Finite-element modeling of the stress-strain state in disk-shaft type parts from dissimilar Ni-based alloys

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Abstract. Finite element modeling of the stress-strain state of disk-shaft type parts of gas turbine engines during pressure welding has been made. Pressure welding was carried out by three schemes of deformation of a disk and/or a shaft. In Scheme 1, the shaft was inserted into the disk by setting the displacement of the upper die, in Scheme 2 simultaneous action of a die on the upper end surface of the disk and shaft was set, and in Scheme 3 the shaft was inserted into the disk by setting the displacement of the die, then the action of the die on the upper end surface of the disk was set. Computer simulation is performed using the DEFORM-2D software package. The deformable nickel base alloys EP975 and EK79 were taken as materials for a disk and a shaft, respectively. The results of computer simulation have shown that for increasing quality of the welded joint between the disk and the shaft it is preferable to use pressure welding which is carried out with a combination of sequence actions on the shaft and disk, since in this case an effective summarized compressive stresses and radial strain were achieved which leads to an increase of the joint quality.

1. Introduction
Small gas turbine engines (GTEs) are widely used not only in aviation, but also in the field of small power engineering [1]. The rotor of a small GTE is a specially profiled disc, on the rim of which the blades are attached with the lock. Torque is transmitted to the disk from the shaft due to their connection to each other. Because of their relatively small dimensions, the disk and the rotor shaft of a small GTE can be manufactured as a whole by hot deformation methods followed by turning processing.

However, the significant labor intensity of this technology makes it preferable to manufacture such parts separately with their subsequent connection. The most promising method of joining individual elements of such structures is pressure welding under conditions of superplasticity [2-3]. One of the main advantages of pressure welding is the ability to preserve the microstructure of the workpieces being welded, which is important for products operated at high temperatures and made, respectively, from heat-resistant nickel alloys [4]. An improvement in the quality of a solid-phase joint can be favored by a scheme of deformation, in which a shear strain components takes place in the plane of the joint [3-5].

In this paper, methods for producing a welded joint by pressure welding carried out by the action of a deforming tool on the disk and/or the shaft in contact with the disk are considered. Deformable nickel alloys EP975 and EK79, respectively, were chosen as the material for the disk and shaft.
2. Computer simulation

Computer simulation is performed using the DEFORM-2D software package. The shaft is a cylinder with a diameter of 12 mm and a height of 12 mm coupled with a truncated cone with a height of 20 mm having the angle 3°. The hole in the disk narrows with the same cone angle as that of the shaft. The total height of the disk is 14 mm and its diameter 28 mm. The disk and shaft are assumed to be made of ultrafine-grained heat-resistant nickel base alloys EP975 and EK79, respectively. The material properties were determined using experimental stress-strain curves obtained under uniaxial compression of the alloys at the welding temperature, which was equal to 1100°C. The value of 0.5 was assumed for the friction coefficient.

To determine the influence of the pressure welding scheme of the samples on the plastic deformation in the zone of their connection, three schemes were considered, set by means of the upper die. In Scheme 1, the shaft was inserted into the disk by setting the displacement of the upper die by 2 mm with a movement speed of 1.9 mm/min, which corresponds to the initial strain rate of the cylindrical part of the shaft $10^{-3}$ s$^{-1}$; in Scheme 2, simultaneous action of a die on the upper end surfaces of the disk and shaft was set. The die displacement was 2 mm with a movement speed of 1.9 mm/min. Finally, in Scheme 3 the shaft was inserted into the disk by setting the displacement of the die by 2 mm with a movement speed of 1.9 mm/min. Then, the action of the die on the upper end surface of the disk was set by setting the offset of the die by 2 mm with a movement speed of 1.9 mm/min.

Figure 1 shows the starting positions of the disk and the shaft for corresponding pressure welding schemes. Deforming tools (die) were assumed to be absolutely rigid, deformable bodies (disk and shaft) had elastic-plastic properties.

![Figure 1](image)

**Figure 1.** The finite element model of disk-shaft for welding by Scheme 1 (a), Scheme 2 (b) and Scheme 3 (c).

3. Results and discussion

The results of simulation have shown that during the welding following Scheme 1, a defect typical for the processes of expansion appears, namely, a small radial groove between the shaft and the disk at the upper surface of the latter is formed. This is completely contrary to the requirements put to the pressure welding. It is possible to prevent the formation of this groove by clamping the disk between two technological plates, or, alternatively, pressing the disk between dies as during welding by Schemes 2 and 3 and simultaneously deforming the disk. The material pressed out into the gap between the dies and the shaft produces pressure on the shaft surface. A compression force arises, which is directed counter to the force applied during the expansion of the disk, and the welding zone is influenced by compression, which is necessary to create physical contact and activate the surfaces to be welded. In addition, when the disk material is pressed out into the gap between the dies and the shaft, all pores that can form during the creation of physical contact at the point of junction from the
The shaft diameter to the disk diameter are healed.

