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ACOUSTIC EMISSION METHOD AT EVALUATION OF THE STATE OF WELDS AND THEIR SERVICE PROPERTIES. PART 1. EFFECT OF WELDED JOINT TYPE ON ACOUSTIC EMISSION

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The majority of existing structures have welded joints. It is of considerable interest to determine the differences in acoustic emission for various types of welded joints and change of the properties of materials in operating structures, which have welded elements, after long-term service, taking into account the time and probable violation of service conditions. The data of testing samples from such materials demonstrate the high sensitivity of acoustic emission method to welded joint type, and to changes of weld service properties. 9 Ref., 2 Tables, 14 Figures.

Keywords: welds, service properties, acoustic emission (AE), AE activity, damage, material destruction, loading, prediction

Service properties of the material are characteristics, which are revealed at material operation directly in the real structures. They are much more diverse that those, which are determined for the material at standard laboratory testing of the samples.

Note that the welded joints always are a source of initiation and development of defects, due to introduction of a great part of the defects into the material directly during welding, as well as generation of residual stresses.

Part 1 deals with the features and differences in AE parameters for welded joints of different types.

Irrespective of the kind of defects in welded joint area and causes for their appearance, be those pores (Figure 1), cracks, lacks-of-penetration or another factor, they are potential sources of material destruction. In this connection, the welded joint area requires priority control at performance of technical diagnostics. Determination of the real residual life of the material and its load-carrying capacity should be also based on assessment of the life and load-carrying capacity of the welded joint. Comparison of base metal properties and those of welded joint metal allows a more accurate estimate of the controlled product condition than just monitoring the base metal state. This work deals exactly with these important issues in the following order:

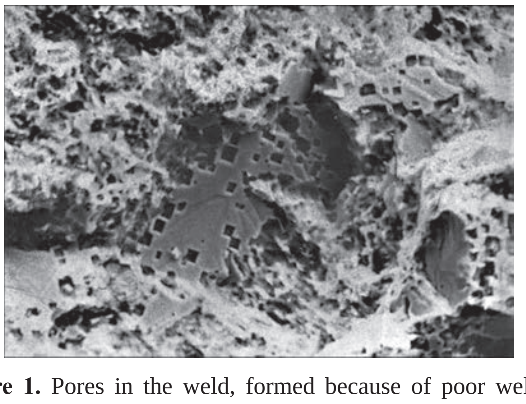

Figure 1. Pores in the weld, formed because of poor welding quality

1. Determination of the differences in AE at rupture testing of samples with welded joints of different types and selection of the most informative parameter that characterizes damage accumulation during deformation.

2. Determination of differences in AE for samples from metal with welded joints from AE for metal without them. Defining the parameter, which will allow determination of presence of welded joints in the tested sample.

3. Checking the efficiency of algorithms for prediction of the destruction, incorporated into the software of EMA type systems, on samples with different types of welded joints.

It should be noted that this paper generalizes the results of testing performed in different years using EMA systems from the 1st to the 3rd generations, which have such differences in presenting the amplitude and noise characteristics of AE signals, as application of the linear and logarithmic amplification modes, respectively. Despite that, the objectives set forth in the paper, have been reached, in particular, due to the fact that, as shown by the conducted research, the absolute values

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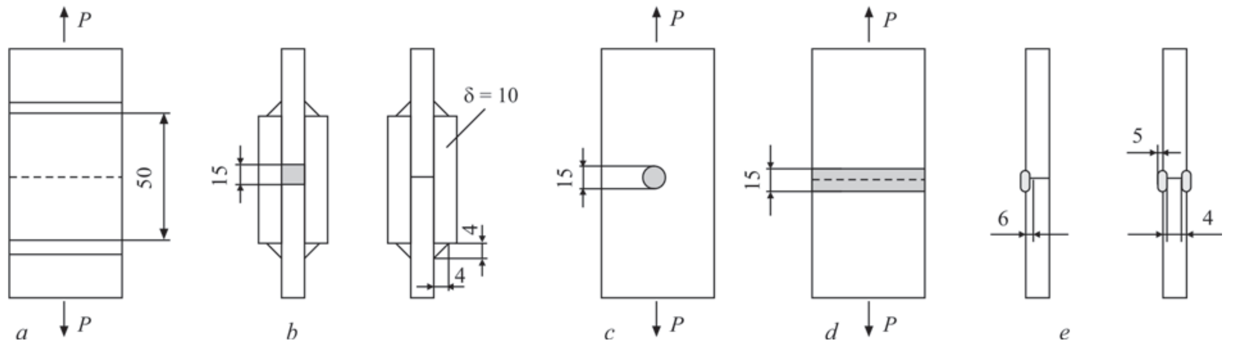

Figure 2. Schemes of welded joints testing (for *a*–*e* description see the text)

of AE signal amplitudes are not of principal importance for evaluation of the state of materials and prediction of their fracture. Somewhat more important, although not decisive, either, is the nature of their relative change during deformation and damage accumulation.

