ANALYZE OF MAGNETIC PROPERTIES AND STRUCTURE IN NICKEL GAS TURBINE BLADE AFTER OPERATION AT FORCED REGIME

1N. N. STEPANOVA, 2M. B. RIGMANT, 3D. I. DAVIDOV, 4D. A. SHISHKIN

1,2,3,4Institute of Metal Physics Ural branch of Russian Academy of Science, Ekaterinburg, Russia
E-mail: 1 snn@imp.uran.ru, 3 davidov@imp.uran.ru

Abstract—The structure of turbine blade made from Nickel superalloy EP-800 was studied after its exploitation with increased operation temperature and rotation speed at the industrial gas turbine. The severe deformation led to structure degradation, the main factor of which is the formation of the stable defects inside particles of the strengthening intermetallic phase Ni₃Al. The severe deformation also led to the appearance of a strain-induced magnetism in initially paramagnetic alloy. The strain-induced magnetism associated with formation of ferromagnetic clusters inside of the particles of intermetallic phase. The obtained magnetic effect correlated with the dynamic stress level and the number of lattice defects in various parts of the blade.

Keywords—Structure, Magnetic Properties, Deformation, Nickel-based Superalloy, Turbine Blade.

I. INTRODUCTION

Recently technological developments are intensively conducted with a view to enhancing the thermal efficiency and output capability of the power generation gas turbines (GTs) [1-2]. Development associates with the improvement of engineering design of the turbine, but the main way of increasing power is to increase the operating temperatures and rotation speed. In this case, material of the turbine blades operates in extreme conditions due to the high temperature and stress level.

Selection of the optimal time of turbine blades operation at the forced regime requires a detailed structural analysis and evaluation of the degradation degree of the blades material. Presently the numerous structural researches undertaken to predict the fatigue life of the blades made from the Nickel superalloys [3-4]. At times the analysis relies on the results of the laboratory experiments, but the studies of the turbine blades structure after industrial operation are of particular interest [5-7].

This paper presents the results of the structure research of a turbine blade operated without the destruction at the industrial gas turbine plant with increasing the operating temperature and the rotation speed of the turbine. The blade material is the superalloy EP-800 widely used in Russian power industry [8]. Structure of the superalloy EP-800 consists of the Nickel solid solution, 40% of the strengthening γ'-phase (intermetallic compound Ni₃Al with a superstructure of the L₁₂ type) and a small amount of carbides (2%).

The intermetallic compound Ni₃Al is a weak ferromagnetic with a Curie temperature $T_c = 41$ K [9]. A deviation from stoichiometry or alloying lead to increases of Curie temperature [10], but at room temperature the Ni₃Al is paramagnetic. As a result, all phases of the superalloy EP-800 are paramagnetic at room temperature and retain this state during its further increase. In the literature, there is no information that any Nickel superalloy changed its magnetic properties after the operation on the standard regime during the warranty period.

On the other hand, some intermetallic compounds, including Ni₃Al, are known to exhibit strain-induced ferromagnetism, the phenomenon in which a paramagnetic intermetallic compound becomes ferromagnetic in part upon severe deformation [11]. Practically super-paramagnetic state was observed. Since any new phases did not revealed after deformation, the description of the strain-induced ferromagnetism performed using the term "magnetic cluster". After annealing the deformed samples are restored paramagnetic properties. Note that the above results were obtained under cold deformation (for example, cold rolling). The only observation of this effect in Nickel-based superalloy ChS-70 after operating at forced regime is [12].

In this article, the degree of structure degradation of the turbine blades made from Nickel superalloy EP-800 was studied by structural and magnetic methods after long-time operation with increased temperature and level of dynamic stress.

II. DETAILS EXPERIMENTAL

The study of structure and magnetic properties was carried out on as-cast polycrystalline blade from the superalloy EP-800 after exploitation at the stationary gas turbine with increased temperature from 800°C in standard regime up to 880°C. Operation time was 9000 h with 17 turbine starts.

