Application of acoustic emission and laser optoacoustics at various stages of defect formation during friction stir welding

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Abstract. This paper covers basic aspects of laser ultrasound and acoustic emission non-destructive testing methods in application of monitoring friction stir welds during its deformation and fracture. Stress-strain curves for such welds were obtained and the mechanical characteristics of welded joints of aluminum-magnesium alloy were determined. Using acoustic elastic effect levels of mechanical stresses were measured. Signals of acoustic emission, stimulated by one-axis loading, were registered and analyzed. It was established that acoustic emission during deformation and fracture of samples of welded joints is associated with the course of the process of plastic flow of the material. The nature of the distribution of acoustic emission parameters in the destruction of welded joints with defects has distinctive features. In conditions of one axis quasi static loading rate event count acoustic emission is the most informative parameter.

1. Introduction
Friction stir welding (FSW) is widely introduced among different industries because of high technological and constructional requirements for products. This technology is effectively applied in aircraft, rocket production and shipbuilding [1].

One of the main reasons for defect formation during FSW is the difference between real and required values of technological welding parameters. This difference may cause significant decrease in quality of final welds and, therefore, whole products [1]. Thereby, active multiparameter control of welding process is needed to obtain desired quality of welded joints.

The purpose of the presented research is an assessment of acoustic emission (AE) method for defect formation control during the process of aluminum alloys FSW.

The behavior of butt welded aluminum-magnesium alloy joints during the elastic and plastic deformation was investigated for development of acoustic emission control principles for FSW control in situ. The investigation revealed specific features of acoustic emission parameters which appeared during the tensile test of joints’ specimens.

The method of laser optoacoustics was used for actual stress measurement in the area of weld root in specimens with different structure of joints.

2. Description of work
2.1. Materials
Specimens were made of butt welded joints produced by FSW. Material of specimens was high strength aluminium magnesium alloy. Specimens No. 1, No. 2 had the same geometry but was made of base material (without weld). Specimens Nos. 3 A, 4A, 6A, 9Ad, 10 Ad were joints with weld in
the middle part (figure 1). Joints in specimens No. 9Ad and No. 10Ad were made from joints which were produced with welding process parameters deviated from optimal ones. Geometric characteristics of these specimens are presented in table 1.

![Drafts of specimen](image)

**Figure 1.** Drafts of specimen: (a) - Nos. 1, 2 (base metal); (b) - Nos. 3A, 4A, 6A, 9Ad, 10Ad (weld joint).

| No. | Initial thickness, \(a_0\) (mm) | Initial width, \(b_0\) (mm) | Gauge length, \(l\) (mm) | Initial cross-sectional area, \(F_0\) (mm\(^2\)) | Alloy |
|-----|-------------------------------|-----------------------------|---------------------------|---------------------------------|-------|
| 1   | 7.4±0.2                       | 20.0±0.2                    | 50.0±0.2                  | 148.0±0.4                       |       |
| 2   | 7.4±0.2                       | 20.0±0.2                    | 50.0±0.2                  | 148.0±0.4                       |       |
| 3A  | 7.4±0.2                       | 19.5±0.2                    | 50.0±0.2                  | 144.3±0.4                       | AMg6  |
| 4A  | 7.4±0.2                       | 20.0±0.2                    | 50.0±0.2                  | 148.0±0.4                       |       |
| 6A  | 7.4±0.2                       | 19.8±0.2                    | 50.0±0.2                  | 146.5±0.4                       |       |
| 9Ad | 7.4±0.2                       | 19.9±0.2                    | 50.0±0.2                  | 147.3±0.4                       |       |
| 10Ad| 7.4±0.2                       | 20.0±0.2                    | 50.0±0.2                  | 148.0±0.4                       |       |

2.2. Stress measurement using laser ultrasound method
Measurements were carried out with use of acoustoelastic effect. Ultrasound waves were generated thermoelastically by laser ultrasound method. This method provides an opportunity to generate nanosecond length waves [2]. The informative parameter for stress measurement in metal constructions is the speed of longitudinal subsurface wave (LSW) [3].

