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Deformation in Superplasticity Regime – An Effective Method of Producing Components from Hetero-Phase Nickel-Based Alloys with Functional-Gradient Properties

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Abstract

The example of a deformable nickel alloy of the Ni–13Cr–10.7Co–4.6Mo–3.4Nb–3.2Al–2.6Ti–2.8W type and Astroloy alloy confirms that a regulated change in the deformation regimes and heat treatment in semi-finished products and parts can create regulated structural states that ensure the achievement of the required characteristics of technological and operational properties.

The paper demonstrates the possibility of using a local fabrication scheme in the superplasticity (SP) temperature-velocity regime to produce gas turbine engine (GTE) components with a regulated change in the microstructure along the cross section (a fine grain microduplex structure in the hub, a mixed "necklace" type in the web and a coarse grain structure with tortuous grain boundaries in the disc rim). The results of mechanical tests of the samples showed that such a controlled change in the microstructure along the cross section resulted in the enhanced properties of various parts of the component in the interval of operating temperatures. A fine-grained microduplex structure, formed in the zone of the part operating at low temperatures, results in the highest strength properties. A coarse-grained structure with tortuous grain boundaries, which was obtained in the most heated zone of the component – the web, resulted in the maximum heat-resistant properties. In the zone of the web working at moderate temperatures, a mixed "necklace" type structure was formed, which resulted in enhanced strength and heat resistance properties due to the effect of sub-structural hardening. Similar results were obtained by deforming the Astroloy powder alloy.

The comparative analysis of the obtained results with the known enables to conclude that deformation in the SP temperature-velocity regime combined with heat treatment in the ($\gamma+\gamma'$)-region is a kind of thermomechanical treatment resulting in short-term and high-temperature properties necessary for essential components made from hetero-phase nickel alloys used in the designs of aircraft and ground power plants.

Keywords

Superplastcity; strength properties; temperature-velocity regime; microduplex structure; necklace structure; fine-grained structure; deformation; thermal mechanical treatment.

Introduction

Nickel-based superalloys used in gas turbine engines (**GTEs**) are exposed to complex effects of temperature and loads [1–3]. Therefore, components of modern and promising gas turbine engines must have a microstructure with a set of properties [1–6] optimized for real operating conditions of the component. It is noteworthy that creation of regulated structures in cast or powder or deformed material is one of the ways to improve physical-mechanical properties of nickel-based superalloys [1–10]. Heat treatment can reduce the sensitivity to notch and increase resistance to crack growth during creep by forming a structure with tortuous grain boundaries [7–8]. The paper [9] showed the principal possibility of making disc preforms with variable structure and functional gradient properties by the HIP method using granules of different fractions. In addition, as shown in [10], the "Dual Microstructure Heat Treatment Method" (US Patent No. 6660110) causes a regulated monotonous increase in the grain size from 1–2 μm in the hub to 30–50 μm in the rim of the disc. Due to this, maximum strength characteristics are in the least heated part of the disk – the hub. At the same time, the highest characteristics of heat resistance are in the most heated part – the rim.

Since nickel-based superalloys have to meet a number of specific requirements, the most important of which are the creep limit and the long-term strength limit, it is necessary to perform the recovery heat treatment after SP deformation according to a standard or special regime [11].

At the same time, it should be noted that an increased level of heat-resistant properties can be achieved by thermo-mechanical treatment (**TMT**) [12–15] rather than heat treatment only. For example, the creation of "necklace" microstructure in products increases the strength properties, fatigue failure resistance and reduces notch sensitivity [12, 13]. The study of the changes in the "necklace" structure of the EP742-alloy after the TMT [15] confirmed that the optimal structure ensuring the best combination of strength at room temperature, long-term strength and plasticity is a polygonized structure stabilized by dispersed particles of the γ'-phase with a subgrain value of 0.3–1.5 μm in the heat-deformed grains.

Along with thermal deformation, high-temperature TMT is often used on the "necklace" type structure for GTE disc made from nickel superalloys [15]. Owing to high-temperature TMT, the optimal regimes lead to a significant increase in the characteristics of long-term and short-term heat resistance in a certain range of test temperatures, an increase in resistance to fatigue failure, strength and plasticity properties at room temperature [15]. At the same time, the decisive influence of high-temperature TMT on the properties of nickel-based alloys is associated primarily with its effect on the grain boundary structure, as a result of which tortuous grain boundaries are formed. Thus, the use of high-temperature TMT of forgings from the EK79 ID alloy in comparison with the existing technology made it possible to increase the strength properties by 50–80 MPa at the same level of plasticity properties, and also significantly increase the time to failure of the samples at 650 °C and voltage 900 MPa [16].

