NON-DESTRUCTIVE TESTING OF WELDED JOINTS

PECULIARITIES OF ACOUSTIC EMISSION SIGNALS IN EVALUATION OF FRACTURE MECHANISM IN WELDED JOINTS ON ALUMINIUM ALLOYS

V.R. SKALSKY, I.N. LYASOTA and **E.M. STANKEVICH**
H.V. Karpenko Physico-Mechanical Institute, NASU
5b Aivazovskogo Str., 79053, Lvov, Ukraine. E-mail: skal@ipm.lviv.ua

High-strength aluminium alloys are widely applied in modern science and technology owing to a combination of their physical-mechanical and corrosion properties. Electron beam welding is used to join structural members, in particular in aircraft engineering. Micro- and macrofractures often occur in operation of such members under the effect of various factors. Crack propagation can be very effectively determined by the acoustic emission method. The purpose of this study was to investigate peculiarities of generation of the acoustic emission signals under static loading of specimens, and identify the character of fracture in different regions of the welded joints on aluminium alloy 1201-T. Crack resistance of the specimens measuring 10 × 20 × 160 mm made from the through electron beam welded joints on 20 mm thick 1201-T alloy plates was investigated by the three-point bending tests. The acoustic emission signals were fixed by using system SKOP-8M. The parallel measuring channel method was employed to select useful signals from noise. As established on the basis of analysis of wave reflections and continuous wavelet-transforms of the fixed acoustic emission signals, the method allows identifying sources of their generation in static fracture of aluminium alloys and their welded joints. Tough (weld and HAZ metals) and brittle-tough (base metal) fractures of a solid solution of copper in aluminium generate signals of low and medium amplitudes (A = = 0.2–0.5 mV), for which the criterial index varies from 0.15 to 0.30. Detachment of melted grains is accompanied by generation of the acoustic emission signals with an amplitude range of A = 0.4–0.5 mV and index κ = 0.3–0.4, whereas cracking of brittle intermetallics is accompanied by generation of high-power signals (A = 0.5–4.0 mV) with index κ = 0.5–0.9. 15 Ref., 5 Figures.

Keywords: *aluminium alloy, welded joints, acoustic emission, microstructure, microfractography pattern, wavelet-transform, fracture mechanism*

Current development of the industry of Ukraine stimulates growth of output of aluminium and its high-strength alloys owing to a combination of their physical-mechanical, corrosion and operational properties, which allows their successful application practically in all areas of science and technology. Electron beam welding (EBW) is used to join critical structural members (aerospace engineering, construction industry, etc.), as this welding method provides high quality of the weld metal when joining heavy sections in one pass.

Micro- and macrofractures may initiate and propagate in structural members made from aluminium alloys during their operation under the effect of various factors. Crack propagation can be very effectively determined by the acoustic emission (AE) method [1]. However, the AE method was little used for evaluation of fracture of the welded joints on aluminium alloys [2]. Therefore, to effectively diagnose the state of the structural members made from aluminium alloys it is important to investigate the AE activity and peculiarities of the AE signals in initiation and development of the processes of fracture in different zones of the welded joints.

Reported are some results of such investigations. In particular, the authors of study [3] employed the AE method for investigation of development of artificially simulated defects in the form of cracks under internal pressure loading of welded vessels made from alloy AMg6M. Based on analysis of the AE signals fixed during an experiment, the authors determined the critical crack size at which the vessel can still remain in operation.

The effect of microstructure of smooth specimens made from commercial aluminium and alloy AMg6M on generation of the AE signals during tension was investigated in study [4]. The AE activity in this alloy is more than an order of magnitude higher than in aluminium, this being

© V.R. SKALSKY, I.N. LYASOTA and E.M. STANKEVICH, 2013

caused by behaviour of grain boundaries and presence of particles of intermetallics. Investigations of behaviour of AE signals in fracture of the welded joints on alloy AMg6M and dependence of the AE signal character on the types of defects are described in study [5]. High activity of the AE signals (6–8 pulse/s), which are characterised by low amplitude, can be observed even at low stresses within the elastic deformation limits (80–90 MPa). It was established that loading of a specimen to stresses that result in formation of plastic deformation (300–320 MPa) causes no pronounced AE. Further growth of deformation is characterised by appearance of isolated AE signals with a low energy and activity. In the deep plastic deformation zone, AE is of a pulse character, i.e. it shows up in the form of «emission of the explosive type». Increasing the load up to fracture is accompanied by generation of the low-amplitude AE signals.

