The analysis of technologies and modeling for forming parts in isothermal conditions

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Abstract. One of the most promising ways to parts making is isothermal in a state of superplasticity. Mathematical modeling is an effective way to determine the necessary energy-force parameters of the process. Examples include the method of analysis and selection of technological processes of parts production in isothermal conditions. The technological processes and simulation of deformation-thermal treatment has been carried out. The simulation ensured the formation of the ultra-fine-grain structure in the blanks under the superplastic roll-out of the shaft from the alloy EhK79. The modeling shows the effect of the microstructure of alloys on the physical-mechanical and operational properties of parts. Model used to predict microstructure evolution is the Johnson-Mehl-Avrami-Kolmogorov model.

1. Introduction
Among the main tasks in the development of the aircraft industry is the production of parts for Gas Turbine Engines (GTE) [1]. The parts work in aggressive environments at high temperatures and high mechanical loads. Appropriately, they are made from modern heat-resistant alloys and steels based on nickel, iron and titanium. The implementation of new high-performance technologies for obtaining complex parts in isothermal conditions is possible only if there is a structure in the blanks of Ultra-Fine-Grain (UFG) [2, 3]. Examples of large-sized UFG blanks from heat-resistant nickel alloys are presented in the works. Ensuring the conditions of formation determines the high quality of the resulting semi-finished products and parts [4, 5]. Further consideration the method of analysis and selection of processes in the form of parts in isothermal conditions. The technological processes of making discs and hollow shafts of isothermal rolling are considered, as well as modeling the effect of the microstructure of alloys on the physical-mechanical and operational properties of parts.

2. Selection of technological processes for forming heat-resistant alloys
The general principle of construction of the morphological analysis and its varieties is the creation of a Morphological Matrix (MM) based on essential attributes belonging to the entire class of the object under study. The morphological approach is a field for search of possible variants of the problem solution.

The stages of the morphological analysis procedure include [6, 7]:
- The exact wording of the problem to be solved.
- Division of essential morphological attributes of the MM.
• Search for possible options of execution of each feature individually and combining them into columns of the morphological matrix.
• Evaluation of all variants of solution of the problem obtained from the MM.
• Selection of the most rational and preferable variants of the problem solution.

To evaluate the variants of technological processes with the help of expert assessments, a morphological matrix was compiled [8, 9]. Any set of all elements is a possible variant of the technology of making hollow shafts of GTE. The main features are selected - the process of preparing the material of the blank, obtaining the required size of the structure of the material, the speed of deformation, etc. To reduce the size of the matrix, criteria were introduced on which the assessment was carried out. At the further stage each alternative was given a ballroom score for each criterion. Thus, 480 variants were generated, and then 120 variants were selected for further clustering. All variants were designed to measure similarity. Of the 120 generated and selected variants, 18 clusters containing similar technological solutions were formed (figure 1). The variants under study have high ratings, which makes it possible to conclude that there are high technical and economic indicators.

![Figure 1. Location of technological processes clusters in the morphological solutions space.](image)

3. Formation UFG structures

The mechanism of deformation of materials in structural superplasticity is grain boundary sliding. In order for grain boundary sliding to be the main mechanism of deformation, it is necessary that the grain size does not exceed 20 µm.

The main method of grinding grains to form an ultra-fine-grain structure in multiphase alloys is dynamic recrystallization. Due to the presence of secondary phases in the interphase space of the matrix, the thermal stability of the resulting structure significantly increases, allowing widespread use of dynamic recrystallization in both laboratory and industrial conditions.

In order to obtain UFG structures in the blanks of industrial nickel alloys, which usually have a large-grain structure, various types of deformation-thermal treatment are used, such as isothermal forging, punching, controlled rolling, equal channel angular pressing, high pressure torsion, as well as other methods of forming processes. To obtain a blank for isothermal roll-out of the shaft from the alloy EhK79 is proposed to use closed isothermal punching. The drawing of the blank under the rollout of the shaft is presented on figure 2.
The kinetics of dynamic recrystallization and the size of the recrystallized grains obtained were described by the model Johnson-Mehl-Avrami-Kolmogorov (JMAK) [10]. The nature of the metal flow at punching practically does not depend on the temperature-speed parameters of deformation. The sequence of form-change is presented in figure 3. The deformation consists of two stages. In the first stage, the blank is deformed to the contact of the side surface of the blank with the matrix, and then there is a reverse squeezing until the final filling of the cavity of the stamp.

The built model allows determining the proportion of recrystallized harvest volume, the average size of recrystallized grains and the average size of the grains of the harvest matrix depending on the degree, speed and temperature of the deformation of the alloy EhK79.

