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IMPROVEMENT OF SERVICE PROPERTIES OF METAL STRUCTURES BY EXPLOSION TREATMENT

A.G. Bryzgalin, E.D. Pekar, P.A. Shlonskyi and **L.V. Tsarenko**
E.O. Paton Electric Welding Institute of the NAS of Ukraine
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine. E-mail: office@paton.kiev.ua

Explosion treatment of metals in the modern sense is represented by different technological processes based on application of the energy of explosion, and allowing improvement of certain service properties of the metals or welded structures. PWI developed technologies of explosion treatment to improve the corrosion resistance, dimensional stability, cyclic fatigue life of welded structures, lower the residual stresses, eliminate defects of tank shape, and increase the strength, ductility, and cold resistance of low-carbon steels. The above technologies have high mobility and responsiveness, and are independent of the external energy sources. Their disadvantage is limited applicability of explosion in settlements and long-term process of obtaining permits. However, there is extensive experience of application of explosion treatment under the conditions of operating industrial production. 15 Ref., 6 Figures.

Keywords: explosion treatment, welded structures, service properties, corrosion resistance, strength, ductility, fatigue life

The concept of «explosion treatment of metals» (ET) consists of a wide range of technological processes based on the specifics of pulsed impact of detonation products of explosives (Ex) on the treated material. The first patent, which describes the technology of joining pipes by high-velocity explosive deformation, was granted in Great Britain in 1898. The best known of the early publications was the report of a group of US researchers on the works on Ex effect on low-carbon steel, performed in 1919–1926. In 1940 the works by British researchers were published, which are devoted to different aspects of the problem of explosion treatment of metals. In 1951 N. McLeod claimed the first invention — explosive hardening of high-manganese steel. This method became applied in industry in the USA, Canada and the USSR. In 1966 the monograph by J.Reinhart and J.Pearson [1] was published that contained a review of investigation results obtained at that time on metal treatment by explosion.

The 1950s can be regarded as the beginning of systematic research and application of the method of pulsed treatment of metals, primarily due to the work of a group of scientists led by M.L. Lavrentiev, who discovered the phenomenon of welding and high-velocity oblique collision of metals, the focused study of which formed the base of explosion welding technology. Further investigations, conducted mainly by the USSR, USA and UK scientists, allowed development of a number of technologies, extensively used in industry [2].

Explosion welding became the most widely accepted of the pulsed technologies.

Unique capabilities of this welding method allow producing tight joints of metals differing by their properties that cannot be welded by any other methods, as well as composite materials of different composition.

High-manganese steels have the capability of an abrupt increase of surface hardness as a result of pulsed high-velocity impact. Surface hardening of steels by Ex is used to extend the service life of rapidly wearing parts of the railway, mining and ore processing machines and equipment. Unlike other known methods of surface hardening (roller rolling, shot-blasting, peening, etc.), which provide increase of hardness to the depth of up to 4 mm, ET allows achieving the hardened layer depth of up to 35 mm and more, that increases the product wear resistance not only due to hardness increase, but also due to a more favourable distribution of residual stresses (RS) induced in the near-surface layer by treatment.

The explosion stamping technology is applied in those cases, when it is impossible to use the traditional stamping methods, as the parts are thick, and it is necessary to lower the reverse plastic deformations to the maximum.

ET is widely used in the technologies of treatment of powder and composite materials [1]. The shock-wave effect at explosion loading allows modifying the properties and treating high-strength, hard, and hard-pressed powder materials; producing large-sized high-density billets and products of a complex shape that cannot be achieved by the traditional technologies.

A.G. Bryzgalin — https://orcid.ord/0000-0001-5886-3069, E.D. Pekar — https://orcid.ord/0000-0001-5025-4445

