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Quality control of welding in titanium panels, made using method of diffusion welding and superplastic forming

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Abstract. Results of studies of nondestructive control of multilayer titanium panel, made by the method of diffusion welding and superplastic forming, are considered. By ultrasonic control of the echo method with the use of a direct piezoelectric transducer, areas on which diffusion did not occur or has not occurred completely, as well as various inclusions trapped in the welded joint area during assembly, are determined. The quality of the formation of the inner surface (corrugated sheet) can be controlled by radiographic inspection, and according to the results of the control, it is possible to detect breaks, cracks, and the violation of the shape of internal partitions that appear from a technological process failure.

1. Introduction

Production of details for aircrafts using methods of diffusion welding and superplastic pneumothermal forming (DW and SPF) allows to obtain products of titanium with shaped forms, production of which is impractical or simply impossible with the use of other methods. The use of superplasticity regimes [1-4] in processes of bulk forming, sheet forming, diffusion welding and pressure welding significantly expands their technological capabilities, reduces the energy intensity of form change, allows to increase the coefficients of use of metal and untreated surfaces, and the quality of the finished products. The state of superplasticity of metals and alloys is characterized by three main features [1]: increased sensitivity of the flow stress to a change in the rate of deformation; high stability of the flow of superplastic materials, which provides a great resource of deformation capability, due to which, the relative elongation in case of stretching of such materials can reach several hundred and even thousands of percent; flow stresses in the state of superplasticity are much less than the yield strength of materials in the usual plastic state. A phenomenon of superplasticity of materials [1,2] is observed under certain temperature and speed conditions: the temperature interval is limited by the temperatures of the beginning of recrystallization (0.4 Tm) and the development of collective recrystallization (0.8-0.9 Tm); an optimal interval of rates of deformation for most of the studied metals and alloys is $10^0 … 10^2$ s⁻¹. One of the most important features of the phenomenon of superplasticity of metals [1] is the strong dependence of the effect on the size and shape of the structural constituents of the material, as well as on the structure change in the process of deformation. It is generally considered [1-4] that the average grain size in a polycrystal that
provides a noticeable manifestation of signs of superplasticity should not exceed 10 μm during the entire time of deformation. During superplastic pneumothermal forming, sheet is heated to the temperature of superplasticity in a sealed punch, then under the influence of gas pressure the sheet takes the form of the cavity of the punch. During the forming of titanium, argon is used to prevent the oxidation of this active metal.

At present time, in the INRTU, diffusion welding and superplastic pneumothermal forming (DW and SPF) of biphase titanium alloys, for example VT6 alloy, are carried out in the temperature range of 850-920 °C, on the equipment presented in Fig.1. There are three most common ways of combined technological process of pneumothermal forming and diffusion welding [1]: molding of a sheet metal article with subsequent diffusion welding of a reinforced set (fittings, stringers); molding of a two-layered part with a profile on the surface of the fitting-out; molding of multilayer panels with a reinforcing set, which is determined by the pattern of applying an anti-weld coating. In the process of the adjustment of SPF regimes for a number of products, it became necessary to control the quality of the final product. The most important criterion for the quality of the process of superplastic forming is to ensure uniformity of thinning (gage interference) of the sheet. During this process, the workpiece material gradually takes the form of a matrix, deformation proceeds with a decrease in thickness and an increase in the surface area. Evaluation of the gage interference is usually carried out on the witness samples by measuring the thicknesses in the thinnest area and at the top of the sheet, which is compared with the initial sheet thickness. The reason for the appearance of gage interference is the violation of the parameters of the regimes of the forming process [1, 2]. At present time, modern computer programs [5-10], developed on the basis of the finite element method, are widely used to estimate the gage interference for modeling the SPF processes of sheet and bulk blanks. The most popular ones are the MARC MENTAL software package, developed by MARC Analysis Research Corp. (USA), and the SPASM3D package, developed by a group of programmers at the University of Florida (USA). In addition to the programs mentioned above, a number of computer-aided design (CAD) systems are widely used in Russia and in the world, such as Q-form, Ansys, SuperForge, SuperForm, Deform-3D, ALPID, ANTARES, MARC/Auto Forge, FORGE 2/3 etc. [2,5], which makes it possible to apply them for modeling the SPF process for solving elastoplastic problems associated with studying the strain-stress state of a material. Despite the success achieved in the modeling of SPF, it should be noted that for production processes, real tools to control the defect of gage interference of produced products are required. Further, it is necessary to consider that SPF is combined with diffusion welding. In this case, defects of diffusion welding, as a rule, are manifested only after the SPF of the titanium panel. Moreover, in the superplastic flow of material (especially aluminum alloys) in the SPF process, diffusion processes do not have time to completely accommodate the deformation, which is occurring by the mechanism of grain-boundary slip [1]. Herewith, pores appear at the grain boundaries and in the triple joints of the grains, and the pore volume grows exponentially with the degree of deformation [1], which ultimately leads to the destruction of the material. For that matter, study of techniques and methods of quality control by universal means for diagnostics of diffusion welding of titanium sheets is an urgent task, as today there are no determined recommendations on equipment for controlling diffusion welding of titanium, that will guarantee product quality and safety [2-9]. Moreover, at present time there are no established control procedures, valuation standards, which would allow one to clarify the quality of the welded joint made by diffusion welding. In this paper, the first steps in the creation of norms for assessing the quality of welded joints at DW and SPF of titanium panels were taken.

