Investigation of residual stress in composites produced by explosion welding with ultrasound

E V Kuz’min, M P Korolev, S V Kuz’min and V I Lysak
Volgograd State Technical University, Volgograd, Russia
E-mail: e.v.kuzmin@yandex.ru

Abstract. The paper presents the results of experimental studies of residual stress in homogeneous steel samples obtained by explosion welding with simultaneous exposure to ultrasound. For experimental determination of residual stress in composites, a method based on sequential removal of thin metal layers from the sample surface and measurement of deformations of the sample from the opposite side using strain gages was chosen. It is shown that the introduction of ultrasound in the process of explosion welding leads to both a redistribution of residual stress and a significant decrease in their maximum values measured in the immediate vicinity of the junction zone of steel samples.

1. Introduction
Composite materials are increasingly used in almost all industries and engineering, with extremely high growth potential and prospects for implementation in key sectors of the economy. Explosion welding is one of the most effective and often the only way to produce a wide range of composites with different combinations of layers and materials [1, 2].

One of the factors affecting the quality of joints obtained by explosion welding is the residual stress in composites that exist in a solid body without external forces being applied to it. The negative effect of residual stress is that when combined with the stress caused by the service load, they can reduce static and fatigue strength, as well as degrade the corrosion resistance of materials. Residual stress can cause deformation of products during machining, curing, changes in temperature conditions, as well as due to load application. Therefore, reducing residual stress and creating a favorable distribution of them is an important technological task. The most common way to solve this problem is heat treatment. However, this method is not applicable for compounds of composite materials with sharply different physical properties (for example, steel – titanium), since a new field of stress distribution with a large gradient occurs when they are heated due to the difference in the coefficients of temperature expansion [3, 4].

The most universal way to reduce residual stress is to introduce high-intensity ultrasonic vibrations into the composite. In this case, the mechanism of action on the metal is to increase the density and mobility of structural imperfections (dislocations and vacancies) under the action of alternating stress, which is accompanied by a decrease in the yield strength of the metal. In this case, internal stress cause plastic deformation in micro volumes and decrease to the acoustoelastic yield point [5–7].

In addition, a number of studies were conducted [8–12], in which ultrasonic vibrations were applied to a fixed plate directly during welding by explosion. It was found that the introduction of ultrasound during explosion welding leads to an increase in the strength of the joint and changes in the parameters of the wave profile of the joint boundary. The impact of ultrasonic vibrations on one of the
plates during explosion welding leads to an increase in the degree of deformation in the vicinity of the joint zone while simultaneously reducing the deformation gradient, accompanied by a decrease in the temperature gradient along the thickness of the composite, which, ultimately, can reduce the residual stress in the composite [9, 10].

Thus, the purpose of this work is to experimentally determine the nature of the distribution of residual stress in composites obtained by explosion welding with the influence of ultrasound.

A number of researchers have addressed the problem of residual stress after explosion welding. Thus, in [13, 14], the method of drilling blind holes and measuring deformations using strain gages was used. The authors concluded that with increasing hole depth, the sensitivity of the method significantly decreases and the study of residual stress at a significant depth is impractical. In [15], residual stress was calculated based on the deformation of thin plates cut from the sample. The presented results demonstrate low accuracy of stress measurement, while a significant difficulty lies in the high requirements for accuracy and quality of cutting. A promising method is to calculate the first-type stress based on the second-type stress obtained by x-ray diffraction [16], but in this case the complexity lies in the need to use expensive equipment. In work [17], the method of sequential milling was used, which made it possible to obtain the stress distribution in the sample at a considerable depth. However, with an increase in the thickness of the sample, the required number of strain gages increases, and at the same time the complexity of measurements.

2. Materials and methods
St3 steel plates 10 mm thick were used as starting materials. Explosion welding was performed with simultaneous exposure to ultrasound on a fixed plate according to the scheme with counter-directional propagation of ultrasonic vibrations relative to the direction of the welding process (figure 1) at optimal conditions that provide high strength of the layers connection [18]. To compare the results of the study, explosion welding of control samples (the same metal pairs) was performed simultaneously under identical modes of explosive loading, but without the influence of ultrasound. The detonation rate of the explosive was controlled by an electro-contact method with the registration of parameters by electronic equipment (TEKTRONIX DPO oscilloscope, CHZ-63 frequency meter). As an ultrasonic generator, we used the UZGI-2 installation with a piezoceramic converter and a cone concentrator, which are characterized by simplicity, reliability in operation and the ability to change the amplitude of vibrations in a fairly wide range.

![Figure 1](https://example.com/figure1.jpg)

**Figure 1.** Explosion welding with ultrasound: base (1); fixed plate (2); throwing plate (3); explosive charge (4); waveguide (5); piezoelectric ultrasonic transducer (6); ultrasonic generator (7).

