APPLICATION OF NANOPOWDERS OF METALS IN DIFFUSION WELDING OF DISSIMILAR MATERIALS

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Comparative analysis of compact materials, deposited and galvanic layers, and powders with different particle size used as such layers is presented. The processes of sintering of nanopowders and their adhesion through sintering to the surfaces of parts welded are studied. It is shown that the use of double mixtures of nanopowders allows intensifying the process of diffusion formation of the welded joint and provides the welds with preset mechanical and physical properties.

Keywords: *diffusion welding, powder intermediate layer, nanopowders of metals, intensification of process of joining, welding temperature, time of welding, pressure, structure of metal in zone of joining*

Technology of diffusion welding along with obvious advantages over the other methods of welding has one significant disadvantage, i.e. low efficiency of the process, which restrains its wide application in industry. In this connection there is a task for the specialists in area of welding to find a method for intensification of process of obtaining of solid state permanent joint.

In diffusion welding the cyclic changes of its main parameters — temperature T and pressure P [1, 2] — is the most simple method for intensification of this process. There are other methods, but they require a development of special technologies, creation of high-frequency and specialized equipment and precision fixture that means significant financial expenses.

Solution can be found due to existence of one more method for the intensification of process of diffusion welding. It provides solution of a complex of tasks and being based on application of the intermediate layers functioning during welding in various ways: reduction of chemical inhomogeneity in joining zone; relieve of the residual stresses and elimination of influence of a difference in values of coefficients of linear thermal expansion of materials being welded; prevention of their plastic deformation; significant reduction of the main parameters of diffusion welding with simultaneous assurance of high strength of joints.

Plastic metals (gold, silver, nickel, copper, aluminum, ect.) are applied, as a rule, for the intermediate layers in a form of foils, wires, powders and films which are deposited on the surfaces to be joined by galvanic method or vacuum deposition [3].

Activity of the surface of the foil, obtained by rolling of molten metal, is almost similar to compact welding materials. It is used as an intermediate layer mainly for preventing formation of intermetallics in the joining zone. Thickness of intermediate layers makes 0.05–1 mm. Their preparation for welding is similar to the preparation of surfaces of the parts to be joined.

Quality of the joints obtained through galvanic or deposited coatings mainly depends on their adhesion to the base metal. In turn the level of adhesion is determined by quality of surface preparation of the parts to be coated. Similarity of the structures of the base and deposited metals is an important factor for providing necessary adhesion. Moreover, mutual diffusion of the base and coating metals promotes their reliable adhesion during coating as well as in the process of diffusion welding, if the diffusion is accompanied by formation of solid solution.

Thin galvanic or deposited films are characterized by high values of surface area to volume ratio, different level of structure ordering, small mass as well as imperfect crystal lattice. This results in development of new effects and evident deviation from the effects taking place in the massive samples. Conditions of thermodynamic equilibrium in the thin films significantly differ from conditions in volume. The film is formed from many discrete nuclei at their strong off-orientation and displacement relatively to each other, that result in formation of the dislocations and network of vacancies over the interfaces of coalescing nuclei and development of elastic stresses in the film.

A powder body is unstable due to excess of free energy. This is first of all related with the presence of highly developed internal interfacial interface of the solid body with the pores [4].

Rising of particle size of metal powders increases their volume shrinkage during pressure sintering process, reduces temperature of beginning of evident shrinkage (Figure 1) and improves strength. The powders which at other things being equal (temperature, compression force, etc.) compacting with higher speed are considered to be more active. The higher powder particle size, the bigger its specific area and the greater system deviation from thermodynamic equilibrium.

