The results of the defect formation control in welded joints during friction stir welding by acoustic emission

K Stepanova1, a, I Kinzhagulov1,2, b, R Iuferev3, c, Y Levkova1, d, A Kovalevich4, e
1 ITMO University, 49 Kronverksky Pr., St. Petersburg, 197101, Russia
2 Engineering Design Center of Space-Systems Support 57 Matrosa Zelezynika str., St. Petersburg, 197343, Russia
3 Peter the Great St.Petersburg Polytechnic University (SPbPU), 29 Polytechnicheskaya str., St.Petersburg, 195251, Russia
E-mail: a ledy.xs93@yandex.ru, b kinzhiki@mail.ru, c roman.iuferev@melytec.ru, dlevkova_yulia@mail.ru, e kovalevi4as@gmail.com

Abstract. Experimental studies of the acoustic emission parameters distribution with structural changes in a welded joint during friction stir welding (FSW) are presented in this work. The parameters of energy, amplitude, activity and median frequency distribution of acoustic emission signals characterize the presence of features in the plasticization processes in case of disturbance of uniformity of plastic flow of a material during defect formation imitation process. An approach, based on the analysis of the parameters distribution of acoustic emission (AE), for the creation of an automated non-destructive quality control system of welded joints during FSW in real time has been proposed.

Keywords: Friction stir welding, acoustic emission, defect formation, quality control, AE signals parameters, computed tomography

Introduction

Due to the possibility of obtaining more durable joints, along with reducing the weight of a structure, improving automation and efficiency of the welding process, as well as the possibility of obtaining permanent joints of hard-to-weld metallic materials, use of friction stir welding for creating critical products of rocket and space technology has increased. The FSW process is implemented under strict control of the welding parameters — welding speed, rotation speed of a welding tool, effort on a welding tool, immersion values of the tool pin into the edges being welded. A slight deviation of one of these parameters can lead to a defects formation and a decrease in the welded joint strength [1].

It was proposed to examine the parameters of AE together with technological parameters to improve the accuracy of welding process control. Acoustic emission method was used is one of the promising methods of non-destructive testing, applicable in dynamic systems and sensitive to local dynamic restructuring of the material structure. Defect control in the process of welds formation will provide an opportunity to detect defects at the initiation stages and promptly make a decision on defects elimination without interrupting the production cycle. This will reduce the time of manufacture of large-sized modules and improve the quality of manufactured products and the critical elements reliability of the rocket-and-space equipment all in all.

There are 4 stages in the process of a weld formation; each stage is characterized by a dominant physical process for this stage [2]:

- phase-1, preparatory - dry external friction;
- phase 2, transitional - the nucleation and migration of dislocations;
– phase 3, equilibrium - plastic deformation;
– phase 4, forging - elastic-plastic deformation during cooling.

Each stage of FSW is determined by parameters which characterize the plasticization process of the material in a welding zone. The dominant parameters of physical processes, which characterize the stages of the welding process, are: the amount of heat released during friction of a tool shoulder and the surfaces of the parts to be welded, the flow parameters of the mixing plasticized metal, characterized by direction, speed, continuity function, pressure in the volume limited by the tool shoulder and a substrate; the amount of plasticized metal in the weld zone, involved during the rotation of the welding tool.

Physical processes that characterize the formation stages of welded joints are accompanied by friction, grain boundary sliding, dislocations clusters formation and motion, phase transitions. These phenomena are the main sources of AE and are accompanied by the emission of acoustic waves into the volume of the material of the welded workpieces [3,4].

Therefore, a hypothesis was proposed: the parameters of physical processes characterizing the stages of welds formation are interrelated with the parameters of acoustic emission signals occurring when there are active AE sources at different stages of FSW.

**Description of work**

Defect formation during FSW leads to a change in the parameters of physical processes, which characterize the stages of welded joints formation. In this case, the occurrence of phenomena (friction, grain-boundary, slip, formation and motion of dislocation clusters, phase transitions) at different points in time leads to a redistribution of the dominant physical processes ratio. As a consequence, this circumstance contributes to the appearance of additional sources of AE [5-8].

The development of a math model of the entire defect formation process during FSW is almost impossible, therefore, math models of individual welding stages of the FSW are created, and the data of one math model can be fully or partially transferred as source data of another math model [9].

As the main type of modeling a model experiment has been chosen. This type of modeling is characterized by the absence of a rigid distinction between methods of empirical and theoretical knowledge.

Characteristic defects in FSW welded joints are the defect “cavity” and the defect “kissing bond” [10].

The object of study – type defect “cavity” – was imitated in the FSW process. Fig.1 (1,2) shows technological openings of various diameters that were made in the edge of the welded workpieces to imitate defect formation during the welding process.

