MULTILAYER STRUCTURES OF INCREASED CRACK RESISTANCE FORMED BY EXPLOSION WELDING

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Application of laminar structural materials is challenging in the solution of problem of increasing the reliability and life of heavy-loaded machines and equipment. The work deals with the possibility of application of explosion welding for producing myltilayer structures with a high reserve of crack resistance, achieved by control of composition and properties of the joining zone by adding barrier layers. As a barrier layer it was suggested to apply metals, not interacting in solid state or those, forming interstitial solid solutions (vanadium, copper, nickel). The analysis of test results of laminar specimens for low-cycle fatigue under conditions of pulsaring tensile cycle allowed establishing the kinetics of fatigue fracture, depending on structural state of interlayer interface of metal composition. It is shown that adding of an intermediate metal layer, characterized by greatly different properties and increased ductility, to the structure of composition leads to increase in crack resistance of material as compared to the similar equivalent. 5 Ref., 3 Figures.

Keywords: *explosion welding, laminar composite materials, multilayer structures, crack resistance of compositions, barrier layers, copper, zone of plastic deformation*

One of the main ways of solution of problems of increasing the reliability and service life of structures of machine parts, operating under severe conditions of loading, can be the development of laminar composite materials, allowing formation of structure and interfaces of layers in accordance with the conditions of the parts service.

Manufacture of laminar composite materials is realized by hot and cold plastic deformation of semi-products using rolling or pressing, thermodiffusion welding, casting, different types of deposition of one or several components on the surface or by combination of these methods. However, the significant drawbacks of the abovementioned methods are their selectivity, associated with a problem of producing a strong physical binding of metals and alloys, greatly differed by a complex of physical-mechanical and chemical characteristics [1]. In this connection, the actuality of technological processes based on feasibility of producing strong metallic compositions almost of any combinations and control of structure and properties of the joining interface does not raise any doubts. Explosion welding can be referred to these processes [2].

The explosion welding has a number of peculiarities, which are due to high intensity of plastic yielding and short-time action of high gradients of pressures and temperatures in near-contact layers of the collided plates. Under the specific conditions of explosion welding as one of the most profitable forms of conversion of kinetic energy of collided bodies into the energy of plastic deformation is the process of wave formation, which greatly influences the structure of contact zone and, respectively, the joint properties [3]. It should be noted that the unique potentialities of the explosion welding were mainly realized as effective means in the technology of manufacture of bimetal products to save the deficit non-ferrous metals and alloys.

In the present work the feasibility of application of explosion welding for the producing multilayer structures, characterized by high reserve of crack resistance, are considered for the first time.

During explosion welding of multilayer compositions both the successive joining of plates and also simultaneous joining of the whole packet for one operation are possible for producing the flat multilayer structures and also spatial ones with symmetric and conical symmetry. The simultaneous multilayer joining at a parallel scheme of orientation of elements being welded found the widest spreading. In this case, firstly the collision of upper plate with an intermediate one is occurred and then the intermediate plate acquires the speed of the upper plate and the combined flying of two plates is realized, and so on.

However, in explosion welding of multisheet compositions the problems are encountered, connected with the change of the process parameters: decrease in angle of collision, decrease in pressure during transition from upper to lower sheet, that in its turn causes the change of layers joining interface: from continuous layer of melts along the entire boundary of contacting to the sinusoidal boundary with the presence of eddy zones or rectilinear boundary without formation of regions of cast structure and, consequently, to the change of adhesion strength of layers. This drawback can be prevented by applying the guiding element of a proper mass. In this case the angle of collision is preset by guiding plate, the pulse of which is not almost changed during interaction with the first sheet, the flying speed of which is equal also to the speed of the guiding plate, that is repeated also for next sheets almost without changing the parameters of collision, i.e. explosion technology allows producing the quality joints both of double-layer and also multilayer compositions (Figure 1).

Figure 1. Explosion-welded two- and three-layer pipes

Development of new laminar compositions with a preset level of properties and rational structure of the material requires the well-grounded selection of components and technology of their manufacture. The selection of material of layers is realized coming from the conditions of the product service, as well as from chemical (thermodynamic and kinetic) and mechanical compatibility of components. The thermodynamically compatible components are those, which are not dissolved in each other and do not form chemical compounds of metals (for example, Mo–Cu, Nb–Cu). The majority of thermodynamically compatible components under definite temperature-time conditions can be compatible kinetically (metastable equilibrium) and provide the reliable operation of the structure. Mechanical compatibility, consisting in conformity of elastic constants, coefficients of thermal expansion and values of ductility of composing materials, predetermine the stress-strain state of the laminar materials.

The serviceability of composite products is determined by the joining zone, non-homogeneous in composition, the structure and properties of which are formed during the explosion welding process by melting the near-surface layers, their mixing and diffusion of the elements. In the zone of joining the producing of transition layers with lower or increased microhardness, as compared to initial materials, formation of brittle intermetallics and so on are possible. Depending on this, the nature of fracture of transition zone is changed: from tough-plastic to cleavage with regions of surface of tough fracture or brittle cleavage [3]. If follows from the above-said that it is necessary to produce the combination of strength of material of transition layers at its rather high ductility that can be provided by technological parameters of the explosion welding.