Investigations of welded samples from nickel NP-2, made by diffusion welding at temperature $T_w = 550$ °C, pressure $P = 20$ MPa and time of welding $t_w = 30$ min using intermediate layers from nickel electrolytic powders PNE-1, carbonyl PNKOT-1 and nanopowders (NP), obtained as a result of thermal decomposition of $Ni(COOH)_2 \cdot 2H_2O$ nickel formate with particle size

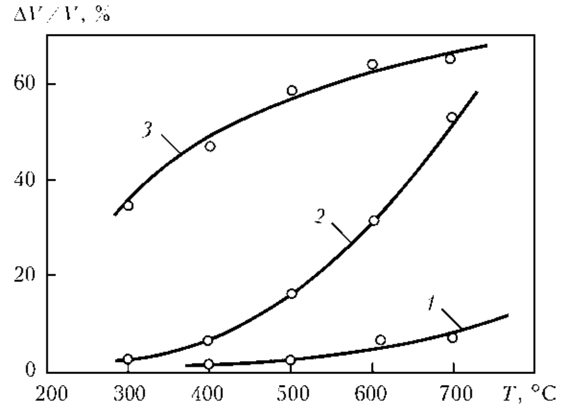

Figure 1. Dependence of volume shrinkage $\Delta V/V$ of electrolytic powder NPE-1 (*1*), carbonyl PNKTO-1 (*2*) and NP (*3*) on sintering temperature at t = const

d = 39.75, 7.63 and less than 0.10 μm and area of specific surface S_s = 0.12, 0.48 and 17.32 m^2/g, respectively, showed that maximum value of tensile strength $\sigma_t \geq 200$ PMa is achieved in welding through NP.

Compacting of the intermediate powder layer is a process of directed transfer of material mass. Diffusion of lattice vacancies over the layer surface takes place thorough their sinks representing itself interparticle boundaries. Amount of such sinks and, respectively, distance between them depends on particle size. Reducing the latter the amount of vacancy sinks increases that activate shrinkage process.

Speed of the processes of mutual sintering of the particles and their adhesion to the flat surface are increased reducing linear dimensions of the particles and are described by ratio [4]

$$X/R = R^{-3/5}f(t, T),$$

where X is the minimum radius of contact neck; R is the radius of particles; t is the time of sintering.

Defectiveness of the crystalline structure is increased together with rising of particle size and specific area of the powder for activation of process of diffusion welding using the powder layer at which two processes, i.e. sintering of powder particles between each other and their adhesion to the flat compact surface, take place simultaneously. For this metal powder are manufactured under non-equilibrium conditions at lower temperature and high speed of heating and cooling when speed of cooling is higher than that of heating. Specifically, this is a scheme of obtaining of NP by thermal decomposition of formates and metal oxalates.

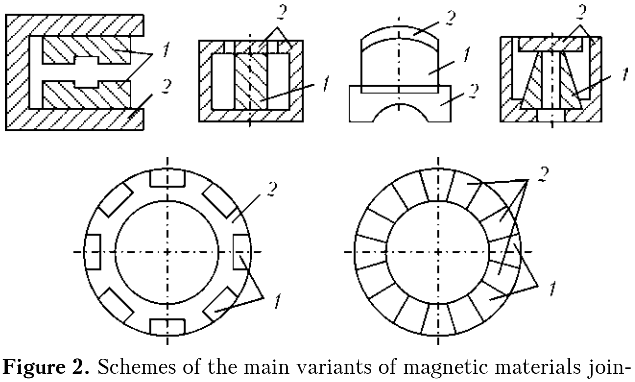

Figure 2. Schemes of the main variants of magnetic materials joining: *1* — constant magnets; *2* — magnetic circuit

Thus, reduction of free energy, connected with the free surface of porous body and defects of its crystalline structure, is the main driving force of sintering process of powder intermediate layer and its adhesion to the base metal. Besides, increase of concentration of dislocations, along which high diffusion mobility of the atoms takes place, can be the reason of rise of powder activity in diffusion welding.

Technology of diffusion welding using powder intermediate layers is applied, for example, in aircraft instrument-making for manufacture of magnetic systems, in particular, for joining constant magnets of YuNDK type with 27KKh alloy, 10880 steel, permalloys and other materials (Figure 2). Diffusion welding was carried out under following conditions: T_w = 550–600 °C, P = 20 MPa, t_w = 30 min. Strength of weld metal made more than 200 MPa (fracture took place along the constant magnet), plastic deformation of parts was absent, initial magnetic properties of the magnetic materials were preserved, further heat and mechanical treatment were not necessary and welded assemblies were ready to further erection. If a comparison with technology of welding without activating layers ($T_w \geq 870$ °C, P = 30 MPa, t_w = 30 min) is made then in this case the strength of weld metal makes 5–7 MPa, plastic deformation is not less than 15 %. Additional thermomagnetic treatment for renewal of the initial magnetic properties is required at that since process of welding is performed at temperature above Curie point. Besides, technological cycle for manufacture of one part was reduced by 30 % using the powder intermediate layer.