In order to solve the posed tasks, it was proposed to conduct a number of tests of 17GS steel samples, in order to reveal the differences in AE parameters, which develops at fracture of material with different welded joints. Series of samples with a transverse cut and several types of welded joints were prepared (Figure 2):

- *a* — with a transverse weld and two-sided cover plates welded to the sample surface;
- *b* — with two-sided cover plates welded to the sample surface;
- *c* — with a spot welded joint;
- *d* — with one-sided transverse weld;
- *e* — with two-sided transverse weld.

Welded joints were made by manual electric arc welding, with 3 mm UONI-13 electrode type.

Standard samples of the first type [1] were used for AE testing, in order to study the state of pipe materials (Figure 3). A tensile testing machine R-20 with a hydraulic drive was used for sample testing.

AE system EMA-2 with linear layout of a four-transducer array on the sample was used (Figure 3). Data processing was performed, using modern EMA-3.92 program. The distance between the transducer centers was equal to 110 mm, controlled zone was 140 mm (70 mm to the left and right from the sample center). Data were processed using cluster analysis during testing and at post-experimental processing. AE events that passed screening by the coordinate characteristic were combined into clusters. The cluster radius was 20 mm that allowed tracing AE localization centers along the sample length within the controlled zone. AE signals were recorded in the range of 100–1000 kHz.

The most typical test results are presented in the form of graphs in Figures 4–8. In them blue lines were used to plot a bar graph of AE event amplitudes (*A*, mV), red lines — a linear graph of loading on the sample (*P*, kg), black — point chart of «Rise time» parameter (*R*, μs), which characterizes the time of the signal rising to a maximum, violet — a linear graph of the total number of AE events (*N*, dimesionless). The abscissa shows the time from the start of the test.

Testing showed that the highest breaking load of 70–95 kN (7000–9500 kg) is characteristic for samples of *d* series, and the lowest of approximately 26 kN (≈2600 kg) — for *e* series. This is quite natural, as the material cross-section area in the working part in such a welded joint is smaller than for other samples. Moreover, off-center tension and bending are realized simultaneously during sample loading. The number of AE signals for samples of this series is small that can be clarified by the following factors:

- less damage introduced by welding;
- occurrence of the majority of AE events already during the cracking process, that is indicated by AE appearance at loads close to breaking ones and high, close to 500 mV amplitudes that are maximum for AE instruments of EMA-2 type.

A characteristic feature is absence of the same acoustic pattern for samples within each of the series, except for samples with a welded spot in *c* series and samples with a two-sided weld of *e* series.

Samples in *b* series are the most different. They failed first in one weld, then in another one. Testing was interrupted after breaking of one of the welds. The number of events for these samples differs 4.5 times, and maximum amplitudes — by 2 times.

For samples with the welded spot (series *c*) and samples with a two-sided transverse weld (series *e*) acoustic emission was observed in an area of rounding-off