3. Results and discussion
To study residual stress after explosion welding, a method based on successive removal of thin layers of metal from the sample surface and measurement of deformations of the sample from the opposite side using strain gages was used [19].

The sample for the study of residual stress is a bimetallic rod, 200 mm long and 20 mm wide. The layers are removed using the gouging method with a minimum cross feed and a cutting speed of no
more than 17 strokes/min. No more than 0.5 mm is removed in a single pass, which minimizes the introduction of additional stress during the cutting process. Processing is performed up to a thickness of 6 mm, to obtain a complete plot, a second sample is used, which is processed from the other side. The strain measurement of the sample is performed using strain gages (base 20 mm, resistance 200 Ohms) connected by a bridge scheme (figure 2a). Sensors R1 and R3 are glued to the test sample, and R2 and R4 for the purpose of thermal compensation are glued to a separate, non-processed sample of the same material (figure 2b). To register the readings, the strain gauges are connected to the computer using an analog to digital converter.

Figure 2. Scheme for experimental determination of residual stress in explosively welded composites: a) connection diagram of strain gages; b) scheme of labeling of strain gages on samples: ADC-analog-to-digital converter; R1 ... R4 are strain gages; processed sample (1); thermal compensation sample (2); cutter (3); removable layer (α).

Figure 3. The interface of the program to calculate residual stress.
Figure 4. Plot of residual stress in the connection St3+St3: welded without exposure to ultrasound (1); welded with exposure to ultrasound (2).

Figure 5. The microstructures of joints of St.3+St.3: welded without exposure to ultrasound (a), welded with exposure to ultrasound (b).
The calculation model is based on the principle of reverse stress, according to which the removal of an elementary layer containing residual stress is equivalent to applying a force to the remaining part of the sample, under the action of which deformations will occur in the lowest layer. The initial data for the calculation are the thickness of the removed layers and their corresponding deformations, measured after removing each layer, as well as the elastic modulus of materials and geometric parameters of the sample.

For computer processing of the received data and determination of residual stress, a computer program was developed [20], the interface of which is shown in figure 3. In the upper part of the window, the user enters the initial characteristics of the composite. These are the thickness, elastic modulus and number of layers, as well as the resulting number of passes after removing each layer. Experimentally measured data (deformations and thickness of the removed layers) are entered in the corresponding rows in the left part of the window. After executing the "calculate" command, the residual stress for the corresponding layer are determined by the thickness of the composite, and depending on the sign, the user can immediately determine the type of stress (compression or tension). Based on the obtained values, plots of residual stress are constructed depending on the thickness of the composite.

Figure 4 shows the diagrams of residual stress in the St3+St3 joints welded at the same modes, without the influence of ultrasound and ultrasound applied to a fixed plate. Samples were cut in the direction of detonation, two from each plate. It is experimentally established that the introduction of ultrasound in the process of explosion welding leads to both a redistribution of residual stress in samples welded by explosion with the influence of ultrasound, and a significant decrease in their maximum values. Thus, in samples welded by an explosion with the influence of ultrasound (test samples), the maximum values of residual tensile stress measured in the immediate vicinity of the junction zone were about 350 MPa, compared to 450 MPa in control samples obtained by welding by an explosion without the influence of ultrasound. The residual compression stress in the studied samples also decreased in comparison with the control ones, both over the entire plot area and at the level of maximum values (figure 4). The unbalance of the plots in the studied samples was 5 %, while in the control samples it was 7.8 %, which allows us to judge the sufficient accuracy of the results.

Metallographic studies of the junction zone of steel samples have shown that both when welding by explosion with the influence of ultrasonic vibrations and without them, the junction boundary has a pronounced wave profile with a minimum amount of fused metal concentrated at the tops of the waves. When exposed to ultrasonic vibrations in steel samples, there is a decrease in the parameters of waves and the amount of molten metal of the compound (figure 5b) compared to control samples welded without the use of ultrasound (figure 5a), which is in good agreement with previous studies [8–12, 18].

4. Conclusions
The method of studying residual stress in composites, based on the sequential removal of thin layers of metal from the sample surface and the measurement of deformations of the sample from the opposite side using strain gages, has demonstrated its suitability and applicability to composites of large thickness in practice.

It is experimentally established that the introduction of ultrasound in the process of explosion welding leads to both a redistribution of residual stress in samples welded by explosion with the influence of ultrasound, and a significant decrease in their maximum values.

The unbalance of the graphs of residual stress plots was no more than 7.8 %, which allows us to judge the sufficient accuracy and reliability of the results obtained.

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