EVALUATION OF MECHANICAL PROPERTIES OF MICROSTRUCTURAL CONSTITUENTS OF WELDED JOINTS

A.Ya. ISHCHENKO and **Yu.A. KHOKHOLOVA**
E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine

Considered is the procedure for evaluation of mechanical properties of small-sized specimens based on determination of microhardness by the depth of penetration of Berkovich indenter in case of continuous indentation. Technical capabilities of this procedure have been assessed by evaluating the properties of γ-TiAl joints made by diffusion bonding. Statistical data on local distribution of microhardness were obtained, and values of Berkovich hardness, Young modulus and ductility coefficient of structural components within the zone of the diffusion bond have been determined.

Keywords: *diffusion welding, γ-TiAl alloy, titanium aluminide, foil, welded joint, mechanical testing, Berkovich indenter, microhardness, Young modulus, ductility coefficient*

Development of new processes of welding promising materials requires new approaches to evaluation of their mechanical properties. Produced welded joints are characterized by small dimensions and diversity of structural components. Strength testing of such objects by conventional destructive methods is highly problematic, which is associated with the influence of additional inner stresses induced during product fabrication, thus lowering the accuracy of testing results. In this connection a procedure is proposed for evaluation of mechanical properties of diffusion joints, which is based on microhardness determination by the depth of imprint of Berkovich indenter at continuous indentation [1–5]. The above procedure is applicable for non-destructive testing of products and allows studying local changes in material properties, including microhardness gradient in the HAZ of welded joints.

To determine mechanical properties of diffusion joints on the microstructural level, three-edge Berkovich indenter [6] was used. It is a diamond pyramid with the base in the form of an equilateral triangle; the pyramid ribs form a 76°54′ angle with the axis, and the faces form a 65° angle. The advantage of the indenter of such a shape is its pointedness, i.e. absence of a crest on the apex, inevitable for Vickers and Knoop pyramids. Presence of such a crest leads to violation of the geometrical similarity of the imprints and, in its turn, to microhardness deviation from its real values in the microindentation region. The main advantages of the trihedral pyramid are the simplicity of its fabrication and pointedness, allowing measurement of microhardness of such hard bodies as diamonds.

The imprints can have minimum dimensions. Berkovich indenter is standardized (ISO 14577–2) as an instrument for micro- and nanoindentation. By the data of [7] microhardness testing by such an indenter is the most widely used analytical method of monitoring the mechanical properties of modern materials with fine structures. The accuracy of digital instruments allows studying the mechanical properties of material structure microinhomogeneities.

During testing the depth of intender indentation on the load on it is recorded both at load increase and decrease. This yields the value of «unrecovered» hardness, thus eliminating the influence of the material elastic recovery on the actual microhardness value [8, 9].

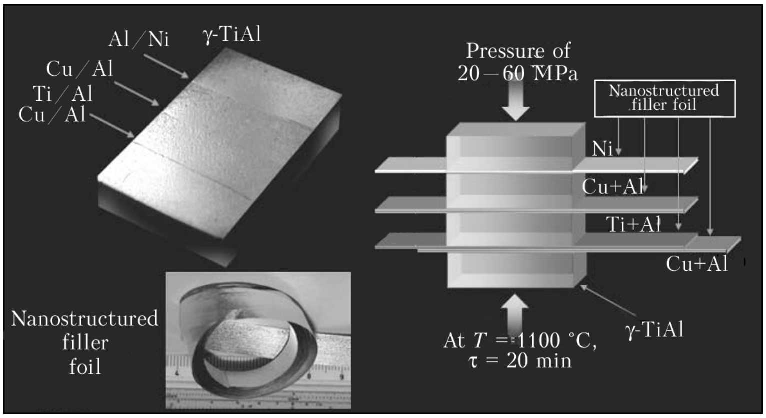

Figure 1. Mock up of a diffusion welded joint of γ-TiAl intermetallic alloy

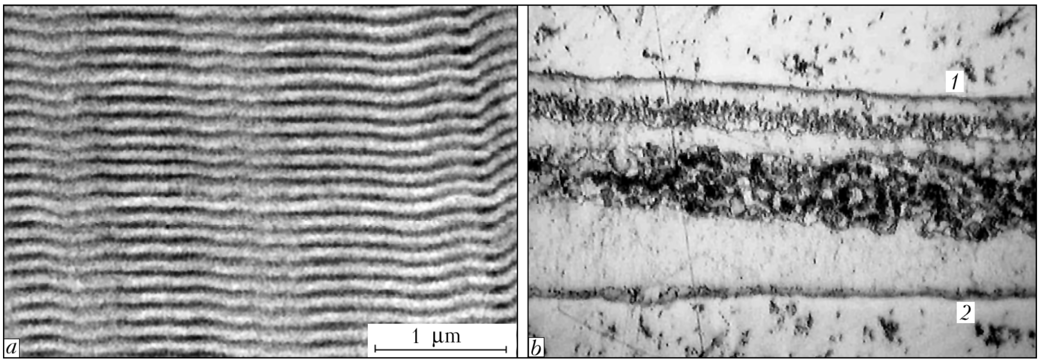

Figure 2. Laminated structure of filler nanostructured foil (scanning electron microscopy) (*a*) and microphotography (*b* –– ×600) of Ti/Al (upper coarse-grained layer *1*) and Cu/Al (lower layer *2*) interlayers in a diffusion welded joint