Studies [6, 7] established the character of generation of the AE signals in tension of smooth specimens cut out from different regions of a welded joint. Deformation of the specimens to 13 % resulted in the total quantity of the AE signals equal to 500–800 pulses, and in the fusion zone under the same conditions — equal to $85\cdot10^3$ pulses. This character of generation of the AE signals is caused by the presence of a considerable amount of structural defects in the transition zone and accumulation of different non-metallic inclusions along the grain boundaries. Similar experiments were carried out by the authors of study [8], during which the effect of heat input in argon arc welding on the character of generation of the AE signals was investigated by subjecting smooth specimens with a welded joint to static tension. It was shown that increase in heat input is accompanied by growth of ductility of the weld metal, while this leads to decrease in the AE activity.

The purpose of this study was to investigate peculiarities of generation of the AE signals under static loading of specimens, and identify the character of fracture of different regions of the welded joint on alloy 1201-T.

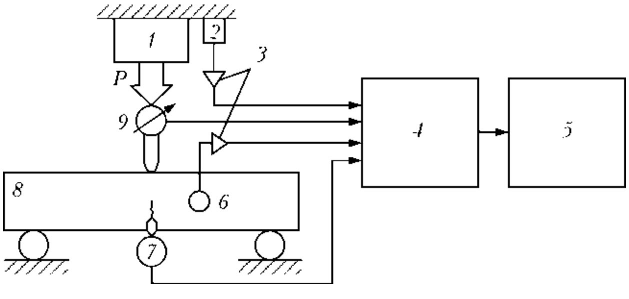


Figure 1. Flow diagram of experimental study of static crack resistance of specimens (*1*–*9* see in the text)

AE test materials and procedure. Static crack resistance was investigated by testing specimens cut from the welded joints on 20 mm thick plates made by through EBW without filler metal to three-point bending. Welding heat input was equal to 337.3 kJ/cm. Heat-hardened aluminium alloy of the 1201-T grade was the material of the welded plates. The tests were conducted on four types of the prismatic specimens measuring 10 × × 20 × 160 mm with the induced crack: I — in base metal, II — in HAZ, III — in fusion zone, and IV — in weld metal.

The specimens were made following the rules and characteristic proportions of geometric dimensions specified in GOST [9]. Length of the fatigue crack together with a stress raiser was 10 mm. Flow diagram of the experimental studies of static crack resistance of the specimens is shown in Figure 1.

The specimens were loaded by using machine SVR-5 *1*, where force P via dynamometer *9* was imparted to test specimen *8*. Displacement of the crack lips was fixed by crack lip displacement strain-gauge transducer *7*. The AE signals generated as a result of fracture were sensed by primary AE converter *6*, which was placed on the side surface of the specimen. Parallel AE channel *2* was used to select useful signals from noise [1]. Electric AE signals were amplified by preamplifiers *3*, after which they were registered by multichannel measuring AE system SKOP-8M *4* [1] and processed by personal computer *5*. Anti-frictional gaskets were used to decrease the effect of spurious AE signals induced by friction in locations of contact of surfaces of the beam specimen with supports of the machine. Loading and displacement of crack lips were fixed by parametric channels of the above system. Diagrams «load P–displacement of crack lips v», as well as acoustic patterns of the AE activity accompanying fracture of the specimens were plotted in the post-processing mode. The test results are given in study [10].

The primary AE converter with working frequency band of 0.2–0.6 MHz was used to sample signals. Measuring channels were calibrated prior to each experiment [4]. The following settings were used for AE system SKOP-8M: quantity of the measuring channels — 4 (two for registration of AE signals), amplification of each channel — 40 dB, sampling duration — 0.5 ms, period of analogue signal digitisation — 0.25 μs, cutoff frequency of low-frequency filter — 700 kHz, cutoff frequency of high-frequency filter —

40 kHz, discriminating threshold — 28 %, level of self-noise reduced to the preamplifier input — 7 μV, and gain factor of the preamplifiers — 34 dB.

