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EVALUATION OF FATIGUE PROPERTIES OF NICKEL BASED SUPERALLOY MAR 247 WITH ALUMINIDE COATING AND CRACK DETECTION BY NON-DESTRUCTIVE TECHNIQUES

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ABSTRACT

The paper presents results of fatigue test conducted on nickel based superalloy MAR 247 with aluminide layer of varying thickness. The trial for identification of damage localization with the use of Eddy Current (ET) and Electronic Speckle Pattern Interferometry optical method (ESPI) was made. It allowed for detection of cracks forming during cyclic loading of the sample. This enabled evaluation of fatigue life of the layer, as the formation of crack precede sample decohesion.

The impact of the aluminide layer thickness on the fatigue life of a nickel alloy samples in the temperature of 900 °C, which is typical value for working conditions of this types of alloys, was also obtained. Wöhler curves were assigned for the samples with the aluminide layer of 20 and 40 microns thickness.

Keywords: super-nickel alloy, fatigue testing, alumina layer, eddy current.

INTRODUCTION

Surface treatment of heat-resistant nickel based alloys is commonly used for improving their heat resistance in the operating conditions, e.g. turbine engines, where temperature can reach up to 1650ºC (at the outlet of the combustion chamber). The protective layer improves the high-temperature corrosion and erosion resistance, which enables to increase the operating temperature. However improvement of the heat resistance of alloys by covering with the aluminide layer can cause depreciation of mechanical strength properties, like creep resistance and fatigue strength.

The goal of conducted research was to estimate the influence of diffusion layer to listed above mechanical properties. Significant difficulty is to observe when the crack of the layer initiate the crack in the substrate and to determine the dynamics of its propagation. Evaluation of the fatigue life and crack propagation in aluminide layer on nickel based alloys are usually limited to microstructural observations of samples after different number of load cycles. This methodology is subject to considerable error. Additionally, each removal of the sample from the testing machine changes the load conditions of further cyclic loads, which strongly affects the reliability of the result. The possibility of using the non-destructive techniques that allow for the detection of crack without removing the sample from the testing machine until it breaks, creates the testing conditions free from the problems connected with changing of the loading condition. The Eddy Current method, commonly used in flaw detection, and ESPI method, which allows full-field strain distribution on sample surface.

Methodology

The coatings were produced on nickel alloy base with the following chemical composition: Cr-25%, Mo-0.5%, Co-20%, Al-0.9%, Ti-1.8%, Nb-2%, Mn-0.3, Fe-0.7%, Si-0.5%, C-0.03%, Ni-remainder (weight %). The aluminizing process was carried out by the chemical vapor deposition method using $AlCl_3$ vapors in hydrogen atmosphere as the carrier gas in temperature of 1020˚C for 4 h in reduced pressure of 150 hPa. The phase composition was analyzed using Bruker D8 Advanced X-ray diffractometer using Cu Kα.

The fatigue test was carried out with MTS810 load frame equipped in TestStarII Digital controller. Test was conducted in the room temperature (RT) and elevated temperature of 900 °C, however, trial of identification of crack initiation with the use of non – destructive techniques was done only for RT for over a dozen sample covered with aliminide layer for stress range of 500 -700 MPa. Specimen geometry is presented in figure 1.

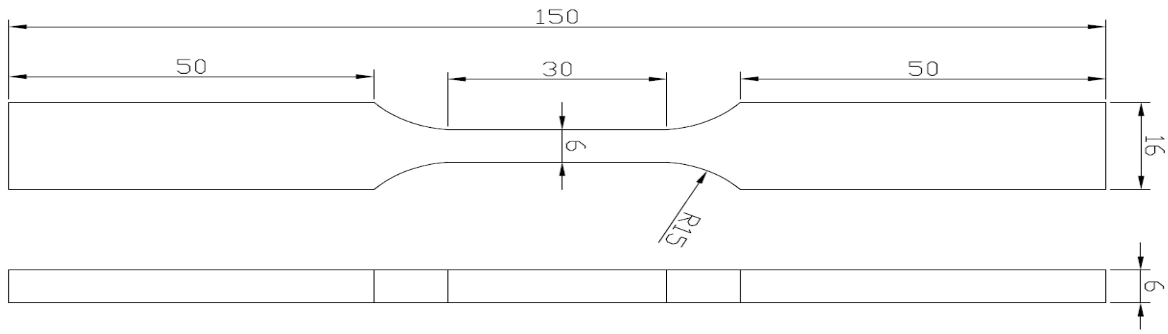

Fig. 1. Sample geometry for fatigue test with elongated gauge length enabling measurement of changeable eddy currents values

ESPI and ET method for detection of initiation and localization of cracks in aluminide diffusion layer required stoppage of fatigue test and static load assurance for the moment of test running.