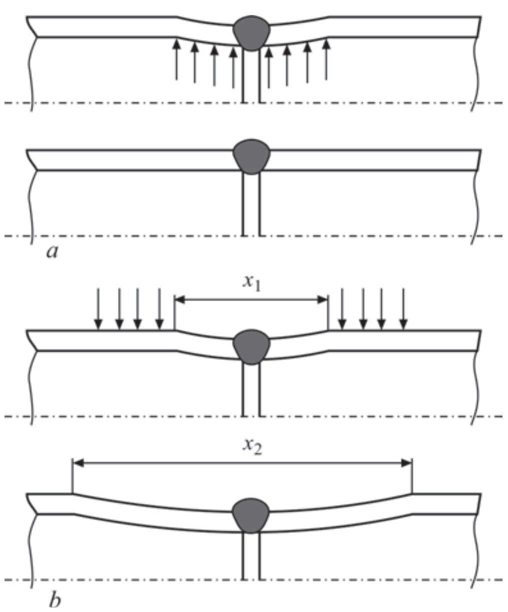

Figure 1. Principal diagrams of ET of girth welds of cylindrical structures: *a* — inner; *b* — external charge

Other kinds of ET, which are not as widely known, but also find application in industry, are new material synthesis, embossment, perforation, when the work tool force is applied due to explosion, riveting, tube-to-tubesheet welding, chips briquetting, etc.

In 1967 it was established at PWI that pulsed treatment [3] can significantly affect the service properties of metal structures.

It is possible to conditionally single out three main mechanisms of the effect of explosion treatment of metals on the change of structure service properties:

1. Change of metal structure, which is expressed in refinement and change of relative location of grains and nonmetallic inclusions, formation of twins and slip lines, significant increase of the number of dislocations, activating the mobility of which, for instance, by heating, leads to a positive change of service properties of the structure metal. This mechanism was used at development of the methods of increasing the wear resistance of cutting elements of mining equipment that is manufactured from high-strength manganese steel, making hardness standards, increasing the resistance of high-carbon steels to hydrogen embrittlement.

2. Changing or formation of new RS fields.

Two methods of realization of this mechanism can be singled out. One of them pertains to welded axisymmetric products, and the other — to flat welded sheets [4].

The first consists in the use of pipe wall throwing that leads to metal expansion in the zone of action of circumferential welding elastic tensile deformations, which is usually applied at ET of girth welds of predominantly large-sized shells, as well as pipelines with unrestricted access inside, or, contrarily, to swaging (upsetting) of the pipe wall in the zones of action of compressive plastic deformations. Figure 1 schematically shows «throwing» variants of ET of girth welds in structures of the type of cylindrical tanks and pipelines.

The parameters of external circular charges can be selected so that pipe radius in the zone of charge positioning after ET was smaller than that of the girth weld that will result in inducing compressive RS in the weld.

The second of the above-mentioned methods used at ET of sheet structures, consists in applying to the welded joint metal the normal pressure created by explosion, which leads to formation of plastic deformations in the treated metal plane — so-called stress-strain trace with biaxial compressive stresses. Their value can reach the metal yield limit, and it depends little on the initial stressed state of the welded joint [4]. Formation of such a «trace» in the metal leads to relaxation of the initial tensile stresses. Figure 2 gives the block diagrams of the location of Ex charges at treatment of flat welded joints.

Comparatively inexpensive and affordable detonation cords (DC) became widely accepted in ET practice. They are extensively used, in particular in the mining industry. Transverse dimensions of the «trace» depend on the quantity and arrangement of the cords on the surface being treated. Due to that the «trace» configuration is easily adjustable, and the «trace» depth can be considerable, reaching tens of millimeters. Thus, it becomes possible to effectively relieve RS in up to 50 mm thick joints. Figure 3 shows the yield bands that characterize the configuration and cross-sectional dimensions of the real «trace» of typ-

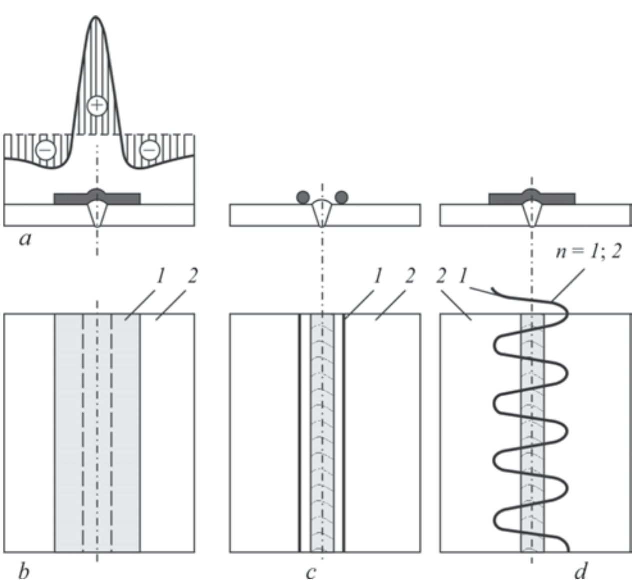

Figure 2. Principal diagrams of ET of welded joints on sheet structures: *a* — welding RS curve; *b* — linear scheme based on strip charge; *d* — «snake» scheme (*1* — Ex charge; *2* — welded joint)

