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Solid-phase joining of the cast intermetallic Ni_3Al-based alloys and wrought nickel-based superalloys via using superplastic deformation

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Abstract. The paper summarizes the results of solid-phase joining experiments performed for intermetallic single-crystal Ni_3Al-based alloys (known as Russian VKNA-alloys) and wrought fine grained nickel-based superalloys using superplastic deformation of the wrought superalloys. For this, two single-crystal VKNA-alloys, VKNA and VKNA-25 and two Russian nickel-based superalloys, EK61 and EP975, were taken. It was shown that the formation of an ultrafine grained structure (d<1 μm) in the EK61 superalloy made it possible to obtain the solid-phase joint of EK61/VKNA under pressure welding at T=800 °C using superplastic deformation of the nickel-based superalloy. Another nickel-based superalloy, EP975, was taken in a fine grained condition (d=8 μm). High-quality solid-phase joints of EP975/VKNA and EP975/VKNA-25 were obtained under pressure welding at T=1125 °C using the superplastic deformation of the EP975 superalloy. The obtained solid-state joints EP975/VKNA and EP975/VKNA-25 were subjected to heat treatment, which led to the formation of coarse γ grains in the EP975 superalloy. This also led to an increase in thickness of the γ phase interlayers up to 500 nm in both VKNA-alloys near the solid-phase joints

1. Introduction
Nowadays one of the most important problems in the aviation industry is the development of methods for producing reliable solid-phase joints of similar and dissimilar nickel-based alloys. As a rule, nickel-based superalloys possess low weldability, with the exception of some them having lower high temperature capability, such as Inconel 718 (the Russian analogue is EK61). In spite of the fact that this problem is of great practical importance for the aircraft industry, there are only a few papers in publicly available sources devoted to the development of robust joining techniques. Particularly, there are engineering challenges related to the development of the disk combined with the blades. The disk and the blades have different operating temperatures, and therefore it is necessary to develop solid-phase joining techniques not only for similar but also for dissimilar nickel-based alloys. As has been demonstrated, pressure welding using superplastic deformation of joined materials is a promising processing route for joining both similar and dissimilar materials [1-9]. Note that this technique is more feasible in the case of fine grained structures in both joined materials. A more difficult case is joining of dissimilar materials, if only one of them has a fine grained structure and the other is made of a single-crystal. This paper presents a brief review of our latest data on the investigation of solid-phase joining of both similar and dissimilar nickel-based alloys using superplastic deformation of one of the joined materials.

2. Materials and methods

Two Russian wrought polycrystalline nickel-based superalloys having different strengthening phases, EK61 and EP975, were taken as starting materials. The EK61 and EP975 superalloys are strengthened by precipitations of the intermetallic based phases Ni_3Nb (γ'' or δ) and Ni_3Al (γ'), respectively. In the EK61 superalloy, the ultrafine grained duplex-type microstructure (with a grain size of less than 1 μm) was prepared by the multiple forging procedure [4-6]. In the EP975 superalloy, a fine grained microstructure with a mean γ grain size of d=8 μm was also prepared by forging [5]. Two intermetallic Ni_3Al-based alloys (known as Russian VKNA-alloys) containing γ' and γ phases were also used for the experiments [5, 9, 10, 11]. Single-crystals of the VKNA-alloys were manufactured by high-gradient directional crystallization. This technique is described elsewhere [10, 11]. The chemical compositions of the nickel-based alloys are represented in table 1 [4, 5, 9, 11].

Table 1. Chemical compositions of the nickel-based alloys under study.