The purpose of the work is to conduct an instrumental analysis of existing methods of quality control of the final product using the example of producing titanium panels.

Equipment and materials. Regimes of diffusion welding and subsequent SPF were applied according to the passport specifications of the producer of the diffusion welding unit SPF60T (France). Such control methods as visual and measurement control, ultrasonic control and radiographic control [6, 11-12] were considered. It is these methods of control that are most often used in the aerospace industry, and, therefore, all the necessary equipment is already available. Three-layer titanium (VT-6) panel, Figure 1, obtained as a result of diffusion welding and subsequent SPF under different technological
regimes was controlled.

Figure 1. Three-layer titanium panel that was controlled

2. Results of studies

Visual and measurement control. A set of measuring equipment "arshin" was used for control. The kit includes: a magnifying glass 10-fold; a measuring ruler in accordance with GOST 427; a checking ruler ShP-11 (0-160) in accordance with GOST 8026; a metal measure, 5 meters in length, beam compass ShTs 150-0.1 GOST 166.

Usually, all welded products regardless of the use of other types of control are checked visually. In many cases, visual inspection is quite informative and is the cheapest and, most time, efficient method of control [8,9]. In case of diffusion welding of titanium (VT-6) panels, it is possible to check the quality of preparation and assembly of workpieces before welding and the quality of the finished welded joints by visual inspection, since due to the special aspects of the process, it is impossible to monitor the welding process itself. Nevertheless, visual inspection gives certain information that can be included in the regulatory documentation. Control of procurement and assembly. Welding materials should be checked visually to identify (determine the absence) dents, burrs, quality of surface preparation, and so forth. The main controlled parameters of this part, Figure 2, include the gap between the sheets of the product, control of the applied weld coating, control of the interposition of the welded sheets, quality control of the tack welds, and control of sheet size. Having checked the sample in Figure 1,2 visually, it can be said that welded joints are formed in the places intended for them; no temper colors are observed; wrong shape of the product is explained by the violation of the process of superplastic deformation and can be explained by the insufficient heating of one side of the product; probably, the process of form calibration is broken. Measuring the dents (Figure 2a) with the beam-compass it was revealed that their dimensions exceed 2 mm, and, consequently, with such violation of the external surface, the inner surface cannot be properly formed [2]. It can be seen from the section that in regions with dents, an unacceptable internal geometry is observed, Figure 2b.

Figure 2. Irregular shape of the sample caused by the failure of the molding process:
a – measuring cavities, b - unacceptable internal geometry
Ultrasonic testing (UT). To control the product, a YD2-70 flaw detector was used. Ultrasonic testing is one of the most common methods of nondestructive testing [7-12]. For a three-layer product with a thickness of 1-5 mm, we choose PET P111-2.5-K12-002 - piezoelectric transducer, direct, combined type, rated frequency - 2.5 MHz with ceramic protection, a diameter of piezoelement – 12 mm, modification - No. 002.

An ultrasound-echo method, a piezoelectric transducer straight type. The control circuit of the direct type converter is shown in Fig. 3. The authors successfully identified the areas on which the diffusion welding did not happen or was not full (Fig. 4).