For assess the adequacy of this modeling method of process of the typical defects formation during FSW, the welds were subjected to computer tomography (CT) after welding. According to results of the computed tomography, “internal channel” defects were found in the places of the temporary openings. (refer with Fig.1 (3)). The test results were confirmed during the metallographic analysis of thin metallographic sample of welded joints. A defect “internal channel” was found in the structure of the weld core (refer with Fig. 1,c).
The formation of the welded joints during FSW occurs at an excessive pressure in the volume bounded by the working surfaces of the tool and the substrate. The welding zone is bounded by the working surface of the welding tool support spindle and the base coat. The metal at the edge of the workpieces is heated by friction to a plastic state and is extruded by the tool pin into the volume that is released behind it.

Thus, when the welding tool reaches the temporary openings in the edges to be welded, the amount of plasticized metal becomes insufficient to fill the space left behind by the welding tool, as a result of which a defect type “internal channel” is formed in the weld.

The formation of a defect type “internal channel” may also appear because of a change in the mixing trajectory of the material, continuity disruption of the flow of material during plasticization in the weld zone, which lead to the formation of a heterogeneous structure of the weld.

During the FSW process dynamically interacting elements are the welding tool, the substrate, plasticized and non-plasticized workpiece material. Intense plastic deformation and layer-by-layer transfer of material around the instrument lead to the forming of acoustic emission signals. Changes in the elements interaction of a dynamic system, for example structural changes in the process of plasticization of a material during defect formation, the interaction of the tool pin with the substrate and etc., causes to a change in the parameters of AE signals [11, 12].

Experimental studies of AE signals parameters’ changes while imitating the defect formation process during the FSW welds formation were carried out on the experimental welding machine (refer with Fig. 2,a). Digital acoustic emission diagnostic system and a set of acoustic emission transducers were used for AE signals registration (refer with Fig. 2,b).
Experimental studies included the following steps:
1) preparatory stage of setting up and testing the equipment;
2) development of the location scheme of AE control;
3) installation and configure AE controls;
4) start of the FSW process and simultaneous recording of AE data.

Two broadband (100-700 kHz) acoustic emission transducers (AET) were used in the location scheme of AE sources (refer with Fig. 2,c). Due to the need to ensure contact of the sensitive elements of the AET and their reliable fixation to the controlled object under limitations, caused by design features of the FSW equipment, the linear location of coordinates of AE sources is implemented.

The key factors in the developing of the location scheme were the absence of mechanical effects on acoustic emission transducers during control; ensuring continuity of the acoustic path along the way of AE signals from sources to acoustic emission transducers; exceeding the threshold level of AE equipment discrimination by signals registered during the AE testing [13].

During adjusting of the AE means of control the interference effect, caused by the equipment noise and the design features of welded products fixing, during the AE signals registering was considered.

Results & discussion

During the experimental results evaluation, the following parameters were analyzed:
- localization of high activity zones of acoustic emission signals (AE-active zones) during the welds formation with defects and flawless;
- distributions of the total amplitude in AE-active zones during the welds formation with defects and flawless;
- dependence of the total AE signal count on the welding process time;
- energy distribution of AE signals in the welding process time;
- dependence of the AE signals median frequency on the welds formation time.

The table 1 below provides values of the AE signals main parameters registered during the welds formation.
Table 1. Values of the AE signals main parameters registered during the welded joints formation

| Welded joints groups for research | № welded joints | Comment | Count event $N_e$ | Quantity valid AE signals*, [%] | During FSW $t$, [sec.] | Medium rate event count $N'_e$ [sec.$^{-1}$] | Total peak amplitude AE in active area, [mV] | Median frequency signals, [KHz] | Weld length, [mm] |
|---|---|---|---|---|---|---|---|---|---|
| flawless | “1-1” | material plasticization | 39 | 12.7 | 73.07 | 0.53 | 989.1 | 150.2±15.5 | 292 |
| | “1-2” | material plasticization | 23 | 10.6 | 91.33 | 0.25 | 620.8 | 148.6±12.3 | 365 |
| | “1-3” | material plasticization | 21 | 14.2 | 50.38 | 0.42 | 640.5 | 150.2±14.9 | 201 |
| defect imitation | “2-1” | 3 technological openings | 56 | 83.6 | 54.73 | 1.05 | 1164.2 | 172.3±11.5 | 208 |
| | “2-2” | 12 technological openings | 50 | 76.9 | 47.60 | 1.05 | 2112.1 | 168.7±13.7 | 200 |
| | “2-3” | 12 technological openings | 48 | 78.7 | 47.40 | 1.01 | 1919.8 | 171.8±15.8 | 196 |

*The percentage of AE signals that satisfy the filtering conditions in amplitude and frequency of the total number of AE registered signals

The localization results of high activity zones of acoustic emission signals (AE-active zones) during the welds formation with defects and flawless are shown in Fig. 3.

