Influence of superplastic deformation on the quality of solid-phase joints obtained by welding of crystalline alloys

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Abstract. Pressure welding using the phenomenon of structural superplasticity is a relatively new technological method based on the additive principle of forming parts. The problem of the quality of a solid-phase joint, which is well studied for superplastic titanium alloys, requires a verification of the versatility of the approaches used to solve it for heat-resistant nickel alloys, as well as for welding of dissimilar crystalline materials. The possibility of reducing the temperature of pressure welding by using low-temperature superplasticity of ultrafine-grained (UFG) crystalline alloys is considered.

1. Introduction
It is known that classical diffusion welding of crystalline alloys, which is carried out at temperatures above approximately 0.8T_m, where T_m is the melting temperature of an alloy, with the welding force limited to values below the yield stress and avoiding a noticeable macroscopic plastic deformation, is a structurally uncontrolled technological process [1]. This circumstance imposes some uncertainties on the possibility of achieving a high quality solid-phase joint after diffusion welding, which is critical for the products of a responsible purpose, in particular in aerospace engineering. Meanwhile, a cardinal solution to the problem of a guaranteed assurance of the quality of solid-phase joints is possible by using the effect of structural superplasticity [2,3]. To date, the determining role of superplastic deformation in achieving the required quality of solid-phase joints at temperatures of about 0.6T_m has been experimentally proven for a number of titanium, aluminum, nickel alloys and stainless steels [3-6]. However, the influence of low-temperature superplasticity, which is exhibited by ultrafine-grained (UFG) and nanostructured alloys, on the formation of a reliable solid-phase joints has not yet been fully studied yet and is of scientific and practical interest to researchers and engineers.

2. Solid-phase welding of titanium alloys
One of the first reports on the successful pressure welding of titanium alloys in the state of superplastic deformation was given in an article by Shorshorov et al. [7] published in 1975 in the journal "Welding production". Quite recently, the authors of [6] made an important conclusion on a possibility of achieving a four times reduction in the welding force and a significant, 6 to 30 times, reduction in the duration of the pressure welding process using the superplasticity effect. This result was the basis for further developments of promising pressure welding technologies based on the superplasticity effect. It is worth to note that the above-mentioned diffusion welding [1], in general, can be considered as a
special case of pressure welding, when strict limitations on the macroplastic deformation of the workpieces to be joined are applied.

In [8-9], the role of grain boundary sliding, which is the main mechanism of superplasticity, in the accelerated kinetics of solid-phase joint formation was first established and studied in detail, and a fundamental conclusion was made about the increased solid-state weldability of superplastic titanium alloys. At the same time, it has been shown qualitatively and quantitatively that the determining factor for achieving the strength of the solid-phase joint at the level of the base material is the level of strain in the junction zone [9]. A decrease of the grain size at temperatures of the traditional superplasticity makes it possible to reduce the necessary strain level to achieve the properties of welded samples approaching the level of mechanical properties of the workpieces being joined. However, given the fact of a structural instability of UFG metals and alloys, in the practice of diffusion welding the average grain size should be taken into account strictly at the moment when the samples to be welded are brought into contact and pressed. For welding massive workpieces made of fine-grained titanium alloy VT6 (Ti-6Al-4V) having the average grain size below 4 µm in the conditions of traditional superplasticity under high vacuum (not worse than \(2.0 \times 10^{-3}\) Pa), the required strain was below 20% [10]. Spherical pressure vessels, which were fabricated from a package of billets by pressure welding in the conditions of superplasticity followed by superplastic forming and then subjected to full-scale tests applying an excessive internal pressure, failed not along the weld joint but outside it [10]. As has been shown by experiments on pressure welding of titanium alloy VT6 with an UFG structure [11,12], high-quality solid-phase joints with the strength at a level of the base material can obtained at temperatures in the range of 750 to 600°C. The determining factors in this case were shown to be the grain size and strain. Table 1 shows the results of mechanical tensile tests at room temperature of samples obtained by pressure welding at 700 °C from the UFG alloy VT6. A physical model of solid-phase joint formation under conditions of low-temperature superplastic deformation was presented in [13].

### Table 1. Mechanical properties of UFG samples of VT6 alloy (average grain size 0.4 µm) joined at a temperature of 700 °C by pressure welding in the state of superplastic deformation (\(\dot{\varepsilon} = 7 \times 10^{-4} \text{s}^{-1}\))

| Strain, % | \(\sigma_{0.2}\), MPa | \(\sigma_{UTS}\), MPa | \(\delta\), % | \(\psi\), % |
|----------|------------------------|----------------------|-------------|-------------|
| 5        | 1047±35                | 1054±30              | 4±3         | 7±5         |
| 10       | 1046±15                | 1052±15              | 17±2        | 61±2        |
| 15       | 1013±15                | 1020±15              | 19±2        | 65±2        |

### 3. Solid-phase welding of nickel-based alloys

One of the most important problems, the solution of which will provide a progress in aircraft engine building, is the development of technological regimes for obtaining a reliable solid-phase joint of heat-resistant nickel-based alloys [14,15]. The main idea of obtaining a reliable solid-phase joint is to implement local superplastic deformation in the junction zone, which was previously successfully implemented for pressure welding of titanium alloys [16-18]. At the same time, the possibility of reducing the pressure welding temperature by using the effect of low-temperature superplasticity was considered as the most important task. Figure 1 shows the result of an original experiment on the pressure welding of a heat-resistant nickel alloy EK61 made at 800°C to obtain a high-quality (virtually pore-free and without additional phases) solid-phase joint. In this experiment, two billets made of coarse-grained heat-resistant nickel alloy EK61 were brought into contact through an UFG superplastic layer made of the same alloy, in which the superplastic deformation necessary to achieve the required quality was localized. It should be emphasized that in this case the coarse-grained samples under welding was preserved almost undeformed. This experiment leads to a new and an important principle for solid-phase welding technology, which tells that in order to obtain a high-quality joint, it is sufficient to provide a superplastic deformation not in both bodies under contact but only in one of them. This
principle has been also successfully tested for welding of dissimilar heat-resistant nickel alloys, in particular, the deformable EP 975 alloy with a cast single-crystal alloy of the VKNA type.

![Metallography of the cross section of the solid-phase joint of the alloy EK61](image)

**Figure 1.** Metallography of the cross section of the solid-phase joint of the alloy EK61: upper and lower zones correspond to the coarse-grained structure of workpieces and the middle zone to the UFG structure of the intermediate layer

4. Conclusions
The experimental studies have shown that pressure welding combined with superplastic deformation allows for obtaining pore-free solid-phase joints of coarse grained heat resistant nickel alloy EK61 using ultrafine-grained layer of the same alloy and of the EP975 superalloy having a fine-grained structure with a monocristalline intermetalic Ni$_3$Al-based VKNA-type alloy. From these results, one can conclude that to obtain a high quality solid-phase joint between similar or dissimilar materials, it is necessary and sufficient that one of the workpieces should be superplastic. The reduction in the average grain size of EK61 alloy down to the ultrafine scale makes it possible to reduce the temperature of superplastic deformation down to about 800°C. This allows one to achieve pore-free solid-phase joints at lower temperatures.

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