Alloy abbreviation	Ni	Al	Cr	W	Mo	Ti	V	Nb	Fe	Co	Re	Cu	La
EK61	Base	1	16.6	-	3.9	0.8	0.5	5	15	-	-	0.55	-
EP975	Base	4.8	8.2	10.2	1.2	2.4	-	1.5	-	15.1	-	-	-
VKNA	Base	8.5	5	2.3	5	1.5	-	-	-	-	-	-	0.015
VKNA-25	Base	8.37	5.7	3	5.14	0.52	-	-	-	4.5	1.6	-	-

The pressure welding experiments were carried out using uniaxial compression and press forces, providing superplastic deformation of fine grained samples of the nickel-based superalloys, i.e. pressure welding led to the strain localization within fine grained samples. Thus, a solid-state joint was formed simultaneously with the superplastic deformation of one of the joined materials. The experiments were performed for small samples in vacuum. After pressure welding of the EP975/VKNA and EP975/VKNA-25 alloys, the samples were subjected to annealing at 1200 °C, followed by air cooling and aging at 950 °C. This was done to evaluate the effect of post welding heat treatment on the solid-phase joint.

Table 2 describes the microstructural states of the samples subjected to pressure welding and the pressure welding parameters. The compressive stresses were chosen as corresponding to the superplastic flow stresses of the fine grained superalloy samples.

Table 2. The pressure welding conditions of the nickel-based alloys under study.

Joined alloys	Microstructural states*	Solid-phase joining temperature, °C / time, min	Compressive stress, MPa	The strain of the fine grained sample, %
EK61/EK61	UFG / CG	800 / 60	100	45
EK61/VKNA	UFG / S-C	800 / 60	100	45
EP975/VKNA	FG / S-C	1125 / 42	45	24
EP975/VKNA-25	FG / S-C	1125 / 42-68	45	24-40

*UFG - ultrafine grained, FG- fine grained, CG - coarse grained, S-C - single-crystal.

The microstructure of the solid-phase joints was examined by scanning electron microscopy (SEM) in the secondary electron (SE) mode. The quality of the solid-phase joints was evaluated taking into account the pore length relative to the total length of the solid-phase joint.

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3. Results and Discussion

3.1. Pressure welding of similar superalloys

The samples prepared from the wrought nickel-based EK61 superalloy had the γ+δ duplex-type ultrafine grained microstructure. The average grain size of the γ and δ phases was less than 1 μm. The EK61 superalloy (as mentioned, this is the Russian analogue of Inconel 718) was used as a convenient high workable material having good weldability [4-6].

As has been earlier revealed, pressure welding of coarse grained samples made of the EK61 alloy is unfeasible at a temperature of 800 °C [4]. Pressure welding of coarse grained and ultrafine grained samples made of the EK61 alloy allowed us to obtain solid-phase joints (figure 1a, b). In the course of the pressure welding, the strain was localized within the ultrafine grained sample, and the strain value was about 45%.

In the central joining zone of the welded samples, i.e. in the hard-to-deform zone, which is characteristic of the uniaxial compression scheme, there are areas where the relative pore length reached 80%. At the same time, in the peripheral joining zone there are areas located at an angle to the axis of the applied load, where the solid-phase joint of a better quality was reached. In some of the peripheral joining areas, the relative pore length reached not more than 10%. This can be ascribed to the fact that the strain was localized in the peripheral areas that is typical of the solid-phase joints obtained during uniaxial compression. This suggests that the stress-strain distribution in the joining zone during pressure welding under the uniaxial compression was rather inhomogeneous. This resulted in the different relative pore length along the solid-phase joint.

The experiment performed for the EK61/EK61 samples showed that the solid-phase joint can be obtained by pressure welding at relatively low temperatures, if one of the joined samples has the ultrafine grained structure and the pressure welding is accompanied by superplastic deformation of this sample. From a practical point of view, it is more interesting to use this effect in respect of nickel-based alloys with a higher high-temperature capability and in the case of dissimilar alloys.