Failure of quality welded joints occurs on the intermediate layer that indicates on complete processes of adhesion between the surfaces of sample and powder and full enough chemical interaction, the evidence of which is a fractogram of fractured surface of welded joint, obtained at T_w = 600 °C, P = 5 MPa, t_w = = 30 min. It is reasonable to consider that the fractogram consists of three zones (Figure 3). It can be observed comparing zones *1* and *3* that the character of their surface (size and depth of pits) is similar and, zone *3*, respectively, is a part of the powder intermediate layer along which the failure took place. It should be noted that failure of the specified sample occurred on two mechanisms: by means of coalescence of micropores (zones *1* and *3*) and chip (zone *2*). The failure, mainly, took place between the particles (intergranular character). This confirms the fact that process of sintering of powder rolling strip (intermediate layer) is carried out on a mechanism of grain-boundary slip of particles.

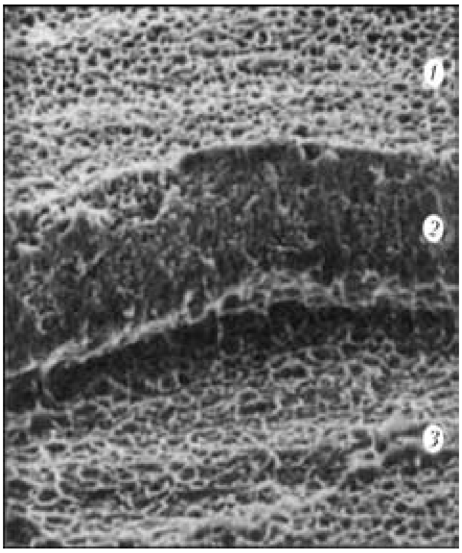

Figure 3. Fractogram (×800) of fracture surface of the welded joint sample: *1* — surface of sintered powder layer after fracture; *2* — section of intermediate sintered powder layer (thickness of layer after welding and fracture); *3* — places of pit

Thermo-activation analysis of process of welded joint formation and sintering of intermediate powder layer was carried out based of dependence of relative strength at fixed pressure of welding $P = 10$ MPa and relative strength $\overline{\sigma} = 0.8$. Their values correspond to value of activation energy of the process of welded joint formation, sintering of intermediate layer $E_a =$ $= 110$ kJ/mol and activation energy of the compact nickel. This allows making a conclusion that formation of welded joint through powder intermediate layer is controlled by process of its sintering, and the latter in turn — by grain-boundary self-diffusion.

Double component powder layers based on the most promising mixtures of NP nickel, copper and cobalt of different compositions were developed and investigated for increasing of mechanical properties of the joints and improvement of special properties of the magnetic systems as well as decreasing thermodeformation influence on welded parts and reduction of technological cycle of diffusion welding.

Kinetics of solid-phase sintering of double mixtures in contrast to single-component mixtures is complicated by the processes accompanying diffusion homogenizing. Excessive free energy of the powder mixture caused by presence of concentration gradient of the components can be very significant. This is energy-wise even when the system is not in equilibrium state according to any other parameter, for example, developed free surface, value of stresses in diffusion zone, etc. New compaction mechanism appears realizing which the movement of particles of different materials is related with their size, developed surface as well as with content of the components.

The intermediate layer, consisting of double component NP, was also applied for joining of hard alloys with steels in manufacture of special instruments.