During development of crack-resistant laminar compositions the feasibility of control of composition and properties of the joining zone is considered by introducing of barrier layers. The application of these layers in development of laminar materials for chemically-interacting components is a quite well-known method [4, 5]. The barrier layer plays a role of inert interlayer, not allowing interaction between the layers being welded. The task of the investigation was the evaluation of possibility of using tough interlayer as a barrier layer, preventing the crack developing, study of crack interaction with interlayer and creation of a rational structure of composite material, capable to reduce the rate of crack propagation, to change its direction and arrest. As a barrier layer it was suggested to use metals, not interacting in solid state or forming the interstitial solid solutions (vanadium, copper, nickel). The most challenging material is copper, which eliminates the possibility of formation of intermetallic and carbide compounds.

To study the crack resistance of laminar composite materials, produced by explosion welding, the investigations of composites on steel 45 base: steel–steel bimetal and steel–copper–steel trimetal were carried out for multi-cyclic fatigue in machine UPM-2000 by scheme of pulsating tension with maximum force of cycle of 250 MPa, coefficient of cycle asymmetry 0.2 and loading frequency of 400 cycle/min. Type and shape of specimen are given in Figure 2.

The tests were carried out at constant loading, i.e. with fatigue crack developing the stresses were increasing in the rest part of the section. The process of fatigue crack growth was investi-

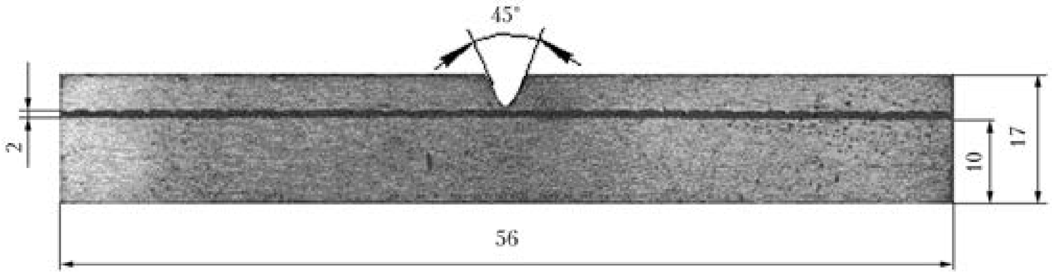

Figure 2. Appearance of trimetal specimen of steel–copper–steel for low-cycle fatigue test

gated on flat rectilinear specimens with a side notch. The presence of sharp side notch predetermined the initiation and propagation of crack in the transverse direction. The notch was made in steel 45, the notch bottom in bimetals was located at the distance of 3 mm from the interface of layers joining, in trimetals it was located at 2.5 mm distance. Under the same conditions not less than 6 specimens were tested. Face surfaces of specimens were polished from the apex of initiating notch into the direction of the future fatigue crack (roughness in the places of polishing was 0.05–0.08 μm), and then the measuring scale with 1 mm factor was applied on the way of crack growth.

Observation of the fatigue crack growth was made by the type MVT microscope, mounted on a special bracket on the machine frame. The crack length obtained for definite number of cycles of specimen loading was measured after the machine stop, moving the microscope objective in horizontal and vertical by means of micrometric screws. The measurement of crack length was made by the microscope limb at 0.01 mm accuracy.

The analysis of obtained results showed that the initial fatigue crack in steel 45 was initiated during $9\cdot10^{-4}$ cycles. The period of fatigue crack propagation from the steel–steel interface in bimetal and steel–copper (interface *A*) in trimetal was similar in principle and amounted to 140,700 cycles. After transition of the fatigue crack through the interface into the second layer in bimetal the final fracture of specimen quickly occurred, and the trimetal withstood even next 122,262 cycles, 18,962 cycles from which the crack was simply propagating in the copper interlayer and 103,300 cycles was required for delamination at the copper–steel interface (interface *B*) and for initiation of the fatigue crack in the second steel layer. The fatigue life of three-layer specimens was 348,000 cycles, and two-layer ones — 237,700 cycles.

Results of experiments, given in Figure 3, allowed establishing the kinetics of growth of the fatigue cracks. The obtained dependence of fatigue crack length on number of loading cycles shows that the change in rate of crack propagation in bimetal up to the joining interface coincides with the change in rate in trimetal up to the steel–copper interface. In bimetal, in which both the base metal and cladding layer are made of the same material, the strong joining of layers, excluding the possibility of delamination at the interface, predetermined the crack transition from one layer into another one at some delay. At the same time, in the three-layer composition the rate of fatigue crack, transferred into copper interlayer, drops immediately. The rate of crack, reached to the interlayer middle, is decreased by 40 % as compared with the crack rate at the steel–copper interface. At crack approaching the copper–steel interface its rate is continuously dropped, the crack is arrested and corresponds to the beginning of the crack growth in the base steel layer.