Examination of microstructure and fractography of alloy 1201-T. To identify fracture sources by the AE method it is necessary to conduct microstructural and fractographic examinations of fractures in the characteristic regions of welded joints. Aluminium alloy 1201-T of the Al–Cu–Mn alloying system is susceptible to substantial decomposition of solid solution of the weld metal and HAZ, in which structural transformations decreasing strength of the welded joints to a level characteristic of metal in the annealed state take place at a temperature of 673 K and higher [11]. Therefore, each zone of the welded joint has its own peculiarities of fracture under quasi-static loading (Figure 2).

At room temperature, microstructure of alloy 1201-T consists of grains. The bulk of the grains is composed of α-solid solution of copper and manganese in aluminium and the secondary Al_2Cu phase uniformly distributed within a grain in the form of fine acicular inclusions, as well as along their boundaries in the form of coarse flakes (Figure 2, *a*). It can be seen from the fractography pattern of the base metal (Figure 2, *e*) that fracture is energy-intensive and corresponds to a brittle-tough fracture type. There are many quasi-cleavage facets. The fracture consists mainly of big protrusions and valleys, the surfaces of which are studded with small facets. Comparison of microstructure and microfractography pattern of the base metal of alloy 1201-T shows that grains precisely coincide with the protrusions and valleys in shape and size, and that the grain size is approximately 120–150 μm. Geometry of inclusions of the secondary Al_2Cu phase in the microstructure is comparable with sizes of brittle cleavages in the microfractography pattern (25–35 μm).

Therefore, the crack in the base metal of alloy 1201-T under its static loading propagates primarily along the grain boundaries, and fracture is of a brittle-tough character, where the tough

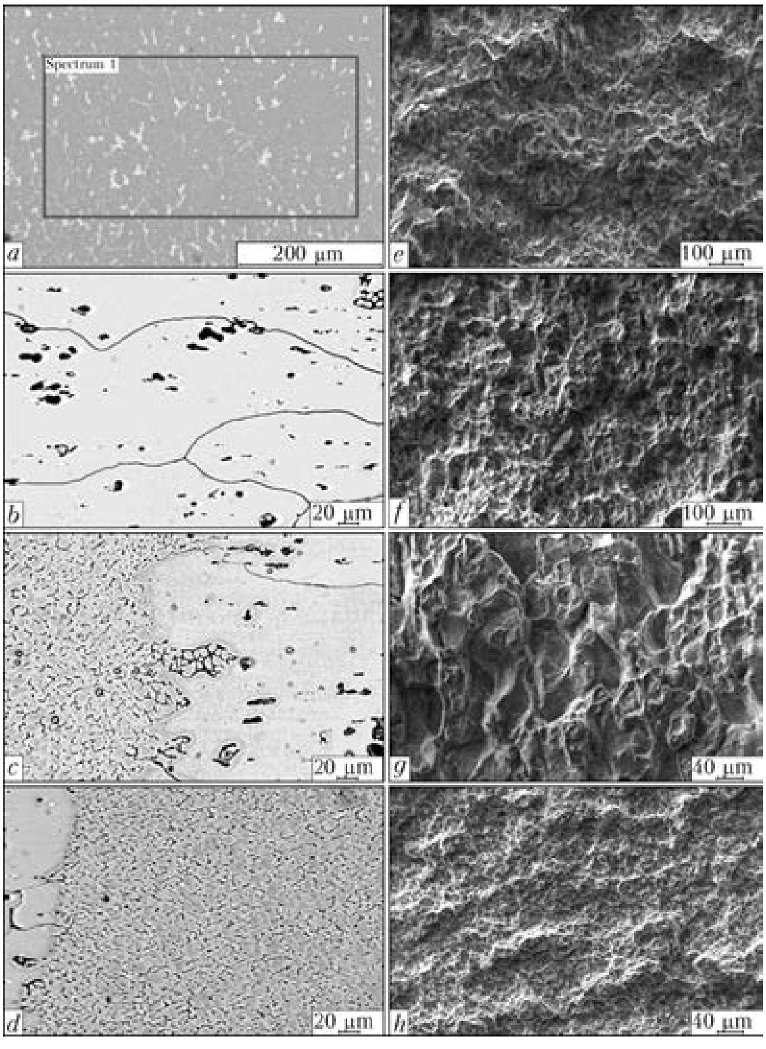


Figure 2. Microstructures (*a–d*) and microfractography patterns (*e–h*) of base metal (*a*, *e*), HAZ metal (*b*, *f*), fusion line (*c*, *g*) and weld (*d*, *h*)

component corresponds to fracture of the α-solid solution, and the brittle component — to cracking of the strengthening phase inclusions.