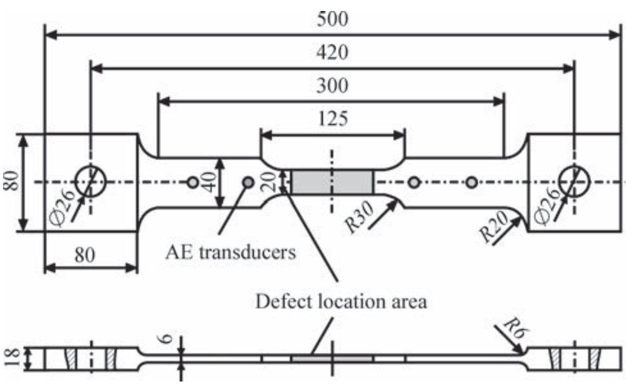

Figure 3. Sample for conducting testing with application of AE technology

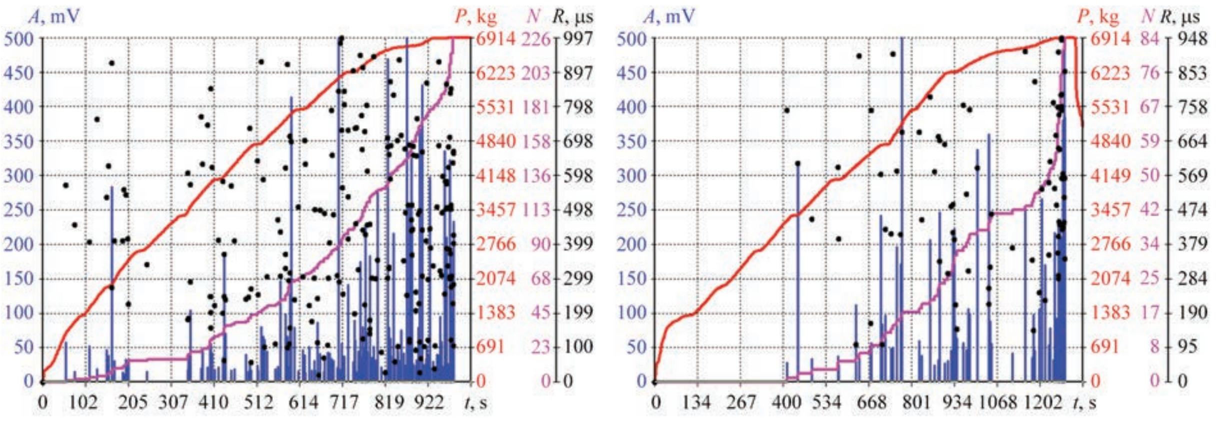

Figure 4. Diagrams of testing sample series *a*

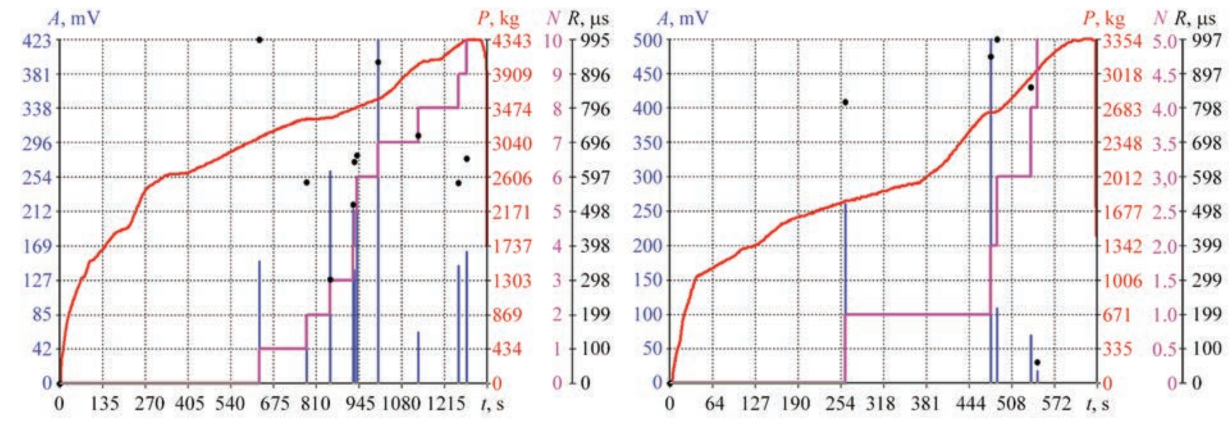

Figure 5. Diagrams of testing sample series *b*

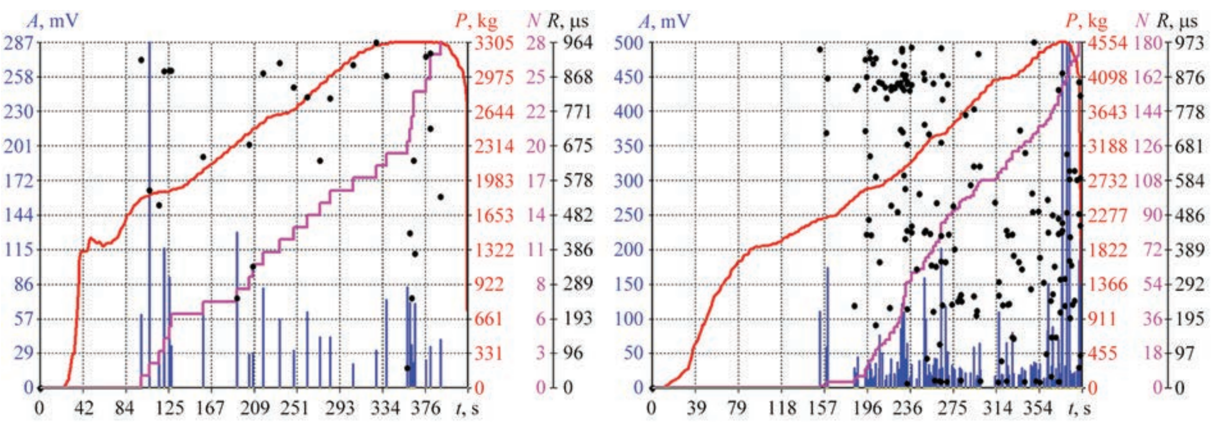

Figure 6. Diagrams of testing sample series *c*

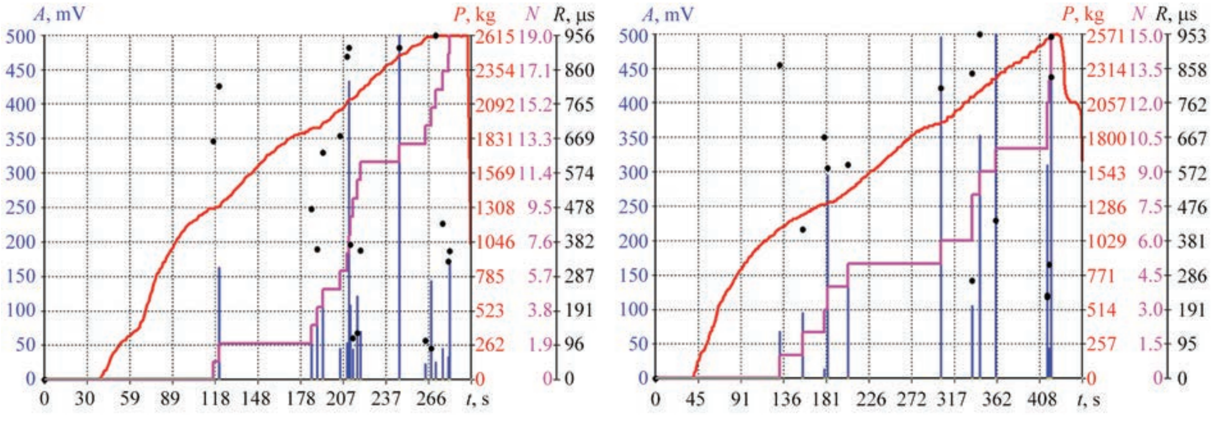