During analyzing of the localization results of AE sources, it was revealed that AE-active zones are located in welded joint zones with a violation of the structure homogeneity, caused by the defect formation imitation with technological openings in the edges.

![Figure 3](image)

**Figure 3** Density of AE signals location: a) – welded joints “1-1”; b) – welded joints “2-1”; c) – welded joints “2-3”; d) – color scale (total peak amplitude AE, mV)

The total amplitude of AE signals in AE-active zones is not directly related to the size of the defect (or inhomogeneity), but depends on the parameters of the physical processes that accompany the structural changes during defect formation.

The coordinates and the length of the AE - active zones are not related to the size of the openings in the edges of the welding blanks, made for the defect formation simulation, AE - active areas are related to parameters characterizing the structure change of the plasticized material and the processes of plastic flow of the material during welding.
Fig. 4 shows the dependence graph of the “overhang of pin” on the position of the welding tool at the current time; the dependence graph of the activity of AE signals, registered during the welds formation in workpieces with defects and flawless, on the position of the tool at the current time.

The parameter “overhang of pin” characterizes the depth of the tool pin penetration into the welded edges.

During conducting of the experiment, in the formation of FSW welds for fixed pressure on the welding tool, the parameter “overhang of pin” was dependent on the geometrical parameters of the welded workpieces and on the parameters of the thermomechanical weld formation processes.

For comparing the parameters of the distribution of AE-data recorded during the welds formation of various lengths, the concept of the weld completion percentage $P$ (%) was introduced (refer with Eq. 1):

$$P = \left( \frac{t}{t_w} \right) \times 100 \%,$$

(1)

where $t$ – current time when registering AE signal; $t_w$ – weld formation time.

The weld completion percentage $P$ characterizes the position of the welding tool at the current time at a constant welding speed.

During the analysis of the acoustic emission activity distribution nature, it was revealed that the samples with imitation of defect formation are characterized by the presence of pronounced "peak" activity at the following moments of weld formation time:

- the introduction of the welding tool pin in the edges of the parts being welded and the exit to the mode with the specified welding technological parameters;
- the beginning of structural changes in the weld, caused by technological openings in the edges to be welded, and causing the defects formation such as “internal channel” of different lengths.
the end of the welding - extraction of the tool pin from the part.

This fact shows that during the welds formation by FSW processes of plastic deformation and friction in the “welding tool – workpiece- substrate” dynamic system are accompanied by acoustic emission. The appearance of structural changes during material plasticization process causes a change in the parameters of AE signals recorded during FSW.

As a result of analyzing of the acoustic emission activity distribution it was revealed that the value of “peak” activity is related to the size of the technical openings, on which the length and nature of structural changes are dependent during defect formation.

The distribution of the values of the "peak" activity is steady for flawless workpieces; the maximum activity value is more than two times lower than the maximum activity value of AE signals recorded during the welding of workpieces with defects.

**Summary**

1. During welds formation with specified welding parameters, the parameters of AE signals (total score, average AE activity, energy of AE signals, frequency of AE signals) remain in the specified range. Change in the distribution of AE signals parameters outside the established ranges occurs if defects appear during welding.

2. The formation of AE-active zones is related to specific coordinates of the welded joint. The coordinates and the length of the AE-active zones formed by the AE sources are not related to the size of the defect (or heterogeneity), but related to the length of a change in the structure of the plasticized material during welding.

3. The total amplitude of AE-active zones is not directly related to the size of the defect (or heterogeneity), but depends on the parameters of the physical processes that accompany the structural changes during defect formation.

4. The average median AE activity during the welding of workpieces with defects exceeds the activity of AE during the welding of flawless workpieces more than 2 times. The existence of AE active zones in the weld affects the value of AE signals activity during defect formation.

5. The average median frequency of AE signals recorded during welds formation is more (more than 12%) than the average median frequency of AE signals recorded during the welding of flawless workpieces. This phenomenon is explained by increasing in the proportion of AE signals with a high median frequency, the sources of which are the defect formation during FSW.

**Conclusions**

The development of methodical and improvement of the existing equipment based on the new regularity of informative parameters of AE signals during FSW will allow developing and practically implementing the technology of acoustic emission for monitoring welds during friction stir welding; which will allow quality control in the production in real time, increase the reliability of defects detection, reduce the defective proportion of responsible products, increase the efficiency of control and, consequently, improve the quality of the manufacture.

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