Microstructure of the HAZ metal consists of recrystallised grains depleted in copper (Figure 2, *b*), which precipitated in the form of the secondary Al_2Co phase along their boundaries and coagulated in the form of local clusters during repeated decomposition of the solid solution. Metal of this region is a bit more ductile compared to the base metal. Hence, the microfractography pattern (Figure 2, *f*) shows predominance of the tough fracture with a rare occurrence of brittle inclusion cracking facets.

Dramatic structural changes can be seen at the weld and HAZ metal interface. Melted coarse recrystallised grains of the base metal merge here with the finely dispersed weld metal (Figure 2, *c*). During solidification of the weld pool the secondary phase precipitates and joins into local inclusions, first of all at protrusions of the melted HAZ grains. Therefore, as a rule, the fusion boundary is characterised by a big cluster of intermetallic phases, which causes decrease in its ductility. Fracture of the specimens is of a macrobrittle character (Figure 2, *g*) with quasi-cleavage facets of cracking of coarse eutectic inclusions.

The high rate of cooling of the weld metal leads to formation of a fine-grained structure (Figure 2, *d*), the strength of which is almost twice as low compared to the base metal. Fracture is of a tough character (Figure 2, *h*) with a bumpy — cup-shaped relief and cells of an evident plastic flow of metal.

As shown by fractography, structural and mechanical heterogeneity of the electron beam welded joints on alloy 1201-T causes a different character of fracture in each zone of the welded joint. In tests of the HAZ metal to static crack resistance, the crack in the majority of cases changed its propagation direction and moved along the fusion line of the welded joint, as much less energy is consumed for the brittle fracture than for the tough fracture. This is indicative of the fact that the given region is dangerous in terms of strength of the welded joint.

Investigation of peculiarities of AE signals generated in fracture of aluminium alloys. Important information on peculiarities of the dynamics of fracture processes in solids can be obtained by using the wavelet-transform method [12].

Studies [13, 14] put forward the criterion for quantitative evaluation of fracture of structural materials from parameters of continuous wavelet-transforms of the AE signals. Software AGU-Vallen Wavelet [15] was used to investigate peculiarities of the AE signals. The Gabor wavelet was chosen as the mother one, as it allows distinguishing local peculiarities of the AE signals and provides their frequency-time presentation.

Considering properties of the wavelet-coefficients of the continuous wavelet-transform of the AE signals and results of theoretical investigations of changes in the amplitude-frequency characteristics of the elastic AE waves in various fracture processes occurring in solids, the following criterial index was proposed for quantitative characterisation of the AE signals and their identification [14]:

$$\kappa = \frac{WT_{\max}\Delta f_0}{\Delta f},$$

where $WT_{\max}$ is the maximal value of the wavelet-coefficient of an AE event at a certain time moment; Δf is the range of the band of the frequency spectrum corresponding to $WT_{\max}$ in the AE event on the wavelet-coefficient WT–frequency f coordinate; Δf_0 is the width of the working band of the AE path determined by the working frequency band of the AE converter (here it is equal to 0.2–0.6 MHz).

Macrofractures of structural materials are subdivided into the tough ($\kappa \le 0.2$), tough-brittle ($0.2 \le \kappa \le 0.3$) and brittle ($\kappa \ge 0.3$) types, depending on the value of the experimentally determined criterial parameter. Further increase in this value is accompanied by growth of the sensitivity of a test object material to brittle fracture [14].

The sequence of processing of the AE signals fixed in fracture of different regions of the welded joint was as follows:

1) continuous wavelet-transform was plotted for each signal, and maximal value of the wavelet-coefficient in an AE event was determined;

2) projection of the continuous wavelet-transform was plotted in plane WT–f upon reaching $WT_{\max}$;

3) width of frequency band Δf (MHz) corresponding to $WT_{\max}$ was determined;

4) value of criterial index κ relative to the above one was calculated.