The chemical composition of the investigated Ni-base superalloy is given in Table 1.
A sample was used to estimate the initial state after a standard heat treatment in a stepwise mode [8]: annealing 1160°C, 5 h; 1060°C, 2 h; 1000°C, 2 h; 850°C, 16 h; after each stage with air cooling.

### Table 1. Chemical composition of the investigated alloy, Nickel - base, wt.%

<table>
<thead>
<tr>
<th>Cr</th>
<th>Mo</th>
<th>W</th>
<th>Al</th>
<th>Co</th>
<th>Nb</th>
<th>C</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.2</td>
<td>6.0</td>
<td>7.4</td>
<td>4.5</td>
<td>9.5</td>
<td>2.2</td>
<td>0.05</td>
<td>&lt;1</td>
</tr>
</tbody>
</table>

Magnetic tests were performed at room temperature using the original device of the magnetic susceptibility measurements (constructed in IMP UB RAS). Its sensitivity is $(\pm 1 \cdot 10^{-4})$. Processing of results is performed using calibration samples. The vibrating magnetometer Lake Shore 7407 also was used for measurements of the magnetization of the samples. Measurements were performed at a frequency of 82 Hz. The amplitude of vibration was 1.5 mm; the relative error of measurement was not more than 1%. Studies of the fine structure was made in the Test center of nanotechnology and advanced materials, Institute of metal physics, UB RAS using a transmission electron microscope JEM-200CX, for x-ray microanalysis was used scanning electron microscope JSM 6490.

### III. RESULTS AND DISCUSSION

#### 3.1. Magnetic susceptibility Measurements

For blades of the EP-800 superalloy, whose upper level is 900°C, the working temperature, as a rule, is 800°C (standard regime) with the operation time 27000 h.

In our case, after operating during 9000 h in the experimental regime (880°C), there was observed an increase in the magnetic susceptibility \( \chi \) of blades material. The distribution of the magnetic susceptibility values on the surface of the turbine blade is shown in Fig.1.

The initial values of the magnetic susceptibility of superalloy EP-800 (before high-temperature deformation) was low: \( \chi = 4 \cdot 10^{-5} \). The increase \( \chi \) was different in different parts of the blade; the maximum magnitudes were obtained for the convex feather part on its “back”, in area where, as well known, temperature and the dynamic stress level were maximal [6]. The back of the feather is a narrow zone running along the axis of the feather on its convex side at the place of maximum curvature. Another critical place is the leading edge of the feather.

In the blade locking part, which was mainly subjected to thermal actions, the magnitude of the magnetic susceptibility \( \chi \) did not change in comparison with the state before the operation \( (4 \cdot 10^{-5}) \). As can be seen in Fig.1, for the EP-800 alloy the changes of magnetic susceptibility were considerable: from \( 4 \cdot 10^{-5} \) up to \( 700 \cdot 10^{-5} \) in the convex feather part. The annealing in a stepwise mode led to the restoration of values \( \chi \) of the samples from the convex feather part to the original level \( 4 \cdot 10^{-5} \).

In this study magnetic susceptibility measurement performed directly on the blades without preliminary preparation of the surface that corresponds to the method of non-destructive magnetic testing.

The surface of blade was oxidized the effect it was necessary to trace the role of oxidation in the magnetic properties change. The high concentration of chromium (12.2 %) leads to the formation of the oxide \( \text{Cr}_2\text{O}_3 \) layer on the surface which is antiferromagnetic with low value of magnetic susceptibility. This is a protective oxide.

Our results obtained by x-rays microanalysis revealed of the redistribution of chemical elements on the feather surface: near its back and leading edge. It the oxide layer there was an increase in the iron concentration from 1 % up to 6 % (iron was not an alloying element and presented as an impurity) together with the decrease in the chromium content from 12.2 % down to 4.6 %. It led to the formation of ferromagnetic iron oxides. As a result, places of the blade the most prone to stress were a subject to surface corrosion. The formation of ferromagnetic iron oxide is both a contribution to the increase of the magnetic susceptibility, and the evidence of the degradation of the structure as a demonstration of diffusion under stress.