ical size formed in low-carbon steel by detonation of DSh-A cord on its surface.

The majority of practically used ET technologies are based on application of exactly this mechanism that explains the need for a more flexible study of the processes proceeding in the metal at the moment of shock wave passage and interrelation between the loading parameters and the stress-strain state of welded structures.

3. Formation of macroplastic deformations in the structure body that allow regulating or changing its shape. Such tasks arise, as a rule, in case of the need to eliminate any defects in the form of large-sized sheet structures, for instance, so-called angularity of site joints of cylindrical tanks that are made by the method of deploying coiled blanks.

Further study of ET effect on the properties of metals and welded joints [5, 6] showed that ET allows solving a rather wide range of tasks, related to improvement of the quality and extension of welded structure service life. At present PWI has the priority in this direction of investigations, as here not only the mechanisms of explosion effect on the structure, stressed state and properties of welded joints have been studied, but various ET technologies have been developed and became rather widely accepted by industry [7, 8]. Let us give the most characteristic examples of ET application to improve the reliability and fatigue life of welded structures and give them new service properties.

1. Metal structures with a high level of working or residual stresses, susceptible to the hazard of a particular kind of spontaneous fracture of metal, known as stress corrosion cracking. It is manifested both in alkaline and acid environments. Proneness of metal structures to fracture in active working media is determined by three main conditions [6]: 1) metal properties; 2) stressed state; 3) environmental impact. Depending on specific conditions, different kinds of structure failure can occur: from mechanical fracture, when the role of the environment is insignificant, to kinds of fracture, when the role of stresses is insignificant, for instance, at general corrosion.

Presence of welded joints in the metal structure lowers its fatigue life under the impact of an aggressive medium. Specific features which determine the causes for, nature, kinetics and mechanism of welded joint destruction, depend mainly on thermophysical and chemico-metallurgical effect of welding, as it causes unfavourable changes of metal properties and stressed state that enhances the negative effect of the environment.

The stressed state affects the corrosion behaviour of metal as a result of the following phenomena [6]:

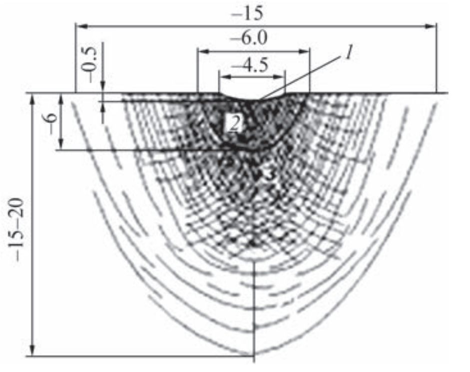

Figure 3. Chernov-Luders bands from DC explosion on the surface of St3 sample (band intensity corresponds to plastic deformation magnitude) [5]

● transfer of additional energy to the metal, causing reduction of its thermodynamic stability;

● violation under the impact of respective deformation, of the integrity and, hence, protective properties of oxide films that leads to graded distribution of surface potential;

● increase of the degree of nonuniformity related to appearance crystalline lattice defects under the impact of deformation and with formation of additional anode potentials.

On the whole, the danger of the impact of the stressed state on activation of the corrosion processes consists not only in increase of the general corrosion rate, but in the change of its nature, and its transformation from the uniform into the local one. Having a slight impact on general corrosion, the stresses intensify the local kinds of corrosion, the most dangerous of which is cracking.

It is established [6] that corrosion cracks are induced by tensile components of the stress tensor, irrespective of the loading method. For all the metals the time-to-fracture is continuously reduced with increase of stress magnitude. At the same time, in the majority of the cases, there is a stress threshold, below which cracking does not occur for a long time, or does not occur at all. The magnitude of threshold stresses depends on the specific conditions: metal properties, stressed state, and corrosion environment. Here, existence of threshold stresses is characteristic both for stresses caused by external loading, and for residual stresses.