The results of studies of the structure formation processes during deformation in a wide range of temperature and velocity described in [11, 17–23] have shown that, despite the large diversity of nickel-based superalloys, their complex chemical phase composition, there are general patterns forming structural states regulated in the hot, warm and even cold deformation. However, as shown in [11, 17, 21–25] one of the major factors to control structure and properties of nickel-based alloys is a strengthening phase state, its parameters and the type of connection with a matrix, combined with a SP temperature-velocity deformation regime. The results of years of systematic studies of the microstructure and properties of nickel-based superalloys were the basis for the development of a number of new and effective methods [26, 27] to produce a wide range of regulated microstructural states of nickel-based superalloys (such as microcrystalline microduplex, submicroduplex, nanoduplex, "necklace", coarse-grained structure with tortuous grain boundaries).

The purpose of this work is to justify the efficiency of deformation in the SP regime for obtaining regulated microstructural states of nickel-based superalloys, which will allow achieving the specified characteristics of the functional gradient properties in the GTE components optimized to the actual conditions of their operation.

Formation of regulated structures and properties in nickel-based superalloys during deformation in the SP regime and final heat treatment

Deformable EP962 alloy. Model samples from the EP962 alloy with a structure cut from a large-sized washer 400 mm in diameter produced by the TMT method, which was described in detail in [23], were used for the study, along with a 1600-ton hydraulic press and an ISFB510 isothermal die block. Some of the samples were deformed in the SP regime by compression to a degree of 25 to 75 % and subsequent heat treatment in the (γ+γ′)-region. Of interest was the comparison of the properties of the samples with a microduplex structure and a coarse-grained structure, as well as a mixed ("necklace" type) obtained under the same processing conditions (Fig. 1).

The mechanical properties of the EP962 alloy in different microstructural states are summarized in Table 1. The data presented in the table show that at room temperature the short-term properties of microcrystalline samples have high strengths, yield strength and high plasticity.

In general, for these properties, samples with a microduplex structure significantly exceeded the corresponding characteristics of samples with a coarse-grained structure. However, at elevated temperatures due to softening in them, a sharp decrease in strength properties to a level below the technical conditions was observed, although the plasticity properties increased. In this state, the samples had low long-term strength. This was apparently due to the large extent of arbitrary (incoherent and high-angle) interphase (γ/γ′) and intergranular (γ/γ) boundaries, whose proportion