Generation and receiving of LSW are provided by dual element transducer. Acoustic contact is obtained with additional pressing through the thin layer of contact fluid between a transducer and specimens.

2.3. Acoustic emission during uniaxial tension specimen testing
Acoustic emission data were recorded under static loading of specimen. Static uniaxial tensile tests were performed with a constant loading rate of 0.2 kN·s\(^{-1}\) at a temperature of +23 °C. Analyzed Informative AE parameters: count event \(N_S\), rate event count \(N'_S\), AE signal rise time \(\Delta t\). These parameters were compared with the level of the applied load \(P\) and the relative deformation \(\varepsilon\). AE was recorded by piezoelectric acoustic emission transducers (AET) with a passband of 100-700 kHz. The
AE signals received by AET were amplified with a 40 dB preamplifier. Elements of the test bench are shown in figure 2.

![Figure 2](image.png)

**Figure 2.** Elements of the test bench: (a) – apparatus for uniaxial tension; (b) – placement of the laser-ultrasonic transducer on the specimen; (c) – placement of the AET.

### 3. Results & discussion

#### 3.1. Results of stress measurements

Before the actual measurement it was necessary to perform graduation of measuring tools to get the value of acoustoelastic coefficient $K_\nu$ which is specific for concrete material, alloy or group of alloys. This coefficient allows to estimate mechanical stresses using the measured LSW speed. Calculation of $K_\nu$ was made according to equation [3]:

$$ K_\nu = \sigma \frac{\nu}{\nu - \nu_0}, $$

where $\sigma$ – mechanical stress in a specimen (according to actual loading), MPa; $K_\nu$ – coefficient of acoustoelasticity of the specimen material, kg·m$^{-1}$·s$^{-2}$; $\nu$ – speed of head subsurface ultrasound wave in specimen material during the loading, m·s$^{-1}$; $\nu_0$ – speed of head subsurface ultrasound wave in specimen material without the loading (zero actual stress), m·s$^{-1}$.

To derive graduation characteristics $\nu_0$ and $\nu_0$ were measured. After that, the value of $K_\nu$ was calculated using specimens No. 1 and No. 6A. The speed was measured according to the scheme (figure 3).

The graduation characteristics (figure 4) here is the linear approximation of measured speed-stress pairs of values on chosen levels of stresses. The average value of $K_\nu$ is based on results of two loading cases – unloading in the elastic area of specimen No 1 and loading in the elastic area of specimen No 6A.

![Figure 3](image.png)

**Figure 3.** The scheme of measurements of the velocity of propagation of the head ultrasound (1 – specimen; 2 – measurement area at the root of the weld, 3 – transducer; $b$ – base length of the transducer).

According to the measurement results, $K_\nu$ was calculated and the graduation characteristic of the dependence of the stresses $\sigma$ on the velocity $\nu$ was built. The average value of the coefficient $K_\nu$ was calculated from the results of two loading cycles – unloading in the region of elastic deformations of
specimen No. 1 and under load in the region of elastic deformations of specimen No. 6A. Figure 4 shows the results of the calibration performed on samples No. 1 and No. 6A.

Using the obtained coefficient $K_\nu$, stresses $\sigma$ were measured in specimens with joints during the loading (table 2, figure 5).

The relative error $\Delta \sigma$ of the measurement result $\sigma$ was determined by the equation (2):

$$\Delta \sigma = \frac{\Delta \sigma}{\bar{\sigma}} \cdot 100\%,$$

where $\Delta \sigma$ – absolute error of the result of measurement $\sigma$, MPa.

![Figure 4. Graduation characteristic for aluminium-magnesium alloy.](image)

The true value of $\sigma_p$ was taken as the calculated value of the stresses in the cross section of the specimen, defined as the ratio of the applied load $P$ to the cross-sectional area $F_0$.