The most dangerous are failures of welded structures in aggressive media. These are stresses related to metal hydrogenation during operation [9]. This fracture is characteristic for structural steels, particularly higher strength steels. The causes for predominant hydrogenation of the welded joints are structural heterogeneity of the welded joint and presence of RS of the first and second kind.

Lowering of RS in welded joints, operating in contact with the environment that hydrogenates the met-

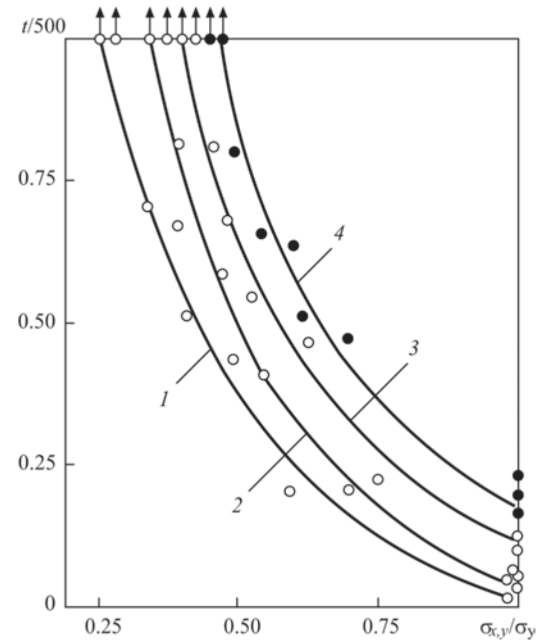

Figure 4. Dependence of fatigue life in boiling solutions of nitrates of butt welded joints of St3 steel on RS magnitude reduced to the yield limit: *1* — metal thickness of 6–8; *2* — 10–14; *3* — 16–22; *4* — 24–30 mm

al, is a necessary condition for increasing their fatigue life. In the majority of the cases, such a lowering is achieved by conducting heat treatment in high-temperature tempering mode. Heat treatment operation requires a lot of funds and time. ET application can be an alternative to heat treatment.

In alkaline environments ET enables ensuring «absolute» corrosion resistance [9] by lowering RS below the threshold values.

Figure 4 shows the fatigue life curves of welded butt joints of low-carbon steel in boiling solutions of nitrates [9].

One can see that RS lowering below the threshold level completely eliminates the possibility of corrosion cracking of the welded joint. It turned out that RS of threshold level depend on metal thickness. Prevention of stress corrosion cracking in alkaline environments is highly urgent, in particular, in aluminium

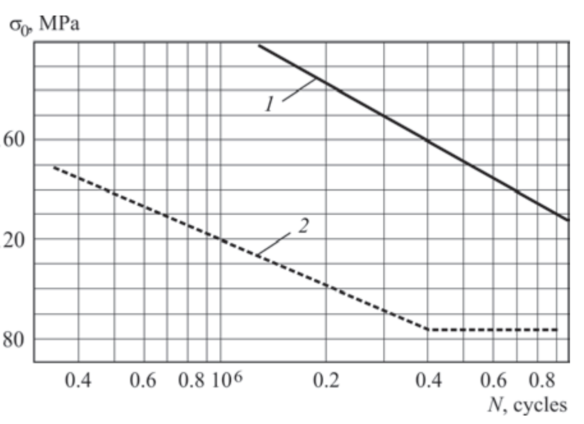

Figure 5. Fatigue life curves of samples with a transverse stiffener of AK type steel: *1* — after ET; *2* — initial state

industry in alumina production. The technology of ET of welded joints of tank equipment and process pipelines of decomposition sections was developed at PWI and became applied in the largest aluminium and alumina producing plants of the USSR and Yugoslavia [10].

2. Positive effect in the form of increase of fatigue life of welded joints at the stage of crack initiation in the high-cycle loading region is achieved at ET, firstly, due to relieving the tensile RS and, secondly, due to inducing compressive RS in the areas of stress concentration. PWI has accumulated extensive theoretical and experimental material, which is indicative of the high effectiveness of this kind of treatment [11]. It is found, in particular, that increase of fatigue resistance can be quite considerable, and it depends mainly on the scheme and intensity of explosion loading, as well as cycle characteristics.