Analysis of changes in deformation distribution observed with the use of ESPI camera allowed for determination of crack appearance in the aluminide layer during fatigue test. Observation was done when fatigue test was stopped after fixed number of cycles. Due to the high resolution of ESPI method of image recording, it was necessary to use hand pump for loading as hydraulic system assembly interfered with the testing. Measurements were repeated until crack of aluminide layer prior to sample rupture was detected.

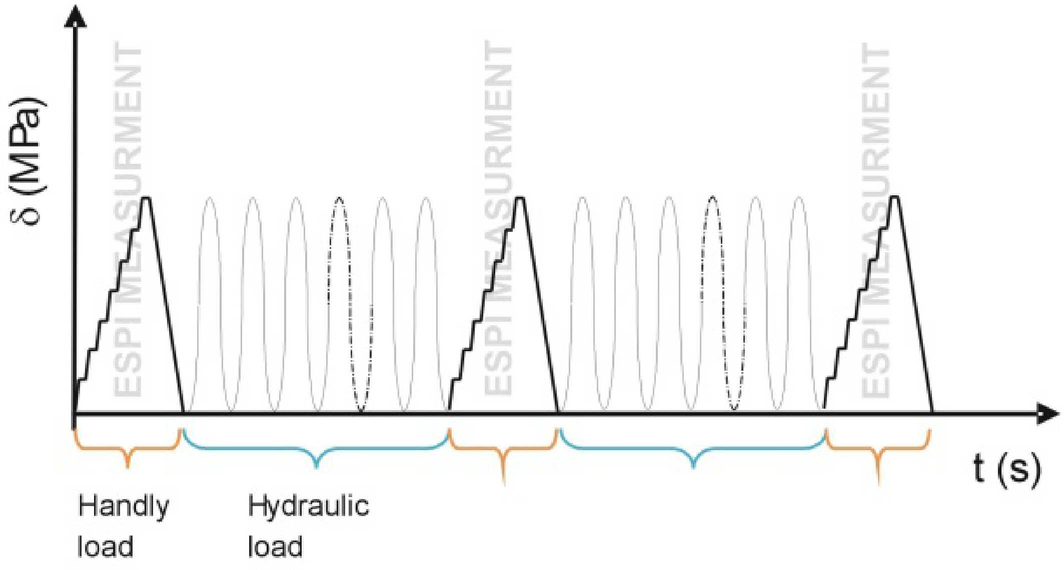

Fig. 2 Diagram presenting sample load in fatigue cycles

For each of observed samples from 5 to 12 deformation distribution images were recorded which allowed for deformation evolution analysis. The measurement of deformation using ESPI camera requires specially prepared sample surface. Displacement measurement is based on the deformation of the interference fringes due to the applied load. In figure 3 exemplary image of displacement measurements by ESPI camera is presented.