**Table 2. Results of stress measurements in specimens.**

| Load | Specimen No. 6A | Specimen No. 9Ad |
|------|-----------------|------------------|
| $P$ (kN) | $\sigma_p$ (MPa) | $\sigma$ (MPa) | $\Delta \sigma$ (%) | $\sigma$ (MPa) | $\Delta \sigma$ (%) | $\sigma$ (MPa) | $\Delta \sigma$ (%) |
| 0.0  | 0               | 0               | 0                | 0              | 0               | 0              | 0               |
| 2.8  | 20              | 18              | 10               | 6              | 72              | 26             | 30              |
| 5.6  | 40              | 40              | 1                | 24             | 41              | 39             | 2               |
| 8.4  | 60              | 61              | 2                | 49             | 19              | 61             | 1               |
| 11.2 | 80              | 86              | 8                | 67             | 16              | 78             | 3               |
| 14.0 | 100             | 104             | 4                | 93             | 7               | 97             | 3               |
| 16.8 | 120             | 126             | 5                | 107            | 11              | 121            | 1               |
| 19.6 | 140             | 148             | 5                | 139            | 1               | 141            | 1               |
| 22.4 | 160             | 165             | 3                | 142            | 11              | 158            | 1               |
| 25.2 | 180             | 187             | 4                | 173            | 4               | 170            | 5               |
| 28.0 | 200             | 209             | 4                | 233            | 17              | 191            | 1               |

As a result of comparison of applied and measured stresses, the relative measurement error on specimen No. 6A did not exceed 10%. The convergence of the results suggests that the stress distribution in the root region and the heat-affected zone of the welded joint of sample No. 6A under the action of tensile forces occurs similarly to the development of the base metal stresses, and the effective stresses in the heat-affected zone are zero.
This fact allows us to conclude that the stress-strain state of the joints made by FSW changes under the action of operating loads in the same way as in the base metal. This conclusion is valid for products from aluminum alloys, physically justified by the fact that the maximum temperature in the welding area is lower than the melting point of material. It reduces welding stresses and makes it possible to create joints of equal strength.

An applied load corresponding to a stress of $\sigma = 200$ MPa led to the occurrence of microplastic deformations in the root region of the weld of sample No. 9Ad. This can be seen in the non-linear part of the diagram (figure 5) with load 1 of specimen No. 9Ad.

The magnitude of the errors at the stages of loading-unloading of sample No. 9Ad allow to conclude about the change in the nature of the stress-strain state in the measurement zone of the welded joint, made with the deviation of the welding parameters.

Figure 5. Stress-speed curves for specimen alloy (9Ad-1 – loading, 9Ad-2 – unloading).

3.2. The results of uniaxial static tensile tests

The structure of FSW joints has a number of characteristic features. In the center of the weld (core), ultrafine grains are formed, the formation of which is the result of dynamic or collective dynamic polygonization. The core structure is called the onion ring because of its ring-shaped structure (figure 6 (a) (4)). The zone of thermomechanical influence (TMAZ) (figure 6 (a) (1)) is intermediate between the zone of thermal influence (TAZ) (figure 6 (a) (2)) and the core and represents the transition from one type of structure to another – from a grain textured structure base metal (figure 6 (a) (3)) to the layered structure of the central part of the weld [4, 5].

In FSW joints specimens, the plane of destruction was perpendicular to the layers of friction formed by the sliding shoulder of the welding tool on the surface.

In the tensile test of specimen of welded joints, it was noted that the destruction of samples Nos. 3A, 4A, 6A occurred in two stages. The primary crack was formed from the root of the seam, then the destruction occurred along the border between TMAZ and HAZ (figure 6) and ended with a break in the upper part of the welded joint. In the lower part, the seam is less durable due to insufficient mixing of the metal, due to the increased heat sink to the welding substrate, which reduces ductility.