Two types of the AE signals were registered in AE tests of the base metal of alloy 1201-T: AE signals with low amplitudes (A = 0.4–0.5 mV) and κ = 0.2–0.3; and high-power AE signals with A = 1.5–2.0 mV and κ = 0.5–0.6.

Like in the case of the base metal, fracture was accompanied by generation of the two types of the AE signals. Characteristic feature of all the signals is their considerable duration (t = = 20–30 μs), compared to the AE signals fixed

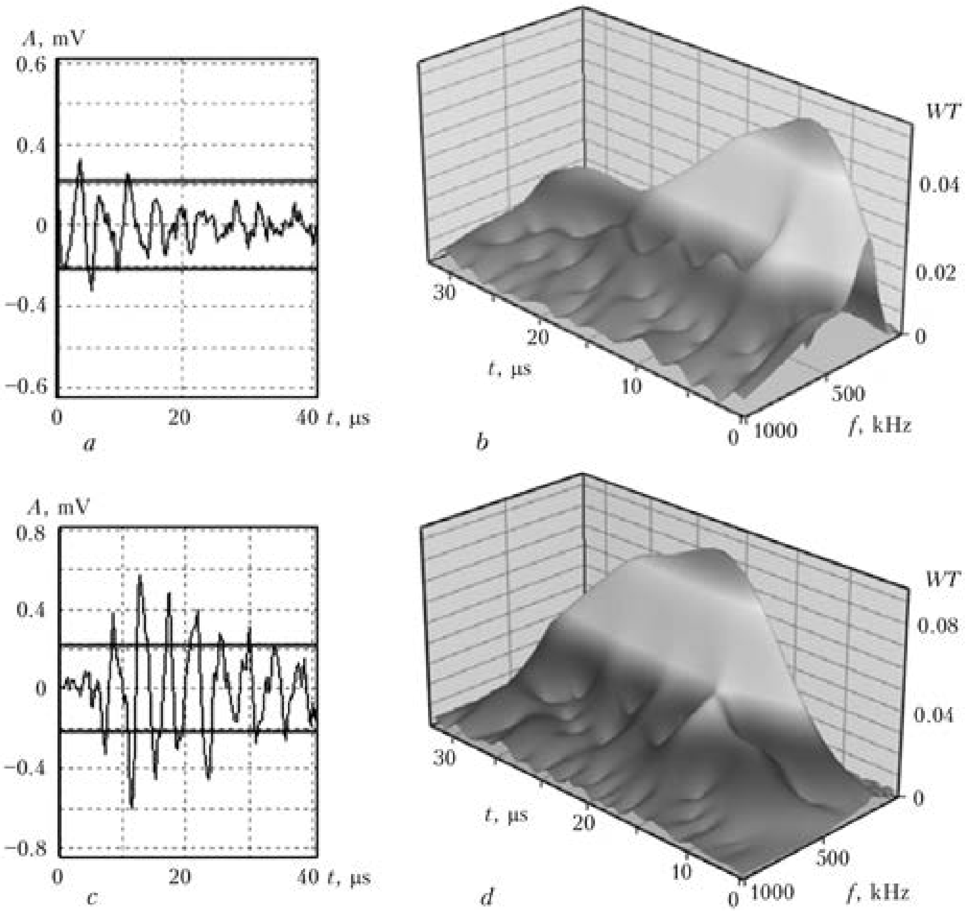


Figure 3. Wave reflections (*a*, *c*) and continuous wavelet-transforms (*b*, *d*) of characteristic AE signals (fracture of HAZ metal on alloy 1201-T)

in fracture of other materials [13, 14], this resulting in the characteristic shape of the wavelet-spectra (see Figure 3, *b*, *d*).

The first group of the signals included weak signals (see Figure 3, *a*) with amplitudes A = = 0.2–0.3 mV, which are characterised by low values of maximal wavelet-coefficients $WT_{\max}$ = = 0.04–0.05 (see Figure 3, *b*), wide frequency bands Δf = 125–130 kHz and κ = 0.15–0.20. These EA signals are generated in tough fracture of the solid solution, which makes up the bulk of the recrystallised ductile HAZ grains.