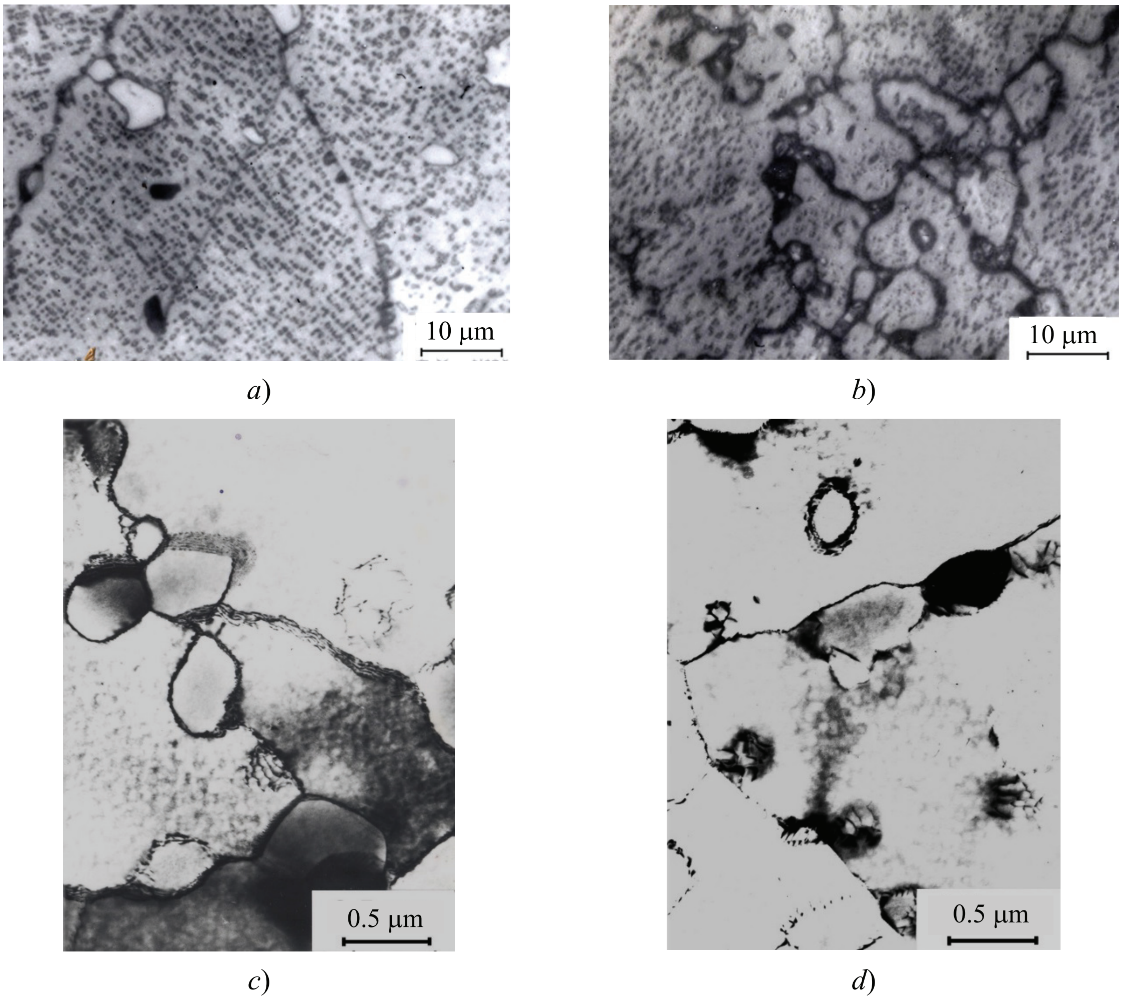


Fig. 1. The microstructure of the EP962 alloy in 3 states after deformation in the SP regime and heat treatment in (γ+γ′)-region:
a – fine-grained state (d_γ=30 µm); *b*, *c* – "necklace" type microstructure;
d – a coarse-grained microstructure with tortuous grain boundaries (d_γ = 120 µm)

Table 1

The mechanical properties of the EP962 alloy in different microstructural states

Microstructure	Room temperature					Temperature 650 °C	
	σ_B, MPa	$\sigma_{0,2}$, MPa	δ, %	ψ, %	KCU, J/m^2	Mechanical stress, MPa	Time to failure, hrs.
Microduplex	1650	1176	24	22,4	0,4	1000	74
Fine-grained (d_γ = 30 µm)	1590	1090	14.5	15.5	0.3	1000	140
Coarse-grained (d_γ = 120 µm)	1500	1020	22.5	17.0	0.31	1000	284
"Necklace"	1630	1255	21.9	18.2	0.34	1000	444
						1050	188
Coarse-grained structure with microstructure with tortuous grain boundaries	1562	1222	20.7	15.0	0.32	1000	520
						1050	243
						1080	102

was not less than 50 %, which created favorable conditions for the intensive development of grain boundary sliding. Heat treatment, including heating to the dissolution temperature of the γ′-phase and aging, resulted in the growth of the matrix grains to a size of 120 μm and the separation of coherent particles of the γ′-phase of the cuboid form. As a result of this treatment, the strength properties in the samples with the original microduplex structure decreased at low temperatures, while the heat resistance increased to the level attained after normal deformation and serial heat treatment.

The microstructural changes in the nickel-based superalloys after deformation in the SP temperature-velocity regime in the EP962 alloy considered in [17, 18, 23] allowed us to establish that under certain deformation conditions, recrystallization does not occur, or it covers individual regions, for example, the initial grain boundaries. At the same time, due to the variation of the structural parameters (change in the dispersion of the particles of the γ′-phase) and the deformation parameters (temperature, degree and strain rate), it is possible to control the amount of the recrystallized volume and thereby obtain, for example, a "necklace" type structure. To the greatest extent, a coarse-grained matrix structure with dispersed precipitates of the γ′-phase was suitable to create thermally stable microstructural states of the "necklace" type and coarse-grained with tortuous grain boundaries.

It was found that the necessary dispersion of the γ′-phase particles in the microstructure was provided by selecting the cooling rate from the quenching temperature (γ-region) in the range of 0.05 to 120 °/min. Depending on the required characteristics of the structure and properties of the component and its dimensions, the optimum cooling rate was chosen to obtain the specified dispersion of the γ′-phase and the deformation regimes (temperature, velocity and degree of deformation). This ensured the regulated development of the processes of recrystallization or polygonization, mainly in the volumes of the initial coarse grains, and in combination with the subsequent heat treatment in the (γ′+γ)-region, it was possible to form the required structural state in the component. To obtain a microstructure of the "necklace" type, it was expedient to perform the deformation in the temperature-velocity SP regime (1050–1100 °C, 10^{-3}–10^{-4} s^{-1}) of the alloy to a 25–75 % degree. Recrystallization covered only boundary areas. It should be noted that at lower degrees of deformation, recrystallization does not develop even in frontier volumes. In this case, conditions are created for the realization of other methods [27, 28], which ensure the formation of a coarse-grained structure with tortuous grain boundaries.