Figure 7. Diagrams of testing sample series *d*

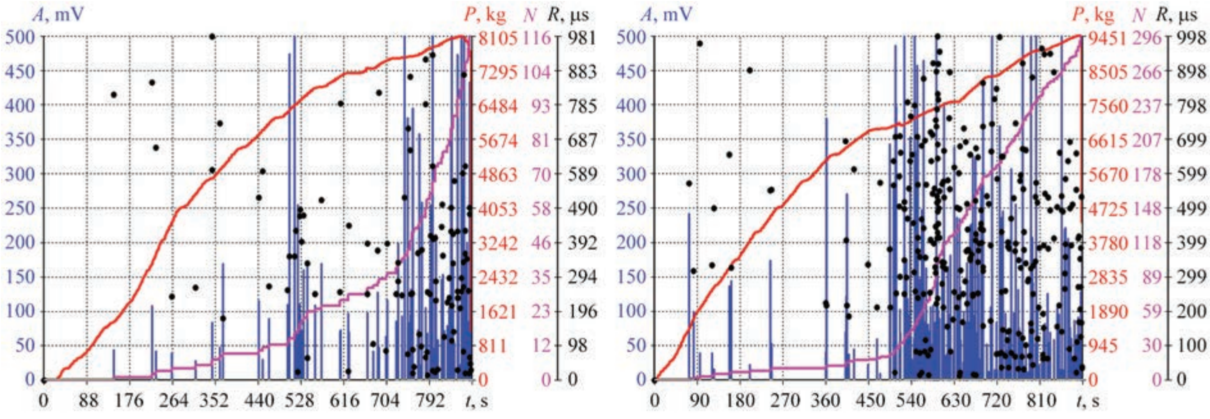

Figure 8. Diagrams of testing sample series *e*

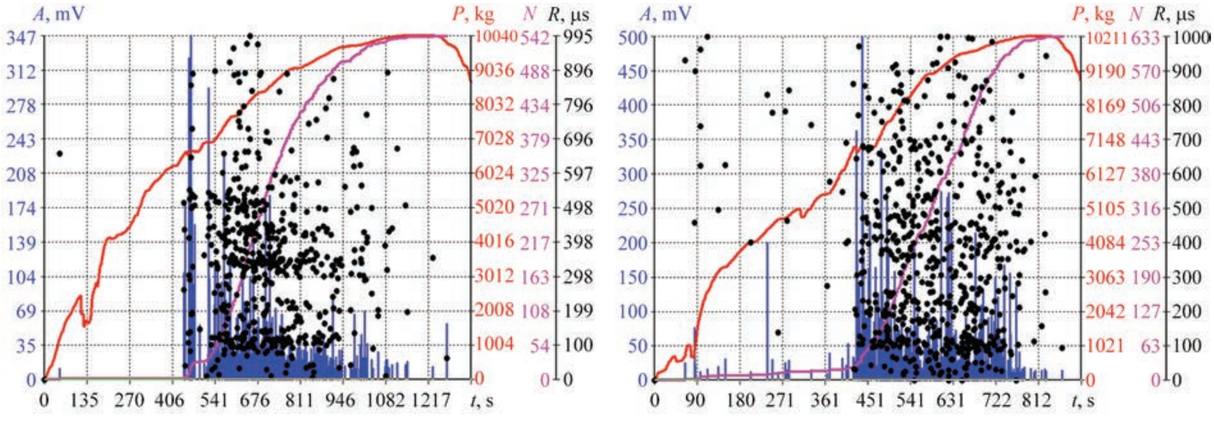

Figure 9. Diagrams of testing samples of monolithic metal from 17 GS steel

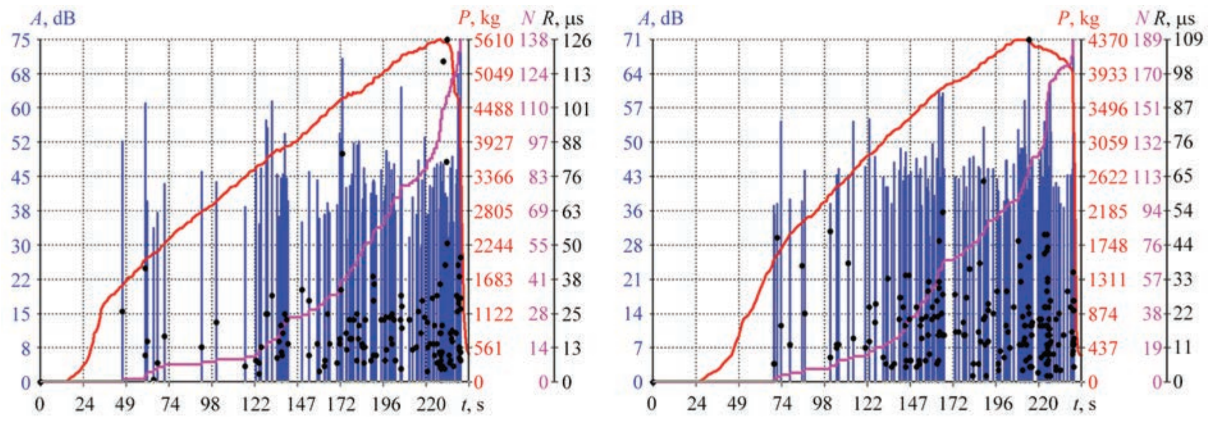

Figure 10. Diagrams of testing samples with two-sided welded-on elements

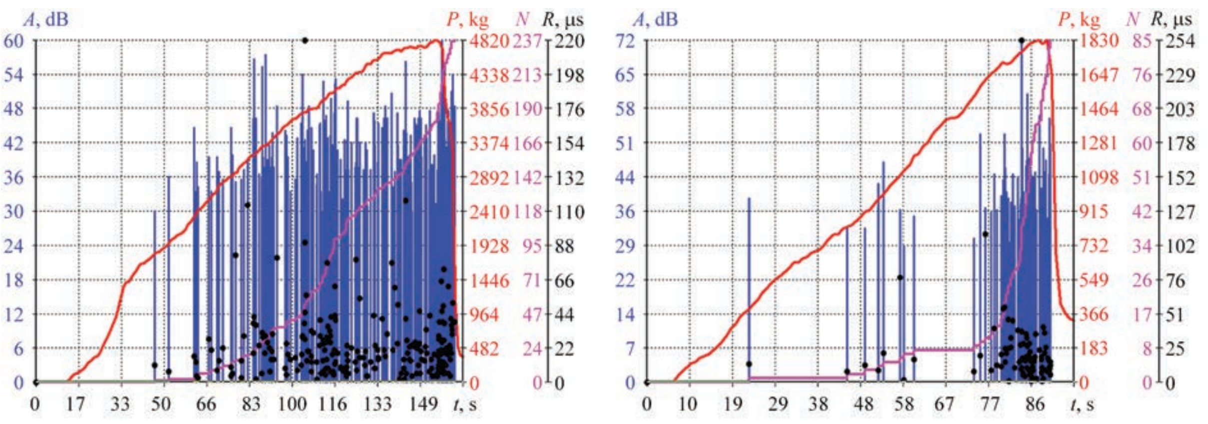

Figure 11. Diagrams of testing samples with randomly performed weld

radii on the working part thickening. It is obvious that for such kinds of welded joints stress concentration in the weld area was the lowest, resulting in more uniform deformation of the sample. This led to appearance of plastic strain zones and beginning of the process of damage accumulation in the area of rounding-off radii, and, eventually, caused occurrence of AE signals.