X-ray inspection. A portable X-ray flaw detector "Arina-5" was used. The control method was about subjecting the whole sample to experimental radiographic examination, a radiation axis is perpendicular to the product (Figure 5). The focal length is 400 mm. Holding time is 3 seconds. Amplifying fluorescent screens were used in shooting, lead screens were not used [12]. The determination of defects of diffusion welding by x-ray examination is shown in Figure 5.6. This kind of control can be successfully used to detect defects of superplastic forming, such as cracks, caused by the excess of the possible elongation and internal ruptures of the corrugations in Figure 6.
The results of nondestructive testing of titanium panels presented above allow to determine the shape defects, size of the cracks, their location, but they cannot say anything about the quality of the welded joint in the process of diffusion welding. That’s why, we carried out metallographic studies of the diffusion joint area.

**Investigation of the microstructure of diffusion joint area.** It is known that the stability of the rheological characteristics of the material is a necessary condition for the qualitative forming in SPF. Rheological characteristics, in turn, are due to the stability of the structure during the heating process and superplastic deformation [1]. The rheological behavior of the material in the state of superplasticity is largely determined by its structure, in order to calculate and select the optimal schemes and regimes of SPF, it is required to determine the initial state and the change in the structure under action of time and temperature during heating and holding the workpiece before SPF. It is known that with the growth of grains, superplastic deformation characteristics deteriorate significantly (a decrease in the relative elongation, an increase in the flow stresses, etc.), which leads to the product defect of molded semi-manufactures in the form of cracks [1-4]. The welded joint area in case of diffusion welding, like the main metal of titanium VT-6, is distinguished by a fine-grained, equiaxed structure, grain size of 8-20 µm. As can be seen in Figure 7a, in the area of a qualitatively performed diffusion joint, the fusion line is practically indistinguishable from the structure of the base material. Figure 7a shows individual microscopic defects in the form of micropores, which have insignificant changes and are much smaller than the grain of the material. The total length of micropore defects along the fusion line does not exceed 0.7-0.8% of the total length of the evaluation area. It is important to note that these defects were not previously detected by instrumental control methods (ultrasound, X-ray). Moreover, performing metallographic examinations of samples, cut from the final product, it is difficult to correlate this type of defect to a particular technological operation, namely this defect was formed in the process of diffusion welding or in the process of superplastic formation. We noted above that in the SPF process, diffusion processes do not have enough time to fully accommodate the deformation occurring by the mechanism of grain-boundary slip. Herewith, pores appear at the grain boundaries and in the triple joints of the grains, and the pore volume grows exponentially with the degree of deformation [1]. At the same time, the location of the defect along the welded joint line makes it possible to classify them as defects of diffusion welding. In the low-quality variant of the compound, the microstructure is shown in Figure 7, b. Defects in the form of pores and nonmetallic inclusions have a size larger than the grain size and the total length of the defects along the fusion line exceeds 30% of total length of the evaluation area.

![Figure 7. The microstructure of the joint area performed by diffusion welding of titanium sheets: a – high-quality weld; b – poor-quality weld.](image)

Thus, the evaluation of instrumental methods of control of parts (type - titanium panel), made by the method of diffusion welding and superplastic pneumothermal forming, makes it possible to determine the following technological moments for technology control:

- initial data obtained by visual and measuring control give information on the quality of the workpiece: formation of areas of diffusion welding, behaviour and uniformity of plastic deformation, shape of the product.
- more detailed information on the quality of the welded joint and the internal geometry of the part can be obtained with the help of physical methods of control.
3. Conclusion

1. In order to check the welding area during SPF for the presence of discontinuities that are considered as poor welding fusion in case of diffusion welding, it is convenient and effective to use the ultrasonic testing method. By ultrasonic control of the echo method with the use of a direct piezoelectric transducer, areas on which diffusion did not occur or has not occurred completely, as well as various inclusions trapped in the welded joint area during assembly, are determined. The depth of location of the defect and the coordinates are determined with an accuracy of fractions of a millimeter. The accuracy of the determination depends on the resolving power of the flaw detector and the frequency of the signal.

2. The quality of the formation of the inner surface (corrugated sheet) can be controlled by radiographic inspection, and according to the results of the control, it is possible to detect breaks, cracks, and the violation of the shape of internal partitions that appear from a technological process failure.

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