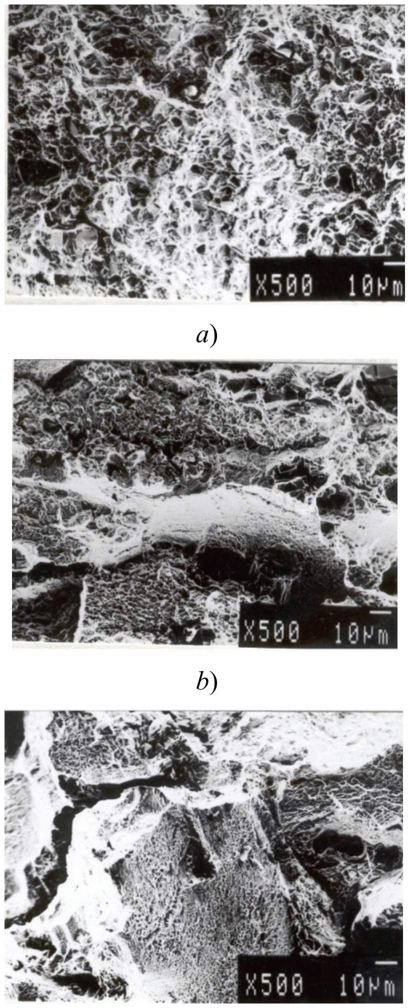
An increase in heat resistance was obviously connected not only with the increase in the size of the matrix grains, but also with a sharp change in the structure of interphase and grain boundaries. For this state, the greatest extent of coherent interphase (γ/γ′) boundaries was characteristic, the share of which among all types of boundaries exceeded 90 %. The requisite level of heat resistance while maintaining high short-term properties was provided by heat treatment, including quenching from a temperature of 20 °C below the temperature of complete dissolution of the γ′-phase ($t_{S\gamma'}$). In this case, it was possible to preserve sufficiently fine-grained microstructure (~30 μm), in which, along with a coagulated γ′-phase with a size of 0.5–0,7 μm, a dispersed γ′-phase was present.

Increased short-term and high-temperature properties were obtained in samples with a "necklace" type structure, in which the substructure of heat-deformed grains was stabilized by coagulated partially coherent particles of a γ′-phase with a size of 0.5–0.7 μm. In this case, large incoherent grains of γ′-phase with a size of 12 μm were distributed in the zone of the "necklace" – chains of small recrystallized grains 4–6 μm in size. The highest heat-resistant properties at a moderate level of short-term properties, substantially exceeding the requirements of technical conditions, were demonstrated by samples with a coarse-grained structure and tortuous grain boundaries. In the electron microscopic analysis, it was observed [21] that in this state coagulated partially coherent γ′-phase precipitates were present inside the large grains of a 120 μm matrix. The peculiarity of this microstructural state is that in the boundary zone there was a substructure decorated with particles of the γ′-phase, the occurrence of which was probably the main cause of the tortuosity of the grain boundaries.

The analysis of fractures of impact samples showed that, depending on the microstructural state, the nature of the fracture changes (Fig. 2). In samples with a microduplex and coarse-grained microstructure obtained after complete treatment with solid solution, there was mainly intergranular destruction. At the same time, the destruction of samples that were not completely treated into a solid solution (states with a "necklace" type structure and coarse-grained with tortuous grain boundaries) was more complex. As can be seen in Fig. 2, in the fracture of samples with a "necklace" type structure, secondary cracks are present, indicating a predominance of secondary fracture perpendicular to the main one. This kind of fracture obviously caused an increase in viscosity, preventing the formation of a main crack. In this case, the substructure that occurs in heat-deformed grains and causes the tortuosity of grain boundaries inhibits the growth and fusion of cracks, which contributes to an increase in the propagation of the crack. This structural state is preferable especially for nickel-based superalloys, which are highly sensitive to notch.

Thus, the findings indicate that the deformation in the temperature-velocity SP regime in combination with heat treatment in a two-phase ($\gamma+\gamma'$)-region makes it possible to create in regulated microstructural states in nickel-based superalloys with the required set of short-term and high-temperature properties. It is also important to note that by creating a certain state of interphase and intergranular boundaries in a material, regulating the proportions of the extent of one or another of their types, one can significantly change the characteristics of mechanical properties.

Data in [20, 23, 25] on the investigation of SP properties show that microduplex, submicroduplex and nanoduplex structures are most effective at the stage of forming components from hard-to-deform nickel-based superalloys, since they provide the maximum realization of the resource of technological plasticity. The results of the study of the mechanical properties of the nickel-based superalloys tension at room temperature showed that refinement of microstructure to micro-, submicro and nanocrystalline states provides a significant increase in the strength properties (σ_B, $\sigma_{0,2}$) and microhardness. It is known that the increase in the strength properties of the investigated alloys and, above all, the yield point is due to a decrease in the grain size and is well described by the Hall-Petch relation, given, for example, in [20] and agrees well with numerous data obtained from other materials [11]. It should be noted that after the SP deformation under optimal conditions, the material has a sufficiently fine-grained structure of a duplex type that is characterized by a low density of dislocations and the presence of incoherent globular particle-grains of γ'-phase. Therefore, in order to restore the heat-resistant properties of nickel alloys, a standard thermal treatment is usually performed: quenching from a single-phase region leading to coarsening of the matrix grains (γ-phase) and subsequent two or three-step aging for homogeneous separation of coherent disperse particles of γ'-phase [11]. After such heat treatment, a uniform coarse-grained structure with a grain size of 50–150 μm is formed, which ensures the required set of properties, achieved mainly by separating the coherent particles of the optimal size. Consequently, this structural state demonstrates a lower level of properties than that achieved by thermomechanical treatment methods, when higher characteristics of yield strength and heat resistance are achieved by additional sub-structural hardening [11–16].