A characteristic feature is formation of destruction in the near-weld zone. As a rule, several centers of AE radiation in the welded joint zone were observed for all the samples, one of which coincided with the location of the weld or spot, while others were at a distance of 5–25 mm from the weld center in the HAZ (Figure 12).

Acoustic signals arriving from the zone of rounding-off radii, differ significantly from signals coming from the welded joint. They are smaller by amplitude and are associated primarily with plastic strain of the sample, so that they are more uniformly distributed in time. AE signals in the welded joint zone are caused predominantly by defects arising in welding. Their amplitude is higher, and the nature of their occurrence is more random. That is why both AE amplitude and activity allow clearly distinguishing between acoustic emission from the welded joint area and that in the plastic strain area.

On the whole, one can see that the nature of AE signal accumulation in the welded joint material during sample deformation is the most fully reflected by such a parameter as total number of AE events (denoted by *N* in the graphs).

In particular, note the change of the slope of the graph of the above-mentioned parameter for samples with welded joints that is clearly seen in the graphs, and can be related to the start of fracture zone formation. If we compare the shape of *N* curve of the sum of AE events for welded joints and for monolithic metal of the same grade (Figure 9), the difference immediately becomes obvious: for material with welded joints in the area of regular AE activity, i.e. when AE events are not isolated and rather uniformly arise in time, *N* curve is concave, and for monolithic material it is convex, on the contrary.

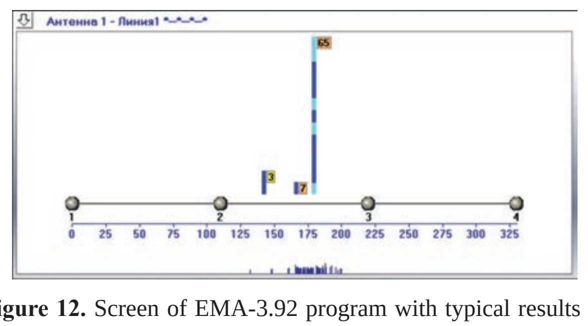

Figure 12. Screen of EMA-3.92 program with typical results of AE event location at welded sample testing. Bars with flags show clusters formed on the base of AE events, colour of strips on the bars corresponds to a certain amplitude range. AE events proper (coordinates along the horizontal, and amplitudes along the vertical) are represented by vertical lines below on the location scheme

Thus, the slope at the turning point of the curve of AE event accumulation is criterial. It allows distinguishing the material with the welded joint from the material without it. This is confirmed by numerous available data of testing various materials.

In particular, studied were the welded samples prepared by the following procedure: samples after rupture testing (without the welded joint) were welded in the rupture site. Welded joint quality was chosen to be arbitrary on purpose, as the samples were used further to check the fracture loading prediction, so that it is not known beforehand. 20 samples with both joint types: two-sided weld and welded spot were prepared. Further-on samples were tested by the same procedure, as others. Testing samples of this type is interesting in that AE can be unambiguously identified as related to welded joint fracture, as, allowing for the Kaiser effect, the base metal during deformation should emit a minimum number of AE events. The difference from the previous test series consists in that measurements of AE parameters were taken by EMA-3 system, and AE amplitude is expressed in decibels, in keeping with application of a logarithmic mode of signal amplification, unlike EMA-2 system.

Diagrams, shown in Figures 10, 11, represent the parameters, similar to those given in Figures 4–8, and the designations are the same, respectively.

The amount of damage increases with time (curve *N* — in the graphs), but in samples without the welded joint this growth slows down at a certain moment of time [2–6]. The difference in testing the welded samples consists in that no decrease in AE activity is observed for them at the final section of loading that, actually, gives rise to a change in the shape of curve *N*. At the same time, a significant scatter of such a parameter as «Rise time» suggests that it cannot serve as a criterial one for the tested samples. Now, the amplitude of AE events does not always correlate with the processes of damage accumulation at fracture, so that it cannot be used as a versatile criterion either.