The destruction of specimens No. 9Ad and No. 10 Ad took place differently. The failure of specimen No. 9Ad and No. 10 Ad occurred according to the weld material. Macrocrack originated at the root of the welded joint in the core zone. The fracture surface is visually divided into two parts - zone I with a rough relief characteristic of static destruction of ultrafine materials, and upper zone II with a dimpled relief similar to secondary fracture (figure 6) [5].
Figure 6. Specimens after tests: (a) – structure zones (1 - TMAZ; 2 – HAZ; 3 – base metal; 4 – weld core; 5 – direction of a tool spin; 6 – direction of weld); (b), (c) – specimens after tests.

The destruction of specimens No. 9Ad and No. 10 Ad took place differently. The failure of specimen No. 9Ad and No. 10 Ad occurred according to the weld material. Macrocrack originated at the root of the welded joint in the core zone. The fracture surface is visually divided into two parts - zone I with a rough relief characteristic of static destruction of ultrafine materials, and upper zone II with a dimpled relief similar to secondary fracture (figure 6) [5].

The destruction of the core of the weld is not typical for the conditions of tensile tests. This circumstance is due to the presence of defects in the structure of the welded joint. The nature of the fracture qualitatively reflected the original structural state of the welded joint. The results of static tests on uniaxial loading are shown in table 3.

| No. specimen | Strain, εmax (%) | Average strain, εmax (%) | Ultimate strength, σuts (MPa) | Reducing of strength, Δσuts (%) |
|--------------|-----------------|--------------------------|-------------------------------|-------------------------------|
| 1            | 16.2            | 16.4                     | 398                           |                               |
| 2            | 16.6            | 16.4                     | 380                           |                               |
| 3A           | 17.8            |                          | 363                           |                               |
| 4A           | 17.5            | 17.4                     | 354                           |                               |
| 6A           | 17.0            |                          | 356                           |                               |
| 9Ad          | 14.5            | 12.3                     | 337                           | 13.5                          |
| 10Ad         | 10.1            |                          | 341                           | 12.3                          |

The results of uniaxial tensile tests are shown in figure 7.

Figure 7. Stress-strain curves: (a) – base metal and welded joint without defects; (b) – welded joints with defects.
The modulus of elasticity of tested welded joints differs by no more than 2-3%, while the modulus of elasticity of the base metal is greater than the elastic modulus of welded joints by 5-7%, which is explained by the greater ductility of the weld material due to the grinding of polycrystals of the material during welding.

The reduced ductility and strength of specimen No. 10Ad is associated with the presence of an angular displacement type defect [6]. During loading, both tensile stresses and bending stresses occurred in the specimen, caused by the pressure of the grippers of the testing machine on the fixed parts of the sample.

The reduced ductility and strength of sample No. 9Ad is explained by the fact that the weld was formed in two passes of the welding tool, which led to the formation of a double-recrystallized structure of the weld.

3.3. The results of the acoustic emission parameters analysis
During AE control a linear type of location was implemented using three AET (figure 2). The parameters of the signals received in the zone between the AET, corresponding to the zone of the subsequent destruction of the specimen, were analyzed. Thus, signals caused by friction in the grips of the testing machine were excluded from the processing of AE.

The amplitude filtering criteria is determined based on the ratio of the useful signal amplitude, which is more than 10 times greater the noise level. According to the rise time of the forefront $\Delta t$, the signals characterizing discrete AE were chosen, since many authors attribute this type of AE to the evolution of macroscopic defects [7]. The results of the AE count event $N_\Sigma$ distribution and the AE rate event count $N'_\Sigma$ distribution during testing of the base metal samples (No.1, No.2) are shown in figure 8.

![Figure 8](image)

**Figure 8.** Diagrams of AE parameters distribution of the base metal samples: (a) - No. 1; (b) - No. 2.

From the standpoint of the kinetic approach, a decrease in the AE rate event count at the stage of plastic flow of No. 1, No. 2 samples can be caused by a slowing down of the movement of dislocation clusters, due to their high density.

The active growth of the AE count event with increasing load is due to the processes of combining dislocation clusters, the destruction of dislocation loops with the formation of destruction foci (microcracks), leading to the formation of macrocracks [8, 9].