a)

b)

c)

Fig. 2. The surface of the fracture of impact samples made from the EP962 alloy after various treatment regimes:
a – microduplex; *b* – “necklace”; *c* – coarse-grained

The analysis of microstructural states (such as “necklace” and coarse-grained with tortuous grain boundaries), obtained as a result of deformation in the SP regime, indicates that they are in many respects analogous to microstructures and corresponding levels of properties obtained in the process of traditional TMT of nickel-based superalloys [12–15]. A microstructure of the “necklace” type is usually formed by TMT using warm deformation [13–14]. A coarse-grained microstructure with tortuous grain boundaries is formed by high-temperature TMT [15, 16]. These microstructural states, as noted above, lead to increased characteristics of long-term and short-term heat resistance, as well as to an increase in resistance to fatigue failure. At the same time,

Table 2

Mechanical properties of the Astroloy alloy at room temperature

Alloy state	$\sigma_в$, MPa	$\sigma_{0,2}$, MPa	δ, %	ψ, %
Initial	1450	1050	21.0	23.1
Microduplex	1588	1209	20.1	24.9
“Necklace”	1636	1251	19.8	25.1

deformations in the SP regime have specific features that have a noticeable effect on the microstructure being formed. First, it is the isothermal conditions of deformation. Secondly, the deformation occurs at lower velocities of 10^{-4}–10^{-3} s^{-1} and degrees less than 50 %. According to [11, 28], deformation with slow velocities causes an increase in the thermal stability of the hardening created by TMT.

Of special interest is the fact that the identity of the thermomechanical parameters of deformation in the SP regime (the coarse-grained semi-finished product is subject to deformation) makes it possible to combine them in one forming process. Thanks to this, a qualitative change in the nature of the structure formation becomes possible, resulting in the formation of products with a regulated change in the cross-section of the microstructure and properties.

Thus, the deformation in the temperature-velocity SP regime in combination with heat treatment in a two-phase (γ'+γ)-region is a variation of the TMT, which makes it possible to obtain an increased level of strength properties at room temperature and, especially, long-term strength at operating temperatures in nickel-based alloys.

The Astroloy powder alloy. Based on the results of the investigation of the Astroloy powder alloy, optimal regimes for obtaining various microstructural states were determined. From the deformed and annealed washers, samples were prepared for mechanical testing. Before the final deformation, part of the samples of the first batch was heated to 1180 °C for 1 hour and then cooled at a rate of 100–120 °/h up to 1000 °C and deformed at 1100 °C by 25 %.

Table 3

Mechanical properties of the Astroloy alloy at elevated temperatures

Alloy state	T, °C	$\sigma_в$, MPa	$\sigma_{0,2}$, MPa	δ, %	ψ, %	Time to failure at stress 760 MPa
Initial*	650	1330	974	19.6	–	
	650					60
	705					60
Microduplex	650	1393	1149	18.0	15.8	
	650					110^{05} fracture
	705					108^{05} fracture
“Necklace”	650	1376	1176	18.7	23.3	103^{15} fracture
	705					
Microduplex	700					112°° fracture
M3 (fine-grained (d_γ = 30 μm)	700					138^{05} fracture
	650					806^{00} non-fracture**
	650					806^{00} non-fracture

* DMRL data, India

** Additional load up to 960 MPa (after testing for 806 hours at a stress of 760 MPa). The sample was ruptured at 650 °C and a stress of 960MPa after 141 hours.

The analysis of the results of mechanical tests given in Table 2 and 3 showed that the strength properties $\sigma_в$, $\sigma_{0,2}$ and long-term heat resistance of the samples were significantly higher than those for the initial material. These results agree well with the data obtained in [4] for the Astroloy type of an alloy after treatment for a “necklace” type structure (Fig. 3).

Thus, isothermal deformation enables to significantly increase the properties of powdered Astroloy nickel-based superalloy in two variants – fine-grained and a “necklace” type structure.

Obtaining a gradient structure in a rolled disc from the EP962 alloy and its effect on mechanical properties

The results given above showed that the deformation in the SP regime is very effective, allowing one to combine SP deformation and TMT in one technological process. In this connection, it is extremely important to study the possibility of using treatment in the SP regime under the conditions of a local deformation scheme to obtain discs with a regulated structure and enhanced properties.