The above data relate to steel samples. At some time, already with application of AE systems EMA-1 based on «Defectophone» instruments, such studies were conducted for aluminium alloys AMtsS and AMtsN (main properties of these two materials are very close). Tested were small-sized samples with different types of raisers (Figure 13, *a*) and wide flat samples AR-02 (Figure 13, *b*) with special frame structure, designed for equilibrium deformation [7, 8] of their central part (it allows obtaining the complete diagram of deformation during testing with the loading branch dropping to zero), with two types of welded joints — two-sided weld and welded spot (automatic arc welding with 1.8 mm AMts electrode, 360 A current, 380 V voltage). Small-sized samples without the welded joint demonstrated extremely low acoustic activity of 1 or 2 AE events during the entire testing period, and these events occurred directly during sample destruction. Even presence of a stress raiser did not affect the low AE activity. Wide samples without the welded joint demonstrated somewhat higher AE activity than the small-sized ones. But it was still essentially lower than in the majority of the tested steels.

However, presence of the welded joint led to an essential increase of the number of AE events, which can be unambiguously related to the volume of material, included into the HAZ. Table 1 gives brief summing-up of testing aluminium samples with maximum number of registered AE events.

The results of all the described tests show that the welded joint is the main source of AE that is recorded during loading, while the number of events depends on the volume of the material included into the HAZ. Another feature is absence of AE up to the moment, when the process of sample destruction starts concentrating in the welded joint zone.

During testing the prediction of breaking load of welded samples by EMA-3.92 software was verified. A typical fragment of program window with hazard indicator, which displays the prediction results, is shown in Figure 14. Explanations for the location array screen are given in the description for Figure 9. Elements of testing control and timer are shown above the location screen, and indicator strip with predicted breaking load is displayed below.

Hazard indicator gives the number of location AE array (No.1 in this case), number of AE event cluster, for which the prediction was made (No.1) and its center coordinates (182 mm), which are calculated from No.1 transducer from left to right. Furtheron, fracture prediction is shown in kg, in keeping with the tensile testing machine scale, as well as the calculated damage level of the sample material expressed in percent, at the moment of issuing the maximum warning No.3 — «Hazard».

Table 2 gives the selected results of breaking load prediction for samples without the welded joint and with joints of different types. It does not seem possible to present all the obtained data in view of the large amount of them. The necessary regularities can be quite clearly seen, analyzing those data, which were included into Table 2.

As one can see from Table 2, for the majority of the samples, the real breaking load falls within the prediction range. Samples of series *b*, *c*, and *d* are an exception, for which the prediction is higher than the real values of breaking load. And even though the lower limit of the prediction falls within the deviation of ±15 % admissible for EMA type systems, the upper limit significantly exceeds it. Let us analyze why such a phenomenon is in place exactly for samples of the mentioned series. The most obvious conclusion is that the samples of these series during testing are subjected to off-center tension. At the same time, the prediction algorithms, incorporated into EMA system software, were based on standards, which envisage the traditional uniform loading of rod samples or tube-shell structures [9]. Thus, in order to adjust the destruction prediction for cases of off-center tension, additional study is needed, which

Table 1. Final results of testing aluminium alloys AMtsS and AMtsN

Sample type	Small-sized	AR-02		
		Unwelded	With welded spot	With two-sided weld
Number of AE events	2	28	398	438

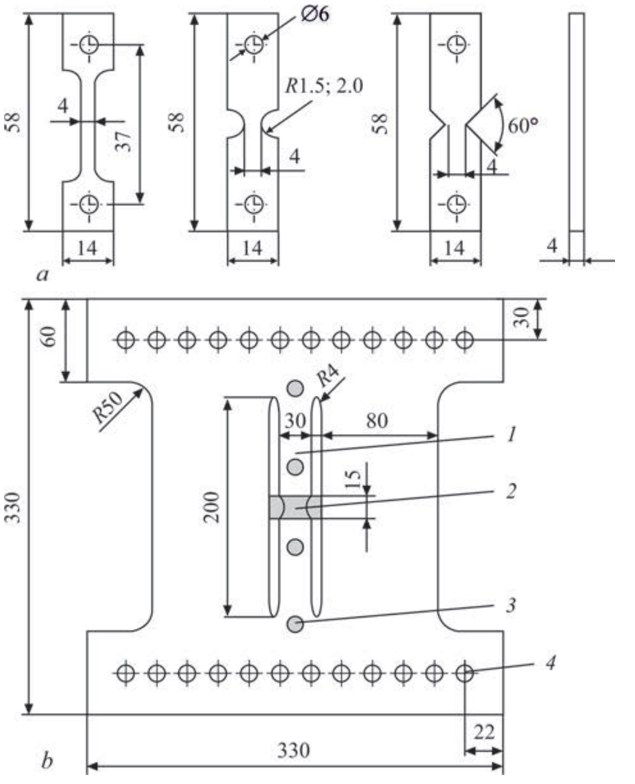

Figure 13. Samples for aluminium alloy testing: *a* — samples with different types of raisers; *b* — wide flat samples (*1* — spring dynamometer; *2* — welded joint area; *3* — AE transducer; *4* — 12 openings of 12 mm dia with 26 mm distance between them)