The results of the AE count event $N_\Sigma$ distribution and the AE rate event count $N'_\Sigma$ distribution during testing of the welded joints samples (Nos. 3A, 4A, 6A) are shown in figure 9.

The microstructure of welded joints, in terms of acoustic emission, has its own characteristics, due to the specificity of a material plastic flow process [10].
For samples Nos. 3A, 4A, 6A, local maxima of AE rate event count fall within the yield strength of the material, which, due to the dislocation theory of plastic deformation of crystalline materials, is explained as the formation of dislocation clusters, their migration, annihilation and the release of dislocations to the surface [11].

The count event recorded at the plastic flow stage of welded joints material (Nos. 3A, 4A, 6A) exceeds this parameter for base metal specimens (No. 1, No. 2), which indicate the presence of additional AE sources related to the structure of the weld: the generation of dislocations at the boundaries of the core zone and thermomechanical zone (TMZ) in particular.

![Figure 9](image.png)

**Figure 9.** Diagrams of AE parameters distribution of welded joints samples: (a) - No. 3A; (b) - No. 4A; (c) - No. 6A.

For samples No. 4, No. 6A, the abrupt accumulation of AE signals (the maximum of AE rate event count) preceding the destruction of the samples is characteristic. Sources of AE in this case were the processes of combining dislocation clusters with the formation of localized microcracks and their subsequent merging into a macrocrack, the growth of which led to destruction [11].

Sample No. 6A is characterized by the presence of local maxima of AE activity at a load level (0.85÷0.9) \( \sigma_{uts} \), probably related to the accumulation of dislocations, overcoming obstacles with the release of stored energy in the form of AE radiation, at the boundaries of the core zone and TMZ.
The results of the AE count event $N_{\Sigma}$ distribution and the AE rate event count $N'_{\Sigma}$ distribution during testing of the welded joints samples (Nos. 9Ad, 10Ad) are shown in figure 10.

For samples No. 1, Nos. 4A, 6A, 9Ad in the area of elastic deformation (up to 200 MPa), low AE activity was observed due to the Kaiser effect caused by the preloading of these samples to determine the acoustoelastic coefficient.

The distribution of AE parameters for samples No. 9Ad, No. 10Ad, made with a deviation of the values of technological parameters of welding, had a number of features.

For sample No. 9Ad, the first local maximum of AE rate event count corresponds to a stress level of $\approx 0.7 \cdot \sigma_{uts}$. For a given sample with a double-recrystallized structure, probably a discrete AE is associated with twinning processes, the emergence and growth of slip bands, with cracking mechanisms that cause spatial and temporal heterogeneity of deformation [9].

For sample No. 10Ad, the first local maximum of AE rate event count was registered at a stress level of $\approx 0.4 \cdot \sigma_{uts}$. This level of stress is in the area of elastic deformations of samples without structural defects. This feature is caused by the initial deformation of specimen No. 10Ad (a defect of the type angular displacement of edges). The uniaxial load applied during the tests led to the formation of additional bending stresses in the weld zone in the sample.

![Figure 10](image)

**Figure 10.** Diagrams of AE parameters distribution of welded joints samples with defects: (a) - No. 9Ad; (b) - No. 10Ad.

The correlation of the AE signals parameters with the parameters of fracture and plastic deformation of welded joints samples, made with deviation of the technological parameters of welding and without them, will allow to proceed to the study of the processes of defect formation during the welding.

4. Conclusion

The results of experimental studies have shown the potential applicability of the acoustic emission method for the defect formation control during FSW of products from aluminum alloys.

During the process of a welded joint forming, AE sources are associated both with the formation of structural inhomogeneities zones (defects) and with a technological change in the stress-strain state of the material.

For reliable interpretation of the registered AE signals, it is advisable to monitor the parameters of the stress-strain state of the base metal and the weld after welding by the laser-ultrasonic method. The difference in the values of the parameters characterizing the stress-strain state will indicate the presence of structural inhomogeneities in the welded joint. Control supplemented in this way will allow obtaining the most informative analysis of the AE information.
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