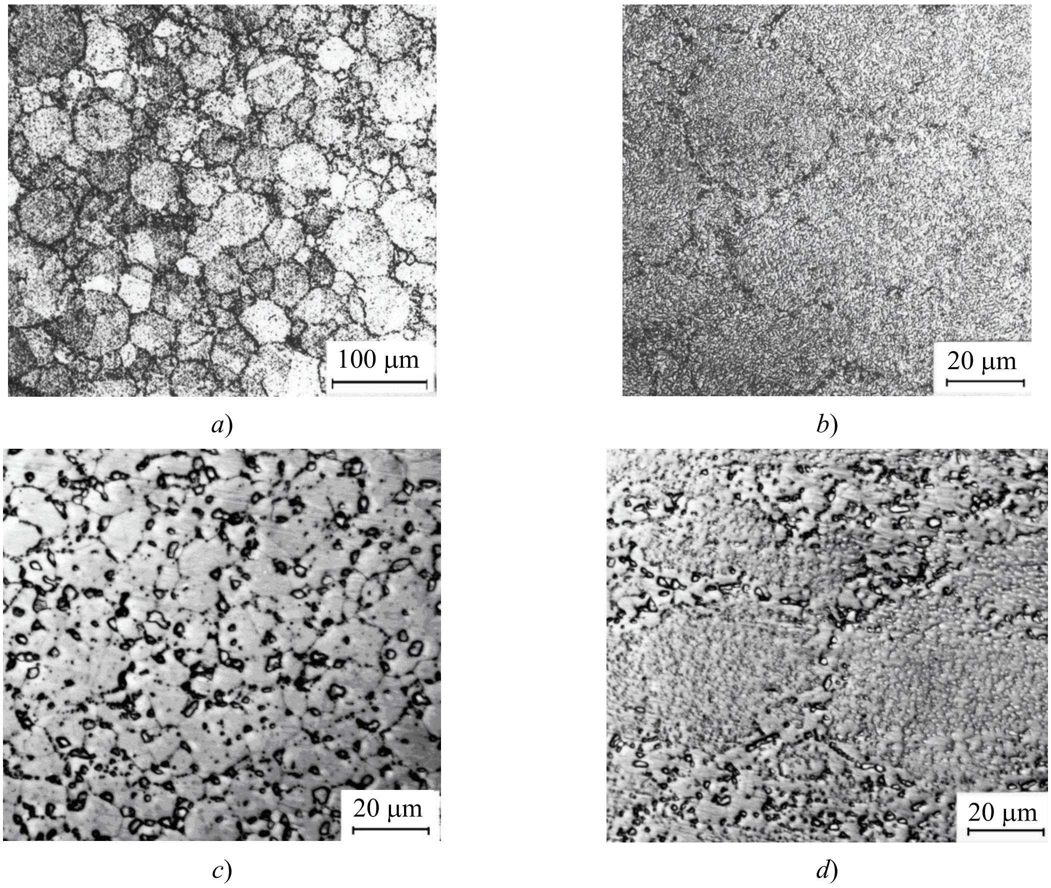
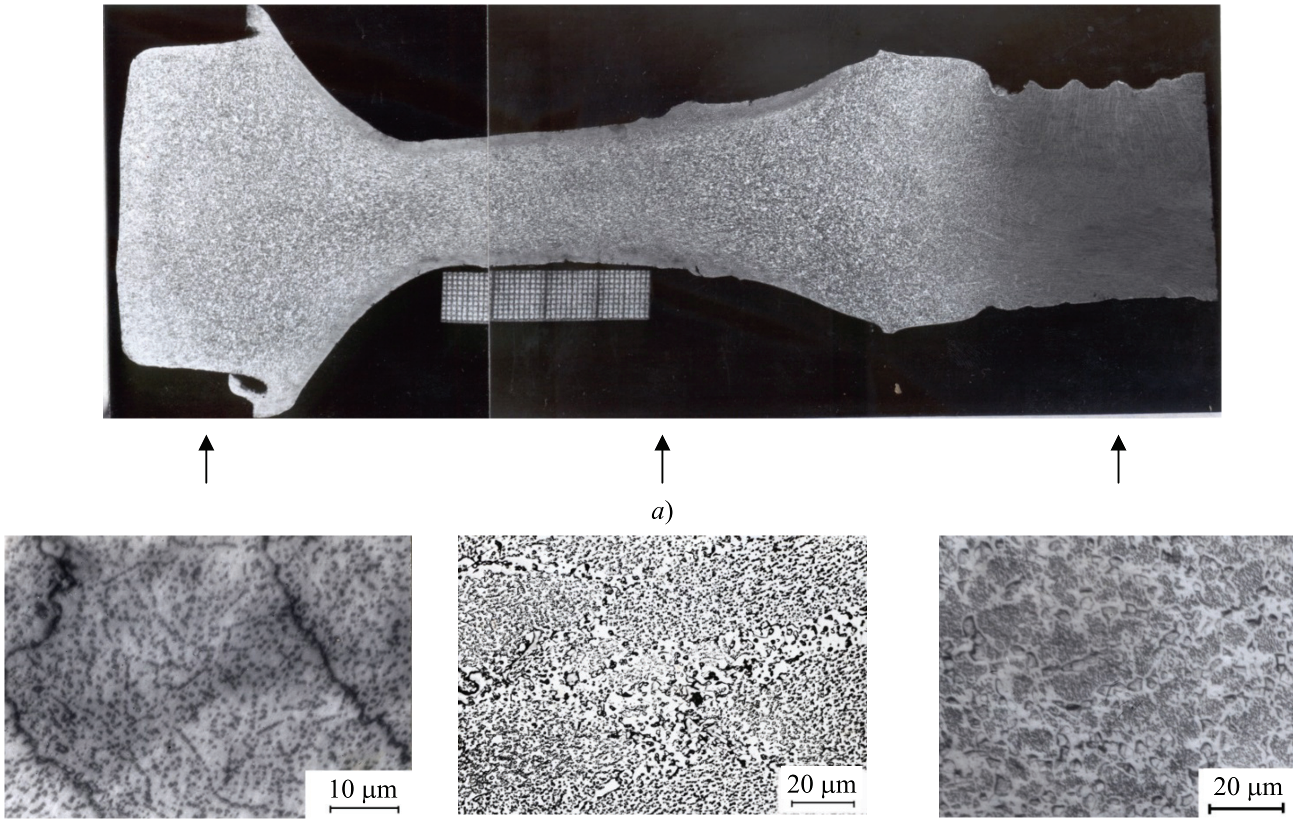