The second group of the AE signals features high values of maximal wavelet-coefficients $WT_{\max}$ = 0.08–0.10 (see Figure 3, *d*) and narrow frequency bands Δf = 95–105 kHz. These signals are generated in quasi-brittle cracking of local clusters and thin layers of intermetallic Al_2Cu located at the grain boundaries.

Peculiarity of fracture of the welded joint fusion line is that it is accompanied both by cracking of the coarse clusters of eutectic inclusions and by detachment of the melted HAZ grains. In the latter case the AE signals with amplitudes A = 0.4–0.5 mV and κ = 0.3–0.4 are generated (Figure 4, *a*, *b*).

Brittle spalling of intermetallics at the fusion line generates strong signals of high amplitudes A = 4–5 mV (Figure 4, *c*), the values of the maximal wavelet-coefficients of which are $WT_{\max}$ = 0.15–0.16 (Figure 4, *d*), and frequency bands are Δf = 80–90 kHz. Here criterial index κ = 0.7–0.9 has the highest value.

The weld in the joint on alloy 1201-T, compared to the base metal, has a finely dispersed structure and is weakened. Fracture in this case occurs by the tough mechanism and is accompanied by weak AE signals (Figure 5, *a*) at κ = = 0.10–0.15. Their distinctive feature is considerable duration (t = 40–60 μs) and presence of several peaks on the wavelet-spectra (Figure 5, *b*), which indicates to simultaneous fracture of matrix and delamination of inclusions.

Therefore, cracking of the intermetallic inclusions occurs by the brittle mechanism ($\kappa \geq 0.3$) with maximal values of κ at the fusion line, as there the biggest cluster of coarse intermetallics is found, and the solid solution of copper in aluminium is characterised by a fracture occurring mostly by the tough mechanism ($\kappa \leq 0.2$). The character changes into the brittle one only outside the welded joint, because hardness of the