The degree of contact of the inner wall of the disk in the shaft can be estimated from the radial components of strain and stress in the contact zone of the billets.

From the distribution of the radial components of strain $\varepsilon_R$ (figure 2), it can be concluded that when welding according to Scheme 1, strain of only one sign "-" are observed in the area of contact between the disk and the shaft; radial strain in the workpieces is unidirectional, while they are very small (figure 2 a).

When welding according to Scheme 2 (figure 2 b) and Scheme 3 (figure 2 c), the picture changes. Strains of different signs are observed on the contact surfaces of the shaft and the disk, which means that the flow of the material of the shaft and the disk goes towards each other. When the die is pressed into the disk under the action of compression, the disk expands in width, exerting significant pressure on the shaft, which promotes the formation of physical contact between the disk and the shaft and improves the quality of the joint. The general nature of the distribution of strain is the same for both schemes. In this case, compared with Scheme 1, the $\varepsilon_R$ values in the near-contact areas of the shaft and disk increase by one and two orders of magnitude, respectively. It can also be noted that with pressure welding according to Scheme 3, the radial strains in the shaft are distributed more evenly.

![Figure 2](image1.png)

**Figure 2.** The distribution of radial strain $\varepsilon_R$ during pressure welding by Scheme 1 (a), Scheme 2 (b) and Scheme 3 (c).

The distribution of the radial stress components $\sigma_R$ (figure 3) showed that in all cases of welding, compressive stresses are observed on the contact surfaces of the shaft and disk. At the same time, when welding according to Schemes 2 and 3, the values of $\sigma_R$ in the joint zone are 3 times greater than when welding according to Scheme 1.

![Figure 3](image2.png)

**Figure 3.** The distribution of radial stress $\sigma_R$ during pressure welding by Scheme 1 (a), Scheme 2 (b) and Scheme 3 (c).

From the distribution of the circumferential components of strain $\varepsilon_B$, it can be concluded that when welding according to Scheme 1 (figure 4 a), strain with the "+" sign are observed on the contact
surface of the disk, which arise due to the fact that the disk material is stretched around the shaft due to an increase in the diameter of the disk hole during distribution. When welding according to Schemes 2 (figure 4 b) and 3 (figure 4 c) due to the fact that the disk is compressed between the dies, the material flow is directed to the surface of the shaft and compression strains are formed in the contact area. It can also be noted that with pressure welding according to Scheme 3, circumferential deformations in the shaft are distributed more evenly than during pressure welding according to Scheme 2.

![Figure 4.](image)

**Figure 4.** The distribution of circumferential strain $\varepsilon_\theta$ during pressure welding by Scheme 1 (a), Scheme 2 (b) and Scheme 3 (c).

From the distribution of circumferential stress components $\sigma_\theta$, it can be seen that when welding according to Scheme 1 (figure 5 a), tensile stresses are localized in the near-contact region of the disk, while during welding according to Schemes 2 (figure 5 b) and 3 (figure 5 c), this area is dominated by compressive stresses. In this case, the maximum value of $\sigma_\theta$ when welding according to Scheme 2 is 2 times greater than when welding according to Scheme 3.

![Figure 5.](image)

**Figure 5.** The distribution of circumferential stress $\sigma_\theta$ during pressure welding by Scheme 1 (a), Scheme 2 (b) and Scheme 3 (c).

### 4. Conclusions
Thus, the results of the studies made have shown the following:

Pressure welding, carried out with a combination of actions on the shaft and the disk, changes the nature of the distribution of circumferential and radial stresses in the contact zone compared to pressure welding carried out only by the introduction of the shaft into the disk.

To create a permanent connection between the shaft and the disk, it is preferable to use pressure welding, carried out using a combination of actions on the shaft and the disk, since in this case there is an increase in radial compressive stresses and the appearance of circumferential compressive stresses.
on the contact surface of the disk. Under the action of compressive stress, the disk material exerts a significant pressure on the surface of the shaft, which promotes the formation of a physical contact between the disk and the shaft, and, as a result, improves the quality of the joint.

When welding using a combination of actions on the shaft and disk, it is necessary to use a sequence of operations, since in this case a more uniform distribution of the radial and circumferential strain components in the shaft is achieved.

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