The paper gives an evaluation of the technical capabilities of indentation for determination of the micromechanical properties of diffusion joints of γ-TiAl made with application of nanostructured metastable filler foils (Figure 1). γ-TiAl –– a high-temperature material (fcc lattice is preserved at 1440 °C) with a high level of oxidation and combustion resistance at up to 900 °C temperature, low density (3.8--4.0 g/cm^3) and increased modulus of elasticity (160--175 GPa at room temperature and 150 GPa at 900--1000 °C) –– is an advanced material for manufacturing aerospace systems and an alternative to titanium and nickel superalloys. However, its industrial application is restrained because of its brittleness, low ductility and high deformation resistance.

Cu/Al, Ni, Ti/Al filler foils used in the joint are multilayer metastable nanostructures [10], consisting of alternating nanolayers of various materials, with less than 100 nm layer thickness, their quantity being several thousands (Figure 2). Owing to the possibility of close contact of layers of various materials, such nanolaminates are unique materials, combining both the quality of laminated systems and specific properties of nanoobjects. Such multilayered metastable structures consist of components which may enter into exothermal interaction with each other [11]. At certain temperature conditions the process of self-propagating high-temperature synthesis (SPHTS) is initiated in such a system. As a result, the initial lamellar structure disappears, giving way to phases of new chemical compounds, formed as a result of interaction of synthesis products.

Multilayer metastable materials offer a number of advantages: monolithic nature of the initial structure and absence of pores in the reaction products; high uniformity of the reaction product composition; small thickness of the initial layers, which allows realization of SPHTS processes at a very high speed; absence of oxide films between the layers and good contact between the layers. The above features make their application promising in the technology of solid-phase joining of materials based on SPHTS.

The object of study is a four-layer welded joint of γ-TiAl alloy (4 mm sheet thickness) produced by vacuum diffusion welding (VDW) for 20 min at 600 °C with application of nanostructured metastable Cu/Al, Ni/Al filler foils and Cu/Al + Ti/Al double filler. Thickness of inner Ti/Al foil layers is equal to 23 nm for titanium, being 24 nm for aluminium. Thickness of filler foils in the joints is equal from 0.015 to 0.050 mm on average.

Investigations are performed using «Microngamma» instrument (Figure 4) designed for determination of mechanical properties of materials by the methods of continuous application of the indenter, indenter scanning (sclerometry), metallography and topography [12].

Computerized microprobe system of the instrument (Figure 3) includes Berkovich indenter, a rod with a sensor for recording the indentation depth, loading mechanism with a broad load range, videocamera with the resolution of 5 Mps and microscope (with 200--1200 magnification), automated system of sample positioning with the program of digital navigation over the studied object, which allows making a precise application to the selected structural microbject. To reduce vibration the instrument is mounted on a vibroinsulating support. Indenter displacement, measured with up to 1 nm accuracy, allows conducting testing at the load from 0.1 to 500 g and shallow depth

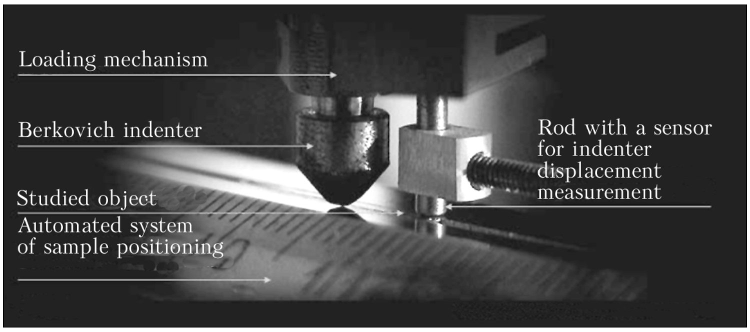

Figure 3. Computerized system with Berkovich intenter for testing the mechanical properties of diffusion welded joints

Figure 4. Instrument «Micron-gamma»

of the imprints. The derived loading--unloading diagram consists of 2000 dots (Figure 5, *a*). Processing of indentation results is performed by a specialized program, which allows automatic determination of the values of hardness and Young modulus at recording of the indenter tip displacement.

In this test hardness was determined by maximum depth of intender imprint at 20 g load. Each series of applications consisted of 16 successive imprints of the indenter with 20 μm step. Loading rate was 2 g/s without dwelling. Testing was conducted by the following schematic: loading/unloading without dwelling. Calculation data are summed up in an electronic table.

At metallographic analysis of a joint with a nanostructured interlayer of Cu/Al system a partial and in some places complete diffusion of the interlayer into the base material is found (Figure 5, *b*). Maximum value of microhardness of this joint was equal to 1.2 GPa at Young modulus E = 86.9 GPa and coefficient of ductility $k_{\rm duct}$ = 0.755, and minimum value was 0.536 GPa at E = 61.6 GPa and $k_{\rm duct}$ = = 0.853, respectively.