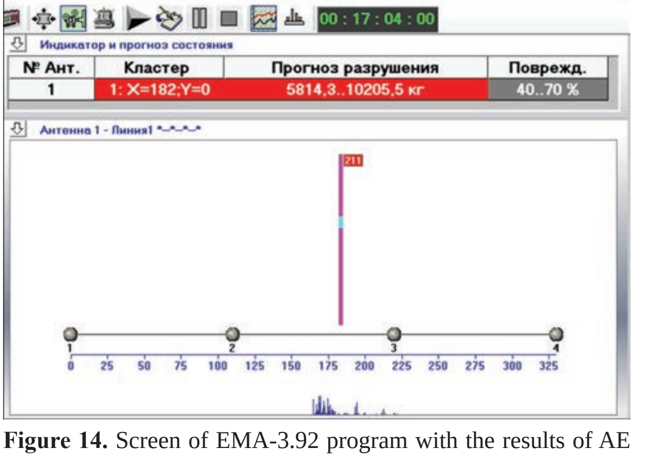

Figure 14. Screen of EMA-3.92 program with the results of AE event location and prediction of breaking load at testing one of the samples

Table 2. Results of prediction of breaking load of steel samples

Sample type and number	Time of predicted fracture, s	Time of fracture start, s	Number of AE events, used in prediction	Current load, at which prediction was made, kg	Level of hazard warning	Fracture prediction — lower limit, kg	Fracture prediction — upper limit, kg	Actual breaking load, kg
Without WJ No.1	352	1153	27	5907	1	8787	15424	10039
Without WJ No.2	249	836	12	4738	1	6857	12036	10211
Series a No.1	402	991	11	4065	1	5814	10205	6914
Series b No.1	1005	1297	7	3702	1	4812	9207	4342
Series c No.1	248	392	13	2734	2	3731	4305	3305
Series d No.1	189	290	4	1956	1	2866	5031	2615
Series e No.1	230	855	3	2936	1	4733	8307	8105
Two-sided welded element No.1	71	228	7	2250	2	3217	5647	5610
Weld of undetermined quality No.1	68	155	8	2600	2	3718	6526	4820

would allow obtaining more valid prediction results either by establishing special coefficients for such a kind of loading, or through adding new standards, on which identification of material state is based.

At the same time it should be noted that the detected prediction error is not critical, firstly, because the lower limit of predicted breaking load falls within the admissible error range, secondly because the hazard warning which is represented by the red colour of the indicator (see Figure 13), is generated by EMA-3.92 program in advance, before the material yield limit has been reached.

Thus, even without making corrections in prediction setting, EMA type systems can provide timely warning about the danger of welded joint breaking up.

Conclusions

1. In the presence of a welded joint in the sample, it is the main AE source. Number of AE events in the samples with welded joints, as a rule, is higher than that in monolithic samples.

2. The process of welded sample destruction is characterized by a more uniform in time AE activity in samples with largest volume of welded joint material and less uniform for samples with a smallest volume of welded joint material.

3. The maximum number and amplitude of AE events correspond to largest volumes of welded joint material, which one can see at comparison of the results of testing samples of *a*, *c* and *e* series with those of *b* and *d* series.

4. Samples with welded joints are characterized by greater diversity of the obtained pattern of AE event distribution in time, amplitude and other characteristics for unwelded samples that is indicative of the influence of welded joint quality on the amount of damage introduced by them into the material. AE activity depends on the level of material damage, caused by welding.

5. The breaking load prediction for the majority of the samples gives satisfactory values. For samples of *b*, *c* and *d* series subjected to off-center tension during testing, the destruction prediction yields somewhat higher breaking load values. This should be taken into account at testing structures, where such a kind of welded joint loading is in place.

6. The sum of AE events is the parameter which can serve the characteristic of damage of welded joint metal. The angle of inflexion of the curve of AE event sum allows distinguishing between testing monolithic metal and metal with welded joint. Ability to assess the volume of metal involved in welding can increase the validity of this characteristic application.

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