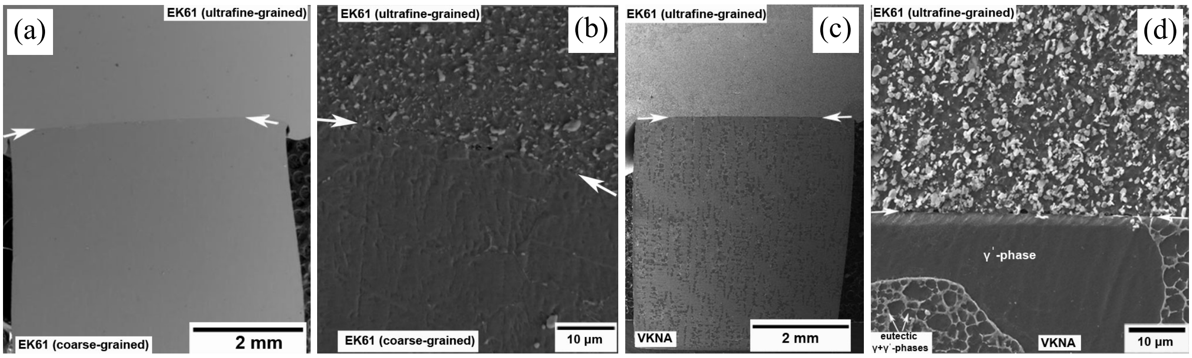

Figure 1. The jointed samples EK61/EK61 (a, b) and EK61/VKNA (c, d) after pressure welding at *T*=800 °C: a and c – the general view, b and d – the solid-phase joint zones; a and b – the coarse-grained samples were joined through the ultrafine grained interlayer; c and d – the VKNA-alloy sample was joined with the EK61 superalloy sample having the ultrafine grained structure. The solid-phase joints are arrowed.

3.2. Pressure welding of dissimilar alloys

The influence of a different type of surface relief on the solid-phase joining was earlier investigated by the finite element modeling [3, 7] that was well agreed with the experimental results obtained in the present work. Particularly, the computer modeling showed that the stagnant zone in the central part of the samples, joined by pressure welding using uniaxial compression, is preserved that degrades the quality of the joint. To exclude the stagnant zone and improve the quality of the solid-phase joint, special reliefs on the joined surfaces can be made. An alternative way can be associated with using the superplastic deformation during pressure welding by uniaxial compression. This idea was tested for dissimilar nickel-based alloys with lower weldability.

Figure 1c, d shows a general view of the joined samples and a part of the solid-phase joint zone of the EK61/VKNA alloy samples. Pressure welding of the EK61/VKNA alloy samples resulted in the strain localization within the ultrafine grained EK61 alloy. This allowed us to avoid plastic deformation of the intermetallic alloy that was important for preserving its mechanical properties. One can see that the so-called diffusion zone was formed in the joint area [6]. In the general case, the width of the diffusion zone depends on the welding temperature and the chemical and phase composition of the materials being joined.

EP975 is a well-known Russian superalloy with a higher high-temperature capability and lower weldability in contrast to the EK61 alloy. The samples of the alloy were taken in a fine grained condition and joined to the VKNA-alloys. The samples of the EP975 superalloy had a $\gamma+\gamma'$ microstructure, the average size of the γ and γ' phases was 8 and 3 μm, respectively. Figure 2 represents the local areas of solid-phase joints of the EP975/VKNA and EP975/VKNA-25 samples subjected to pressure welding at T=1125 °C. It should be noted that such joined combinations can be used to produce real aircraft parts, e.g., BLISK-type parts [5, 8, 9].