Having transferred into copper interlayer the crack changes the direction of its propagation, deviates from the plane of effect of maximum tensile stresses and develops in the direction of effect of maximum tangential stresses. Change in direction of the fatigue crack propagation in copper interlayer was caused by change in type of the fatigue crack formation. Copper is the metal with high energy of packing defects, in which transverse sliding is provided due to high capability of sliding of screw dislocations from one crystallographic plane into another one. In the copper interlayer a large number of microcracks is observed at cyclic loading, crack branching is occurred, most of which interrupt their growth, however, a part of microcracks continues their development with joining between themselves and forming an avalanche macrocrack.

With approach to the copper–steel interface, the fatigue crack is deviated from the initial direction of movement and propagated into both sides along the interface. In this case the growth of the avalanche crack is interrupted, and the crack itself is remained in the tough interlayer (horizontal area of curve *2* in Figure 3). Delay in crack movement during transition from copper

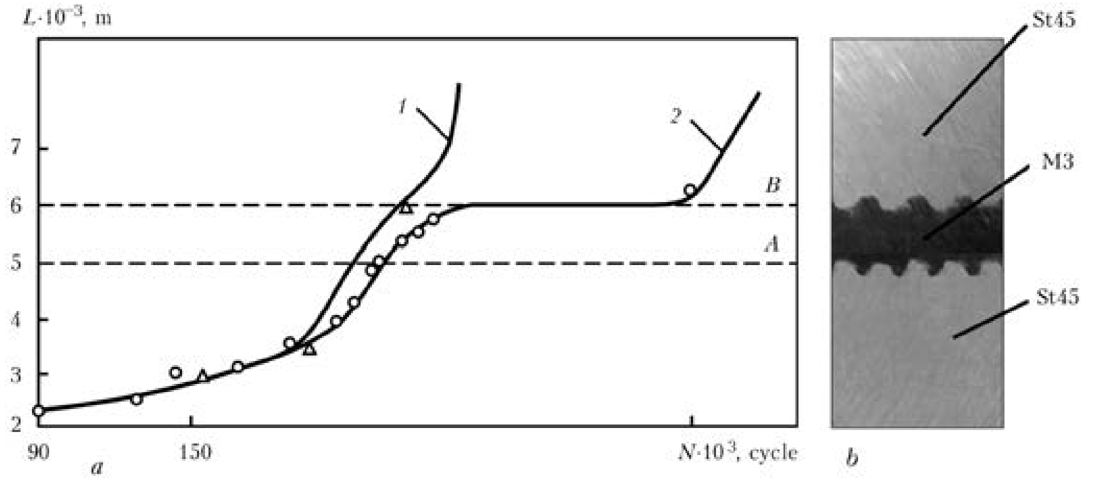

Figure 3. Kinetics of growth of fatigue crack in laminar specimens of steel 45 base in testing under conditions of pulsating tension (*a*): *1* — steel; *2* — steel–copper–steel; *A* — interface in steel–steel bimetal; *B* — copper interlayer in steel–copper–steel trimetal; *b* — appearance of interface of steel 45– copper M3–steel 45 joining

layer into steel one is connected with the crack movement along copper–steel interface and with mechanism of its initiation in the steel layer. Copper–steel interface became a barrier, which arrested the growth of fatigue crack and increased significantly the fatigue life of the metal composition. The process of fracture of the second layer of steel is occurred similarly to the fracture in the first steel layer.

Physical nature of metal fracture at cyclic loading is connected with accumulated plastic deformation [5]. The formation of zones of the local plastic deformation at the notch apex during testing of specimens under conditions of pulsating tension was studied by the visual observation of polished surface. The zone of deformation and fracture surface were investigated additionally by using the optic microscope.

Thus, the following regularities of formation of zones of local plastic deformation and crack movement were established. During the process of loading at notch apex under 45° angle relative to axis of load applying the two symmetric zones of local plastic deformation are formed in the form of pellets, representing the concentration of front of plastic deformation, the sizes of which are increased with load growth. Developing of these zones up to the moment of reaching the value of loading, close to maximum one, is occurred symmetrically, then the growth of one of them is delayed, while that of the second one is increased intensively and the avalanche crack is beginning to be formed in it. Local plastic deformation during explosion welding is developed in surface layers with the formation of hump of deformation and depression. Crack initiation is observed at the specimen surface near the notch edge within the region of maximum metal yielding (transition from deformation hump to depression). Fracture has a discrete nature and represents a joining of pores and tears in the region of the local plastic deformations. Trajectory of crack movement has an intricate configuration and depends on number and properties of the layers. At transition of crack from the material with close values of elasticity modulus into another material, its crossing through interface is observed without changing the propagation direction. Transition of crack from the material with lower modulus of elasticity to material with the higher modulus is difficult, the long time crack movement is observed along the interface. Adding of intermediate metal layer, characterized by greatly different physical-mechanical properties and increased ductility, to the composition structure leads to the increase of crack resistance of material as compared to the similar equivalent.

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