Figure 5 gives the fatigue curves of samples from low-alloyed high-strength steel with a transverse stiffener, tested at a symmetrical loading cycle.

3. One of the important characteristics of strength of metals and welded joints exposed to variable loads is their ability to resist propagation of the already existing fatigue cracks. The significance of this characteristic consists in that the stage of crack propagation, determined by the number of cycles to fracture, can be equal to 70–90 % of the total fatigue life of the product. ET can be used to induce in the metal intensive «stress–strain traces» with preset distribution and magnitude of biaxial compressive stresses, which are a barrier to crack propagation and are capable of slowing down or totally preventing their propagation, as well as preventing their transition into brittle cracks [5].

4. The need to relieve RS arises also in those cases when their natural relaxation under the impact of variable loads can lead to inadmissible changes of the dimensions, geometry or relative position of the parts or sections of the structure, disturbance of the seats, etc. ET application in this case allows avoiding the appearance of warpage that affects the service properties of critical structures. Figure 6 illustrates the change of RS as a result of ET of the closing butt joint of a water conduit of approximately 6 m diameter in Tashlyk hydroelectric pumped storage power plant [5].

5. In practice characteristic form defects, so-called angularity, often develop in the area of closing vertical site welds in the large-sized tank facilities manufactured by the industrial method from coiled blanks and designed for petroleum product storage. In tank operation at their filling and emptying these defects have the role of stress raisers and cause wall damage as a result of low-cycle fatigue. Now the technology of ET of site butt joints of tanks of up to 10–50 thou m^3

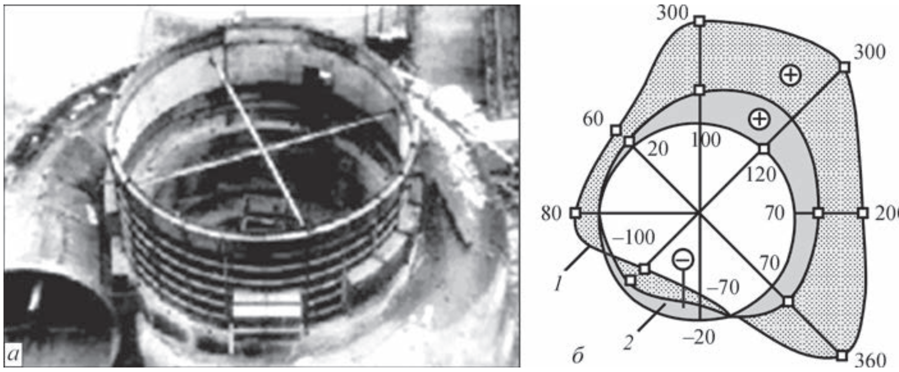

Figure 6. General view of a water conduit volute of the hydraulic unit of a pumped-storage plant (*a*) and curves of circumferential RS in the closing butt joint (*b*): *1* — in the initial state; *2* — after ET

volume has been developed and is used in production that allows extending the structure fatigue life 5 to 10 times [12]. The above-mentioned developments have already been brought to the stage of commercially applied technologies.

In 1980s PWI developed new technologies of combined explosion-thermit and preliminary ET of the edges to be welded, so-called explosion-welding treatment [13, 14]. The package of the proposed technologies enables improvement of the mechanical properties and structure of the metal by changing its fine structure as a result of intensive loading during explosion and further homogenizing of the structure during heat treatment or welding.

The majority of ET technologies that have become accepted in practice now, are based on the ability of this kind of postweld treatment to significantly lower and redistribute the RS. As was shown in [15], this effect can be achieved for a rather wide class of structures with up to 50 mm wall thickness.

Characterizing on the whole the considered effects, which are due to ET of welded joints, we will note that it enables achieving an improvement of a set of important properties of the welded joints up to the level matching the base metal that ensures the equivalent strength of welded structures operating under extreme conditions. The ET advantages and effectiveness are the base for its wide industrial application. Development of the technologies based on application of the studied treatment mechanisms should be performed for each specific case.

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