Fig. 3. The microstructure of the Astroloy alloy in the initial state (*a*, *b*) and after thermomechanical treatment (*c*, *d*):
c – microduplex structure; *d* – the "necklace" type structure

The initial blank for rolling the disk with a regulated structure was a preform from the EP962 alloy with a microduplex structure. The rolling of the disk was performed in the following SP regime: at a temperature of (1100 ± 10) °C in the velocity range 10^{-3}–10^{-2} s^{-1} [21]. As a result of rolling the preform with a diameter of 410 mm, a high-quality disc in a configuration approximating the finished product was obtained (Fig. 4). Evaluation of the deformation efforts showed that despite the increase in the rolling temperature by 60 °C, the use of a disc preform with a coarse-grained structure of the web and rim zones led to a significant increase in deformation forces exceeding the corresponding values for a preform with a homogeneous microcrystalline structure. An important feature of the rolling in the SP regime is that the microcrystalline structure was formed in the surface layer to a depth of 2–3 mm. This circumstance, apparently, was the reason for an increase in the deformation capacity of the preform with a coarse-grained microstructure of the web and rim zones and the absence of cracks on the surface of the rolled disc.

Due to the adjustment of the parameters of the initial microstructure of the preform and rolling in the SP regime, as was shown in [28], a disc with a regulated change in the microstructure along the cross section was produced (Fig. 4). The microduplex structure of the initial preform was preserved in the disc hub, and a coarse-grained microstructure with a grain size of 120–150 μm in the γ-phase and a bimodal distribution of the γ′-phase precipitates by the size was obtained in the rim. About 15 % were relatively large particles of γ′-phase 0.5 μm in size, coagulated during deformation, and the remainder were dispersed particles precipitated from the supersaturated solid solution upon cooling from the deformation temperature. A mixed microstructure was formed in the web, consisting of radially deformed large grains surrounded by small grains of γ′-phase 3–5 μm in size and coagulated incoherent precipitates of γ′-phase with a size of 1–2 μm.

The disc with a regulated microstructure was subjected to incomplete quenching at a deformation temperature that was below the temperature $t_{S\gamma'}$. This allowed to a certain extent to preserve in each of its zones the required character of the microstructure resulting from deformation, and after subsequent aging



a)

b) *c*) *d*)

Fig. 4. Macro (*a*) and microstructure (*b*, *c*, *d*) of the disk of the EP962 alloy after rolling in the SP mode and heat treatment:
b – the coarse-grained microstructure with tortuous grain boundaries in the rim; *c* – the "necklace" type in the web;
d – the fine-grained microstructure in the hub; rolling at 1100 °C + heat treatment in the (γ+γ′)region

to ensure the hardening of the alloy by decomposition of the solid solution and separation of a part of the γ′-phase.

Thus, an equiaxed microstructure with a large grain size (31 μm) was formed in the disc hub. At the same time, a significant part of the large precipitates of the γ′-phase dissolved and was again released uniformly in the web of the γ′-phase grains in the form of dispersed particles with a size of 0.1–0.15 μm. An insignificant number of large particles of γ′-phase of 0.6 μm in size was also observed. In the web of the disc, a microstructure of the "necklace" type was more clearly formed, in which, after aging, three groups of γ′-phase particles were observed. Large round-shaped particles of γ′-phase of 1.5 μm in size as components of the microduplex structure were located mainly along the grain boundaries. Medium cuboid particles (0.55 μm) located in the volume of deformed grains and most often in the form of chains decorating the subgrain boundaries, as well as disperse particles were distributed homogeneously throughout the volume of the material.