Metallographic examination of the joint with nanostructured Ni/Al interlayer did not reveal any visible diffusion (Figure 5, *c*). A precisely outlined recrystallization zone on the boundary of the base material and interlayer with higher microhardness values is visible. Maximum microhardness value of this zone is equal to 1.905 GPa at E = 121.9 GPa and $k_{\rm duct}$ = 0.705, and minimum microhardness value of 0.432 GPa is recorded in the central part of the interlayer at E = 89.8 GPa and $k_{\rm duct}$ = 0.938.

At metallographic analysis of the joint with two nanostructured interlayers of Cu/Al and Ti/Al systems a slight diffusion of Cu/Al interlayer is noted with development of coarse-grained dark-coloured intermetallic interlayer and formation of a homogeneous weld from Ti/Al interlayer (Figure 5, *d*). The gradient of variation of microhardness and modulus of elasticity for these interlayers is small. Average value of microhardness of the interlayer of Ti/Al system was equal to 1.972 GPa at averaged E = 159.8 GPa and $k_{\rm duct}$ = 0.781, and for interlayer of Cu/Al system it was 1.180 GPa at E = 120.3 GPa and $k_{\rm duct}$ = 0.823.

Thus, statistical data of local redistribution of microhardness in the HAZ of the diffusion welded joint of

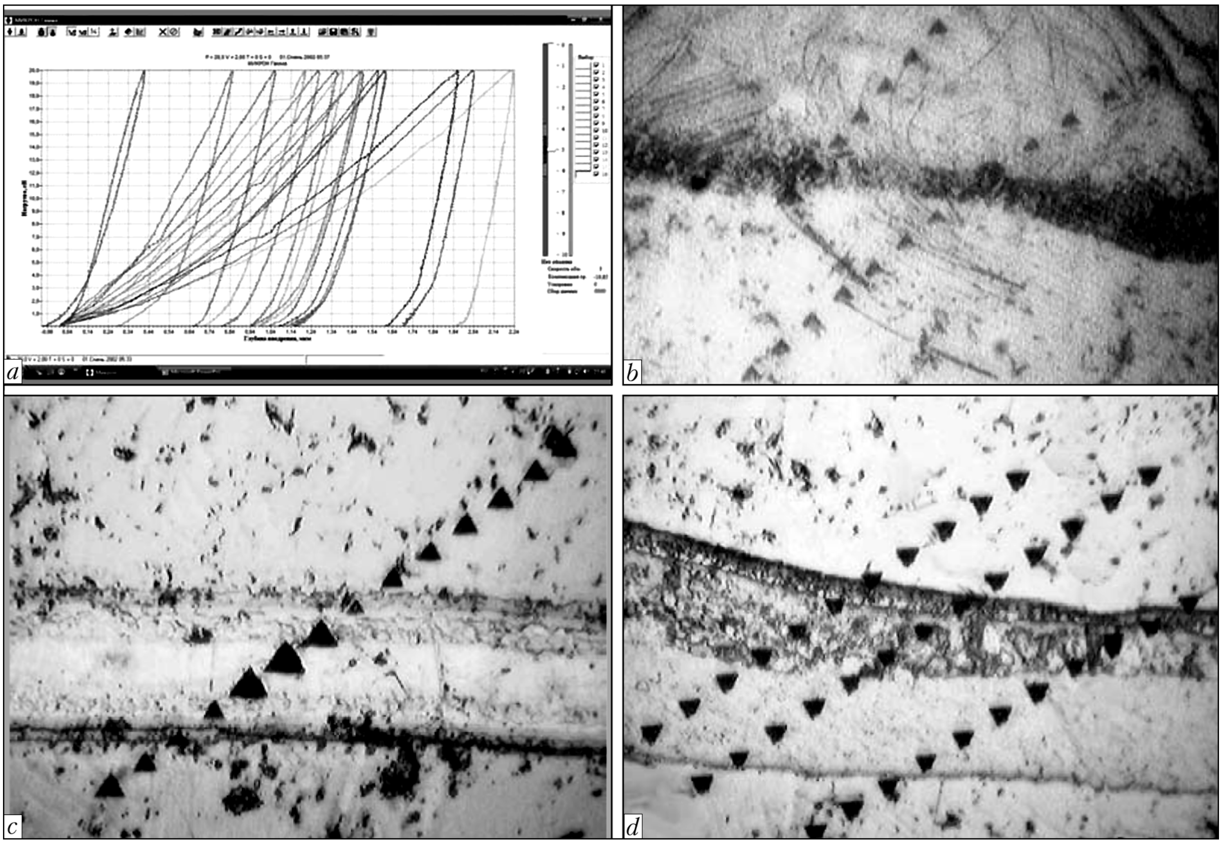

Figure 5. Loading--unloading diagram at indentation of a joint with Ni/Al interlayer (*a*) and microphotographs (×600) of nanostructured Cu/Al (*b*), Ni/Al (*c*) and Cu/Al with Ti/Al (*d*) interlayers with indenter imprints (▼)