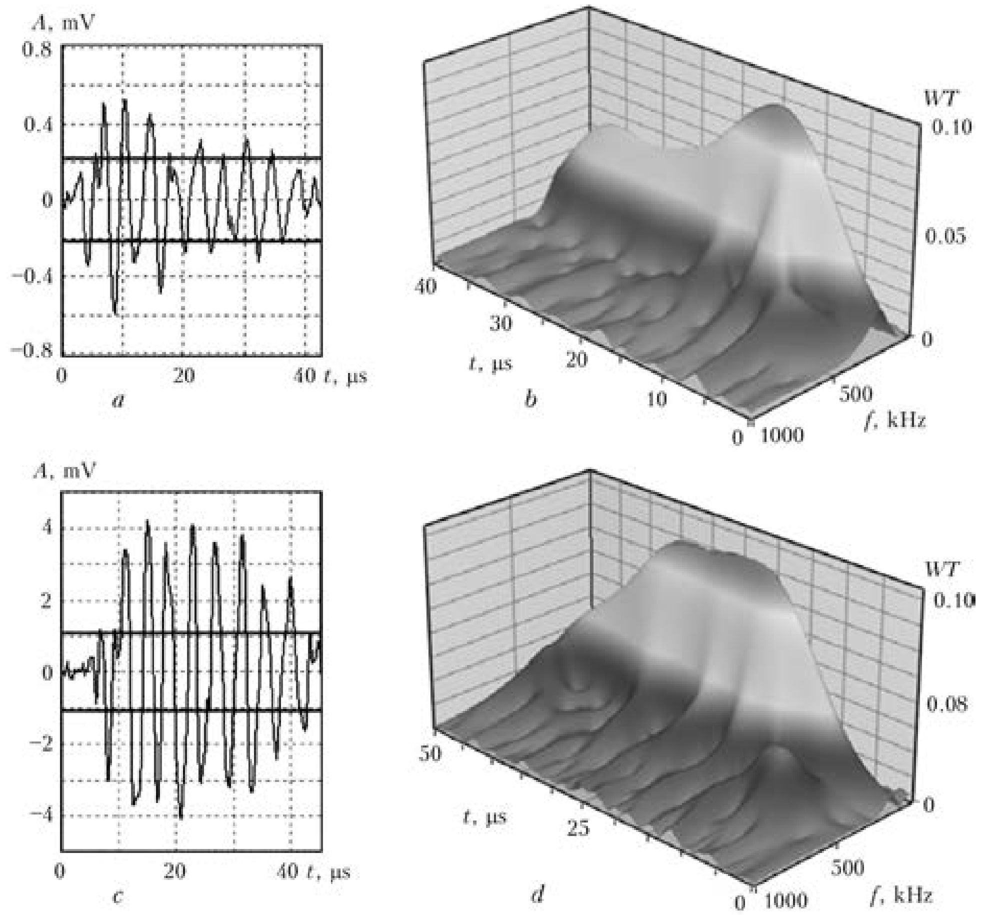


Figure 4. Wave reflections (*a*, *c*) and continuous wavelet-transforms (*b*, *d*) of characteristic AE signals (fracture of fusion line of welded joint on alloy 1201-T)

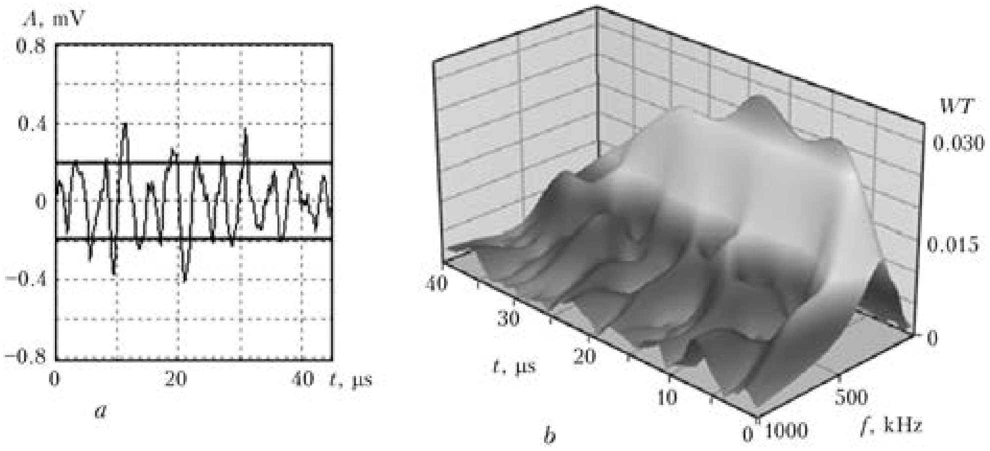


Figure 5. Wave reflection (*a*) and continuous wavelet-transform (*b*) of characteristic AE signals (fracture of weld metal in welded joint on alloy 1201-T)

base metal is much higher than that of the weld and HAZ.

Conclusions

As established from analysis of fixed wave reflections of the AE signals and continuous wavelet-transforms, the AE method allows identification of sources of the AE signals under static loading of aluminium alloys and their welded joints. Tough (weld and HAZ metals) and brittle-tough (base metal) fractures of the solid solution of copper in aluminium generate the AE signals of low and medium amplitudes ($A = 0.2$–0.5 mV), for which the criterial index varies within 0.15–0.30. Detachment of the melted grains is accompanied by generation of the AE signals with an amplitude range of $A = 0.5$–4.0 mV and $\kappa = 0.3$–0.4, whereas cracking of coarse intermetallics is accompanied by generation of the high-power signals ($A = 0.5$–4.0 mV) with index $\kappa = 0.5$–0.9.

It was found from the experimental test results that the most dangerous region (in terms of strength of structures) is the fusion line between the weld metal and HAZ, which is characterised by a dramatic change in size of structural components and mechanical characteristics. In this case the fracture occurs by the quasi-brittle mechanism. As a result, under static loading of the welded joint the crack propagates into this region, moving along the clusters of secondary phases and melted planes of the HAZ grains, thus decreasing the consumption of energy for fracture. In this case, the AE signal parameters change according to the mechanisms of fracture in different zones of the welded joints.