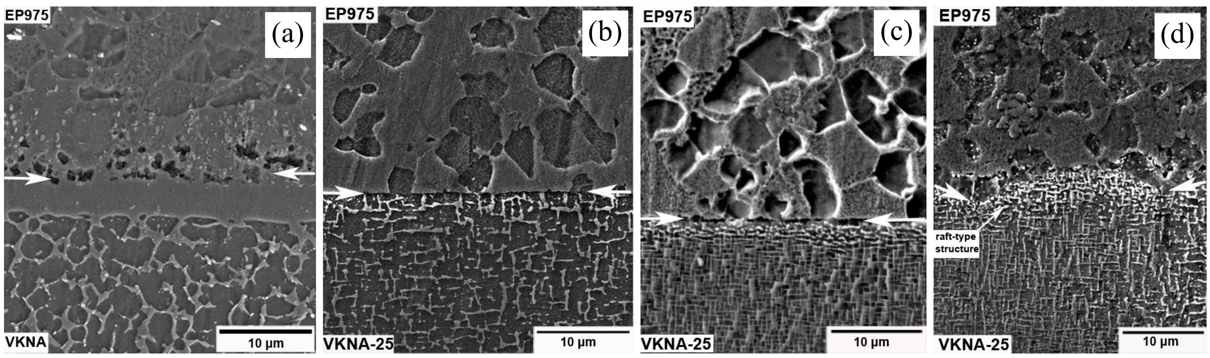

Figure 2. Local sections of the solid-phase joint zones after pressure welding at T=1125 °C: a - EP975/VKNA, b-d - EP975/VKNA-25. The strain of the EP975 sample was: b – 24%; c – 30%; d – 40%. The solid-phase joints are arrowed.

A distinct interface is visible between the alloys after the solid-phase joining. One can see that after pressure welding at T=1125 °C, the microstructure of the EP975 superalloy remains fine grained (figure 2). No microstructural changes in the VKNA and VKNA-25 alloys far from the joining zone were revealed as compared to the VKNA and VKNA-25 alloys before pressure welding (figure 2). At the same time, a diffusion zone with a width of up to 40 μm was formed. Apparently, this occurs during the superplastic deformation of the EP975 alloy. It was shown that the diffusion of chromium and cobalt developed from the high-alloying superalloy EP975 to the VKNA-alloys, while the diffusion of nickel took place in the opposite direction [5, 9].

The influence of the superplastic strain value on the solid-phase joint formation was studied for the EP975/VKNA-25 alloy samples. An increase in the strain value resulted in the formation of an uneven contact interface in the joining zone, which improved the quality of the solid-phase joint (figure 2 b-d). The microstructures of the VKNA-25 alloy differed from the joining zone and close to the joint zone, and this difference increased with increasing the superplastic strain value. Apparently, the deformation was localized in the areas adjacent to the joint at a depth of 3-5 μm, where a raft-type microstructure was formed (figure 2 d).

Heat treatment of the joined samples resulted in the formation of a coarse-grained microstructure in the EP975 superalloy. The average size of the γ phase grains reached 165 μm, the γ' phase particles of about 500 nm in size were precipitated. In the VKNA-alloys there were no significant microstructure changes after heat treatment. Nevertheless, some increase in the width of the γ phase interlayers up to

500 nm was observed near to the solid-phase joint zone. The heat treatment, including aging, contributed to the activation of diffusion of refractory alloying elements. After the heat treatment a monotonous change in the content of alloying elements in crossing the solid-phase joint was observed.

4. Conclusions

Pressure welding of the EK61 and EP975 superalloys in fine grained states with single-crystals of the Ni_3Al-based alloys (VKNA and VKNA-25) was successfully fulfilled using relatively low joining temperatures and compressive stresses providing superplastic deformation of the fine grained superalloys during pressure welding. Using this technique, sound solid-phase joints were obtained.

With decreasing the grain size of one of the joined alloys, the pressure welding temperature can be significantly reduced. This is associated with decreasing the superplasticity temperature. As was demonstrated for the EK61/VKNA alloys, the solid-phase joint was attained after pressure welding at the temperature as low as T=800 °C. The use of the EP975 superalloy with a fine grained microstructure allowed us to obtain the solid-phase joint of good quality after pressure welding at T=1125 °C. Thus, the superplastic deformation of one of the joined materials can assist in attaining high-quality solid-phase joints in the case of nickel-based superalloys and single-crystals of the Ni_3Al-based alloys.

Acknowledgments

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