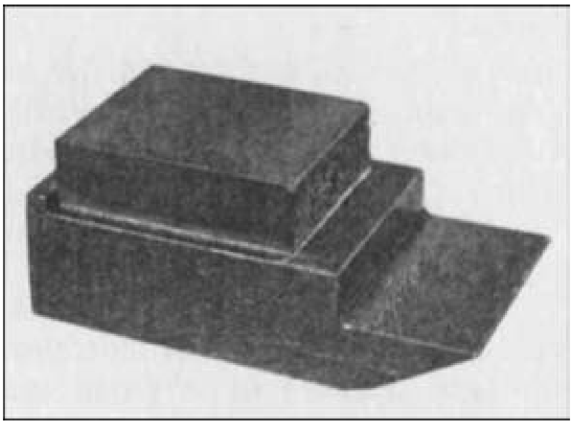

Figure 4. Appearance of the part from diffusion-welded hard alloy VK6 with steel U8

In many respects, strength of the welded joint of hard alloy with steels is determined by quality of preparation of surfaces to be joined, in particular, by roughness of higher than 1.25 and parallelism deviation of less than 0.02 mm. Therefore, their welding is carried out through porous shrinking intermediate layers leveling deviation of their sizes from required values. The intermediate powder layers based on Ni–Co, Ni–Cu, Cu–Co double mixtures with different content of components were investigated. The best result was obtained for intermediate layers from NP of Ni–Co system.

Diffusion welding of hard alloy VK6 (94 wt.% WC and 6 wt. % Co) with steels U8 (Figure 4) and 35 was carried out through spacer with 75 % Ni + + 25 % Co. This composition, as showed our experiments, is optimum for specified pair of materials. The same spacer composition was used in welding of VK20 alloy (80 % WC and 20 % Co) under following conditions: $T_w = 850$–900 °C, $P = 10$–15 MPa, $t_w = 30$ min. Tensile strength made $\sigma_t = 600$–900 MPa, failure occurs along the hard alloy.

Mutual diffusion of elements being joined in welding of hard alloy with steels using the intermediate layers from mixtures of nickel and cobalt forms a

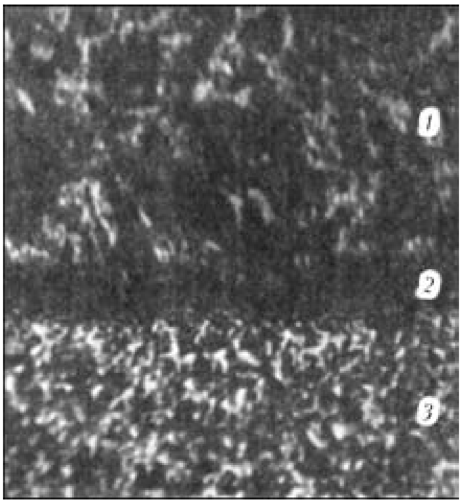

Figure 5. Microstructure (×350) of joining zone of hard alloy VK6 (*1*) with steel U8 (*3*) through powder intermediate layer (*2*)

transition zone. Virtually all elements of materials being joined take part in its formation. Nickel, which can diffuse in alloy to 25–30 μm depth along the grain boundaries, shows the highest activity in formation of the transition zone. As a result, on the one hand, cobalt is substituted to nickel in alloy (at that the grains of tungsten carbide partially dissolve in nickel forming nickel–cobalt solid solution) and, on the other hand, intensive development of the diffusion processes between cobalt in the alloy and cobalt in the spacer takes place.

Figure 5 shows a microstructure of joining zone of hard alloy VK6 with steel U8.

Application of the intermediate layers from NP mixtures in diffusion welding instead of brazing, for example, by copper or brass, for tool manufacturing allows saving up to 75 % of expensive and scarce alloy, increasing quality and reliability of hard alloy to steel joint, rising service life of tool 1.4–1.5 times and reducing laboriousness for its manufacture. Unfortunately, specified technology has significant disadvantage, i.e. low efficiency in comparison with brazing but this is eliminated by high quality of the part. Application of multi-position fixture can increase efficiency of welding process.

Thus, process of diffusion welding can be intensified by means of application of highly active energy-rich intermediate layers based on NP. It is important that particles having maximum developed surface together with minimum size.

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