4. Johnson-Mehl-Avrami-Kolmogorov model to predict microstructure evolution
The same metals and alloys, with the same chemical composition, can have a different microstructure. This is due to different approaches and methods of forming parts and their heat treatment. The microstructure has a significant effect on the physical, mechanical and operational properties of parts. The most common model used to predict microstructure evolution is JMAK model, which calculates the proportion of recrystallized volume and average grain size depending on the parameters of deformation and holding conditions.

The analysis underwent dynamic recrystallization. The simulation of grain growth is carried out right before the punching operation (for non-deformable metal). The simulation was carried out under
isothermal conditions (the temperatures of work piece, environment, and tool were equal). The essence of the experiment is to perform the operation of hot forging "upset" (figure 4) of a cylindrical billet with dimensions: diameter 5 mm, height 8 mm.

![Figure 4. Upsetting of a cylindrical billet.](image)

For a full comparative analysis, 12 simulations were calculated with various input data (table 1).

| №  | Degree of deformation | Height, mm | Temperature, °C | Strain rate, 1·s⁻¹ | Deformation velocity, mm·s⁻¹ |
|----|-----------------------|------------|-----------------|--------------------|-----------------------------|
| 1  | 0.7                   | 3.97       | 970             | 0.01               | 0.058                       |
| 2  | 0.7                   | 3.97       | 970             | 0.10               | 0.575                       |
| 3  | 0.7                   | 3.97       | 970             | 1                  | 5.753                       |
| 4  | 0.7                   | 3.97       | 1080            | 0.01               | 0.058                       |
| 5  | 0.7                   | 3.97       | 1080            | 0.10               | 0.575                       |
| 6  | 0.7                   | 3.97       | 1080            | 1                  | 5.753                       |
| 7  | 1                     | 2.94       | 970             | 0.01               | 0.051                       |
| 8  | 1                     | 2.94       | 970             | 0.10               | 0.506                       |
| 9  | 1                     | 2.94       | 970             | 1                  | 5.057                       |
| 10 | 1                     | 2.94       | 1080            | 0.01               | 0.051                       |
| 11 | 1                     | 2.94       | 1080            | 0.10               | 0.506                       |
| 12 | 1                     | 2.94       | 1080            | 1                  | 5.057                       |

As an example, the figures show the fields: the proportions of dynamically recrystallized volume (figure 5), average size of dynamically recrystallized grains (figure 6) and average size of grains (figure 7), obtained as a result of modeling the dynamic recrystallization of the Huang’s model, according to input data presented in table 1. Three JMAK models proposed by Huang [11], Jong-Sang Na [12] and Chen Liging [13] were used to analyze grain growth.
Figure 5. The proportions of dynamically recrystallized volume (JMAK Huang model).

Figure 6. The average size of dynamically recrystallized grains (JMAK Huang model).

Figure 7. The average size of grains (JMAK Huang model).

For a full comparative analysis, 10 simulations were carried out with different input data (table 2).
Table 2. Grain Growth Simulation Route

| №  | T, °С | t, h |
|----|-------|------|
| 1  | 970   | 0.5  |
| 2  | 970   | 1    |
| 3  | 970   | 2    |
| 4  | 970   | 4    |
| 5  | 970   | 10   |
| 6  | 1080  | 0.5  |
| 7  | 1080  | 1    |
| 8  | 1080  | 2    |
| 9  | 1080  | 4    |
| 10 | 1080  | 10   |

Simulation of the calculation of the volume fraction of dynamically recrystallized grains showed that the value varies with a change in the temperature signification, the degree of deformation, and the strain rate. It appears to be a similar development trend: with an increase in the strain rate and temperature, the value of the average grain size decreases. This result was obtained after a deep analysis of calculation of the average size of dynamically recrystallized grains.

Modeling the calculation of the average grain size showed a similar development trend for all three models: everywhere, over time, the average grain size will increase. In the models of Chen Liging and D. Huang, the average grain size at 1080°C practically coincides, and the values of the third model proposed by Young-Sang Na, on average, are 2 times less than in the others.

5. Conclusion
In the article include the method of analysis and selection of technological processes in the form of parts in isothermal conditions. The technological processes and simulation of deformation-thermal treatment has been carried out. The simulation ensured the formation of the ultra-fine-grain structure in the blanks under the super-plastic roll-out of the shaft from the alloy EhK79. The modeling shows the effect of the microstructure of alloys on the physical-mechanical and operational properties of parts. As the model used to predict microstructure evolution is the Johnson-Mehl-Avrami-Kolmogorov model.

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