#### 3.2. Electron microscopic Studies
The electron microscopic studies were performed on the samples cut from the different parts of the blades after operation in experimental regime. Note that the electron microscopic analysis did not revealed formation of any new phase. In the samples, which were cut from the convex part of the feather, the studies revealed a large number of defects in both the solid solution and in the intermetallic particles of $\gamma'$-phase ($\text{Ni}_3\text{Al}$) (Fig.2.a-b). The main defects were stacking fault defects within the deformed particles of intermetallic $\gamma'$-phase (Fig.2.c-d). The stacking faults are always present in $\gamma'$-phase after high-temperature tests with a high degree of deformation. The stacking faults were visible on the dark-field images. It proved that they belong to the strengthening intermetallic phase (superstructure stacking faults).

In the locking turbine part there were no defects inside $\gamma'$-particles and the only structural effect was a coagulation of intermetallic phase under heating (Fig.3.a). The annealing of the deformed samples in a stepwise mode led to the restoration of defect-free state inside $\gamma'$-phase particles (Fig.3.b).

In the feather carbide reaction occurred when the carbide NbC was replaced by carbide (Cr,Mo,W)$_2$C$_6$. Additional carbides are allocated on the grain boundaries and the defects inside the grain. Thus in the investigated turbine blade the same processes of structural degradation take place as in the blades operating on standard regime, but under high stress and temperature these processes are accelerated. The structure degradation is real because the increases in operating time at the experimental regime led to the emergency destroy of the blade after 9390 h (13 months).

Thus we see the correspondence between the number of the crystal structure defects in the various parts of the blade and the values of the magnetic susceptibility. Note, the long-time operation of turbine blades from superalloys in the standard regime did not lead to the formation of stable defects complexes inside particles of the strengthening intermetallic phase. The defects located preferably in the solid solution. Such type of structure did not lead to the appearance of ferromagnetic properties of the paramagnetic alloy. Thus magnetic cluster can be thought of as a complex of defects inside the intermetallic phase.

### 3.3. Magnetic Measurements by vibrating Magnetometer

The independent magnetic measurements were held using a vibrating magnetometer Lake Shore 7407. The measurement by vibrating magnetometer was conducted by certified methods on verified device, but this method of study was destructive. The experiment was carried out on the samples in the form of thin plates (0.3 mm). They were the workpiece parts of foils for the electron microscopy described above. Samples were cut in such a way that they do not include oxidized surface.

Field dependence of the specific magnetization $M(H)$ is representing in Fig.4. The results were consistent with a previous experiment: the values of magnetic susceptibility increased in the convex feather part of the blade after operation 880°C, 9000 h and the field
dependence of magnetization represents a curve with saturation for the same sample.

Hysteresis also observed, but the hysteresis loop is very narrow, suggesting the formation of superparamagnetic state. In Fig.5 hysteresis loop for the sample cut from the blade are shown at a different scale.

![Hysteresis Loop for Samples cut from the convex feather side on its back.](image)

**CONCLUSIONS**

Thus, the structure degradation was observed in the turbine blade made from superalloy EP-800 after operation at experimental forced regime (880°C, 9000 h). In the feather material the high density of dislocations and stacking faults presents, including those belonging to the strengthening intermetallic phase.

It is found that the initially paramagnet superalloy EP-800 acquires some ferromagnetic properties after long-time exploitation with increased operation temperature and rotation speed. The obtained magnetic tests results are correlated with the dynamic stress level and the number of lattice defects in various parts of the blade.

The surface oxidation can be an additional factor to the magnetic susceptibility increase due to iron oxide formation by the diffusion under stress.

The formation of the stable defect complex inside the γ’-phase testifies of its softening. The properties of the intermetallic phase approach those of a solid solution, and the γ’-phase ceases to be strengthening component. A measurements of the magnetic susceptibility by the improved sensitivity device allow detecting such defects inside the γ’-phase and lead to use the magnetic nondestructive testing methods for evaluating the output capacity of turbine blades.

Due to structural changes, the blades from the superalloy EP-800 should not be operated at the experimental regime for more than one year.

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