The electron microscopic analysis of the microstructure of the web confirmed an increased dislocation density and its subgrain structure in the heat-deformed grains. The microstructure of the disc rim after heat treatment underwent insignificant changes. The average size and shape of the grains was preserved, while most of the grain boundaries became tortuous, which was apparently due to the formation of subgrains, as well as local migration of high-angle boundaries. In this case, the γ′-phase precipitates were observed only in the form of 2 groups: medium and dispersed, while the shape, size and distribution were in many ways analogous to the fine microstructure of the web.

To assess the mechanical properties, tests were carried out on samples cut from various zones of the disc. The results of these tests are given in Table 4.

The analysis of mechanical properties shows that in the non-heat-treated state the disc has non-homogeneous properties. In the hub, the strength and plasticity properties are high, while in the web and the rim they were noticeably lower and in some cases lower than the requirements of the technical conditions. It is important to emphasize that in all zones heat resistance was unsatisfactory.

Table 4

The mechanical properties of the disk from the EP962 alloy with a regulated microstructure

Place of sample cutting	T, °C	$\sigma_в$, MPa	$\sigma_{0,2}$, MPa	δ, %	ψ, %	KCU, J/mm^2	D_{rel}, mm	Heat resistance at 650°C	
								σ, MPa	τ, hrs
Hub	20	1497	1027	22.8	17.2	0.39	3.1	1050	13
Web	20	1368	976	21.6	15.7	0.42	3.1	1050	14
Rim	20	1390	992	22.2	16.1	0.5	3.1	1050	36
Hub	20	1590	1173	19.4	16.3	0.38	3.1	1000	164
Web	20	1581	1263	16.4	16.9	0.34	3.0	1020	379
								1050	209
Rim	20	1540	1240	14.6	15.8	0.31	3.0	1050	197
								1080	111
Hub								1000	165
								1020	135
								1080	175
The transition part from the hub to the Web	20	1570	1199	15.4	16.2	0.26	3.0	1000	181
								1020	279
								1050	264
Web								1050	267
The transition part from the web to the rim	20	1538	1238	13.4	17.5	0.28	3.0	1050	274
								1080	179
Rim								1100	113
Specifications 1-3-87	20	≥1400	≥1000	≥13.0	≥14.0	1000	2.9–3.2	≥1000	–

The highest values of the strength and plasticity properties of this disc were observed in the hub. In the web and the rim, these properties were somewhat lower than in the hub, but in altogether they met the requirements of the technical specifications, and were even higher in terms of strength (by 10–25 %). The heat-resistant properties, on the contrary, reached a maximum value in the rim, with $\sigma_{100}^{650} = 1080$ MPa, and the time before failure at the standard load (1000 MPa) was 4–5 times higher than the norm.

In the web, the long-term heat resistance of the samples, although somewhat inferior to the samples from the rim, remained high at $\sigma_{100}^{650} = 1050$ MPa. A moderate level of long-term heat resistance was achieved in the hub: the time to failure at a load of 1000 MPa averaged 1.5–2 times the norm. In the transition parts of the disc from the hub to the web and from the web to the rim of the disc, the values of the short-term mechanical properties were close to the average values of the properties observed in the neighboring zones and completely met the requirements of the technical specifications.

Additional low temperature aging at 700 °C for 24 hours enabled to further increase by at least 20–30 MPa the level of long-duration heat resistance in all zones of the disc.

After heat treatment, the mechanical properties changed significantly. An important circumstance is that the regulated change in the microstructure and properties across the section obtained in the disc was the most rational, since it largely met the actual conditions of operation of the GTE discs. Indeed, the highest values of strength and plasticity properties, as well as the required level of heat resistance, were obtained in the disc hub, which usually heats up during operation to 200–300 °C lower than the rim and experiences maximum loads. At the same time, in the most heated part of the disc – the rim, the maximum heat resistance was achieved at a sufficient level of short-term properties.

Due to the combination of the local deformation scheme and the SP temperature-velocity regime, not only the required level of properties was achieved, but also it was also possible to significantly reduce the required deformation force and simultaneously increase metal recovery as compared to traditional technological processes involving TMT.

Conclusions

1. It is shown that the deformation in the SP temperature-velocity regime in combination with heat treatment in a two-phase (γ′+γ)-region is a kind of TMT, which allows obtaining in nickel superalloys an increased level of strength properties at room temperature and, especially, long-term strength at operating temperatures.

2. It is shown that the rolling of discs in the SP regime in combination with heat treatment in a two-phase (γ′+γ)-region is not only an effective method of forming, but also a kind of differentiated TMT, which makes it possible to produce components for GTE discs with a regulated change in the microstructure along the cross section (coarse grain with tortuous grain boundaries in the rim, such as "necklace" in the web and fine grain in the hub of the disc) and high functional gradient properties.

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