1. Nazarchuk, Z.T., Skalsky, V.R. (2009) *Acoustic emission diagnostics of structural members*. Kyiv: Naukova Dumka.
2. Skalsky, V.R., Lyasota, I.M. (2009) Application of acoustic emission phenomenon for diagnostics of fracture of welded aluminium alloy joints (Review). *Mashynoznavstvo*, **9**, 42–47.
3. Mezintsev, E.D., Tikhy, V.G., Karasyov, L.P. (1982) Application of simulated defects in testing of the technical diagnostics acoustic emission system. *Avtomatich. Svarka*, **9**, 28–30.
4. Tikhonov, L.V., Prokopenko, G.I. (1991) Detonation mechanisms of deformation, fracture and acoustic emission in aluminium and its alloys. *Tekhn. Diagnostika i Nerazrush. Kontrol*, **1**, 73–76.
5. Tikhy, V.G., Sanin, F.P., Borshchevskaya, D.G. (1982) Study of dependence of the acoustic emission signals on the character of welding defects in alloy AMg6. *Avtomatich. Svarka*, **9**, 36–38.
6. Skalsky, V.R., Sergienko, O.M., Golaski, L. (1999) Generation of acoustic emission from cracks propagating in welded joints. *Tekhn. Diagnostika i Nerazrush. Kontrol*, **4**, 23–31.
7. Skalsky, V.R., Koval, P.M. (2005) *Acoustic emission in fracture of materials, products and structures*. Lviv: SPOLOM.
8. Venkitakrishnan, P.V., Sinha, P.P., Krishnamurthy, R. (2006) Study and analysis of effect of various thermal processes in AA2219 annealed sheet using acoustic emissions. *Mater. and Design*, **27**, 770–775.
9. *GOST 25506–85*: Methods of mechanical tests of metals. Determination of crack resistance (fracture toughness) characteristic in static loading. Moscow: Standart.
10. Skalsky, V.R., Lyasota, I.M. (2012) Application of the acoustic emission method for determination of moment of initiation of macrofracture in aluminium alloy welded joint. *Tekhn. Diagnostika i Nerazrush. Kontrol*, **3**, 7–12.
11. Lozovskaya, A.V., Chaika, A.A., Bondarev, A.A. et al. (2001) Softening of high-strength aluminium alloys in different fusion welding processes. *The Paton Welding J.*, **3**, 13–17.
12. Astafieva, N.M. (1996) Wavelet-analysis: theoretical principles and application examples. *Uspekhi Fizich. Nauk*, 166(**11**), 1145–1170.
13. Skalsky, V.R., Bujlo, S.I., Stankevich, E.M. (2012) Criterion for evaluation of brittle fracture of glass from acoustic emission signals. *Defektoskopiya*, **5**, 26–34.
14. Skalsky, V.P., Botvina, L.R., Stankevich, O.M. (2011) Diagnostics of fracture mechanisms in steel 38KhN3MFA by using wavelet-transforms of acoustic emission signals. *Tekhn. Diagnostika i Nerazrush. Kontrol*, **3**, 12–17.
15. Vallen system: The Acoustic Emission Company. *www*.vallen.de

Received 09.07.2012

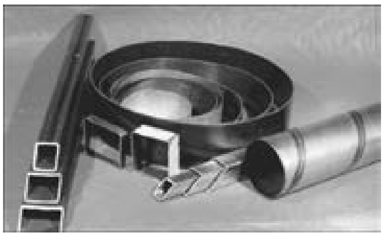
NEWS

Technology and Equipment for Manufacture of Rectilinear Welded Pipes of 20–76 mm Diameter Using the Method of Electric Welding with High-Frequency Currents

Strip is formed into a tubular billet from a coiled metal by multi-stand successive forming, the edges of this billet are brought together under an acute angle, heated, approaching the site of their abutting by high-frequency currents and upset up to obtaining the welded joint. The process of welding is continuous. Cutting of ready pipes is performed by a fly cutting device automatically.

Technical characteristics of the equipment:

Welding speed, m/h	30 ÷ 50
Capacity of HF power source, kW	100 ÷ 250
Capacity of electric drives, kW	90
Thickness of pipe wall, mm	1.2 ÷ 3.5
Length of pipes, m	up to 8 and more
Material being welded	cold-rolled or hot-rolled coiled steel, aluminium



Field of application. Machine building, construction, furniture industry, consumer's goods.

Efficiency. 3–4 km per shift.

Payback. The term of payback depends on annual program and at a full loading of pipe-welding mill it can be 1 ÷ 1.5 years.