental equipment, and random processes of different origin. In this connection, we obtained feature vectors using the apparatus of multilevel discrete wavelet transform. The discrete wavelet transform is a frequency processing technique based on simultaneous signal filtering by a low- and high-frequency filters constructed on the basis of a given wavelet function:

$$y_{l}[n] = \sum_{k=-\infty}^{\infty} X[k]g[n-k],$$

$$y_{h}[n] = \sum_{k=-\infty}^{\infty} X[k]h[n-k].$$
(2)

Here, y_l and y_h are the coefficients of multilevel wavelet decomposition for a low- and high-frequency filter, respectively; g and h are the gains of the low- and high-frequency filters; X is the processed discrete signal; and k is the index defining the discrete signal value.

The direct construction of feature vectors included two stages. On the first stage, the coefficients y_l were determined which characterize the low-frequency form of the signal, and thus random high-frequency components were suppressed. In the calculations we applied 9-level discrete wavelet decomposition to individual blocks, into which the experimental signal was divided, using the Daubechies wavelet functions [15]. On the second stage, the Hilbert transform was applied to the wavelet decomposition coefficients to exclude the influence of resonance vibrations of the piezoelectric detector. The Hilbert transform is based on filtering the discrete signal X(k) which yields the values of $X_g(k)$ with the initial amplitude and phase displaced by 90⁰. The instantaneous amplitude change can be represented as:

$$E(k) = \sqrt{X^{2}(k) + X_{g}^{2}(k)}, \qquad (3)$$

where the values of E(k) present the envelop of the source signal. Arrays of these values were used as feature vectors in further processing.

Hidden regularities in the experimental data were revealed using principal component analysis [16]. According to this method, the signal characteristics calculated for individual blocks by successive application of wavelet and Hilbert transforms were considered as points of a multidimensional space. The regularities were revealed by transition to a coordinate system that allowed reducing the dimension of the initial space and was constructed so that its first axis (component PC1) was oriented in the direction of the maximum scatter of experimental points and the second axis (component PC2) was directed along the

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scatter of points next to the maximum value, and so on. The obtained data were represented in the form of matrices whose lines were the numbers of the signal blocks and the columns were the corresponding feature vectors. The generated matrices were then clustered. The calculation results were represented as projections of multivariate data on the principal component plane. Each point on the obtained projection corresponded to one signal block; blocks with close properties formed clusters of closely spaced points.



Figure 2. Processing algorithm of an acoustic emission signal.

4. Results and Discussion

The discussed approach has been applied to analyze acoustic emission signals detected under tension of aluminum-magnesium alloy specimens with welded joints. The typical calculation results that describe the entire test period from the beginning of tension to specimen separation into parts are displayed in figure 3 on the plane of two first principal components. Scatter plots for modes 1, 2 and 3 are provided in figure 3(a), 3(b) and 3(c), respectively. Each point in figure 3 denotes the frequency characteristics of one signal block of length ~ 0.4 s extracted from the whole acoustic emission signal and reflecting the deformation processes on the corresponding loading curve portion.

As we can see from figure 3, all points are clearly divided into two clusters: a group of almost overlapping points 1 referring to the long period of plastic deformation (stages A, B, C), and a group of highly scattered several points 2 describing the rapidly developing process of fracture (stage D).

The large scatter of points 2 is due to the fact that instantaneous values of the signal detected on the fracture stage increased, which leaded to the growth of the wavelet decomposition coefficients. The position of the point clusters in figures 3(a)–(c) is indicative of significant differences in the characteristics of the acoustic emission signal on different loading stages. The differences are due to the change of the dominating acoustic emission sources. These are evidently the dislocation fluxes on the plastic deformation stages which escape to the surface and internal interfaces, while on the fracture stage these are the incremental growth of rapidly propagating main cracks [7].

Of particular importance in diagnostics is to reveal processes occurring prior to fracture, i.e., on the plastic deformation stages. To do this, the proposed approach was applied to analyze the part of the acoustic emission signal which was detected in the plastic deformation domain. This implied the processing of the acoustic emission signal detected on stages A, B, C and formed the first cluster in figure 3 by the principal component method.

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Figure 3. Projections of acoustic emission signal characteristics on the plane of the first principal components under tension of aluminum-magnesium alloys with a welded joint: (a) – mode 1, (b) – mode 2, (c) – mode 3; 1 – plastic deformation stages A, B, C; 2 – fracture stage D.

The obtained typical results are given for three welding modes in figure 4.

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Figure 4. Projections of acoustic emission signal characteristics on the plane of the first principal components under tension of aluminum-magnesium alloys with a welded joint in the plastic deformation region: (a) – mode 1, (b) – mode 2, (c) – mode 3; 1 – stage A, 2 – stage B, 3 – stage C.

As it is seen from figure 4, the points for all modes are divided into three clusters each of which describes one of the three plastic deformation stages A, B and C. A distinctive feature in figure 4(a) corresponding to mode 1 with permanent welded joint is that the points of these three clusters almost do not overlap. This means that different dominating acoustic emission sources act on stages A, B and C,

which reflects the change of dominating plastic deformation mechanisms with the load increase. In figures 4(b) and 4(c), the groups of points describing signals on different stages are highly overlapping. This view of clusters indicates that several different acoustic emission sources act simultaneously, without domination of a certain source in transition from one stage to another for specimens with welded joints with defects. This is related to the fact that at a large number of various defects in the weld zone (microvoids, microcracks, etc.) plastic deformation occurs due to a simultaneous contribution of several competing mechanisms. Additionally, the less number of points in figures 4(b) and 4(c) is indicative of shorter plastic deformation stages with earlier cracking and fracture.

5. Conclusion

The paper discussed a method of acoustic emission diagnostics of materials in the conditions of static deformation. The diagnostics is based on the processing of detected acoustic emission signals using the principle component method; the informative features used were the coefficients of discrete wavelet decomposition of the signal. The applied processing method allowed establishing a relationship between detected acoustic emission signals and features of plastic deformation and fracture on different loading stages. It was shown by the example of aluminum-magnesium alloys with friction stir welded joints that the proposed approach enables accurate diagnostics of occurring deformation processes and control over structural defects nucleated in different welding modes.

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