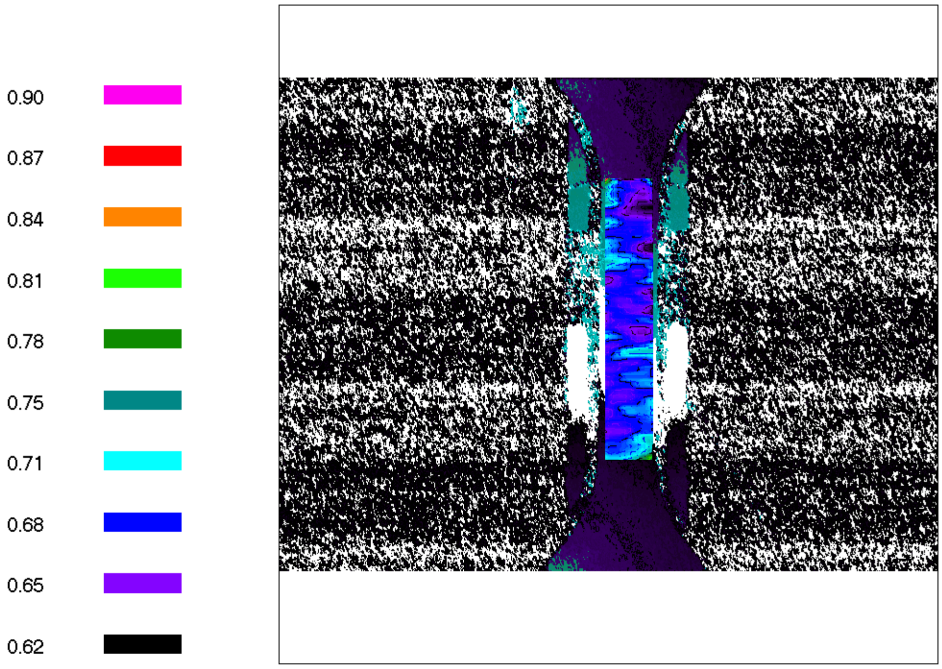

Fig.3. Interference image with superimposed map of specimen deformation generated by the ESPI

Measurements with the use of eddy current technique had a diagnostic nature. Its goal was to detect surface discontinuities of the coating. Test were performed on the gauge length of sample during test stoppage with the maximum loading equal to fatigue stress, when detection of sample crack was expected.

RESULTS

Within the conducted investigation, the influence of the aluminide layer thickness on fatigue strength was estimated. The evaluation was based on Whöler's curves obtained for samples with the aluminide layer of 20 and 40 µm thickness, for the room temperature and 900 ºC. Wöhler characteristics for specimens with the aluminide layer in temperature of 900˚C is shown on the Fig. 4.

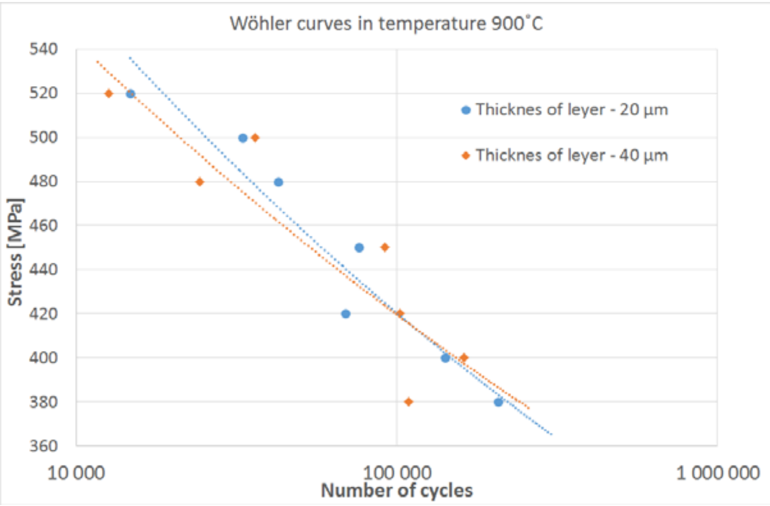

Fig. 4. Wöhler characteristics for specimens with surface deposited by aluminide layer

Based on the results obtained for measurements in elevated temperature and fortest conducted in RT, it can be concluded, that influence of layer thickness in the range of 20 – 40 µm is negligible, allowing for research continuation for one type the sample layer. Detailed investigation of crack formation were made on sample with 20 micron aluminide layer.

Detailed analysis of fatigue test with cyclic load of 600 MPa which was subjected is presented in fig. 5, which shows the deformation maps worked out with the use of ESPI technique and images prepared after each sequence of fatigue test. Images were recorded with the use of described procedure, starting from the image after first cycle and an interval of 10,000 cycles. The last measurement was made after 50,000 cycles. Sample rupture was found after 50,155 cycles. Deformation values are expressed in dimensionless units [mm/mm] * 10^{-3} (see fig. 5).

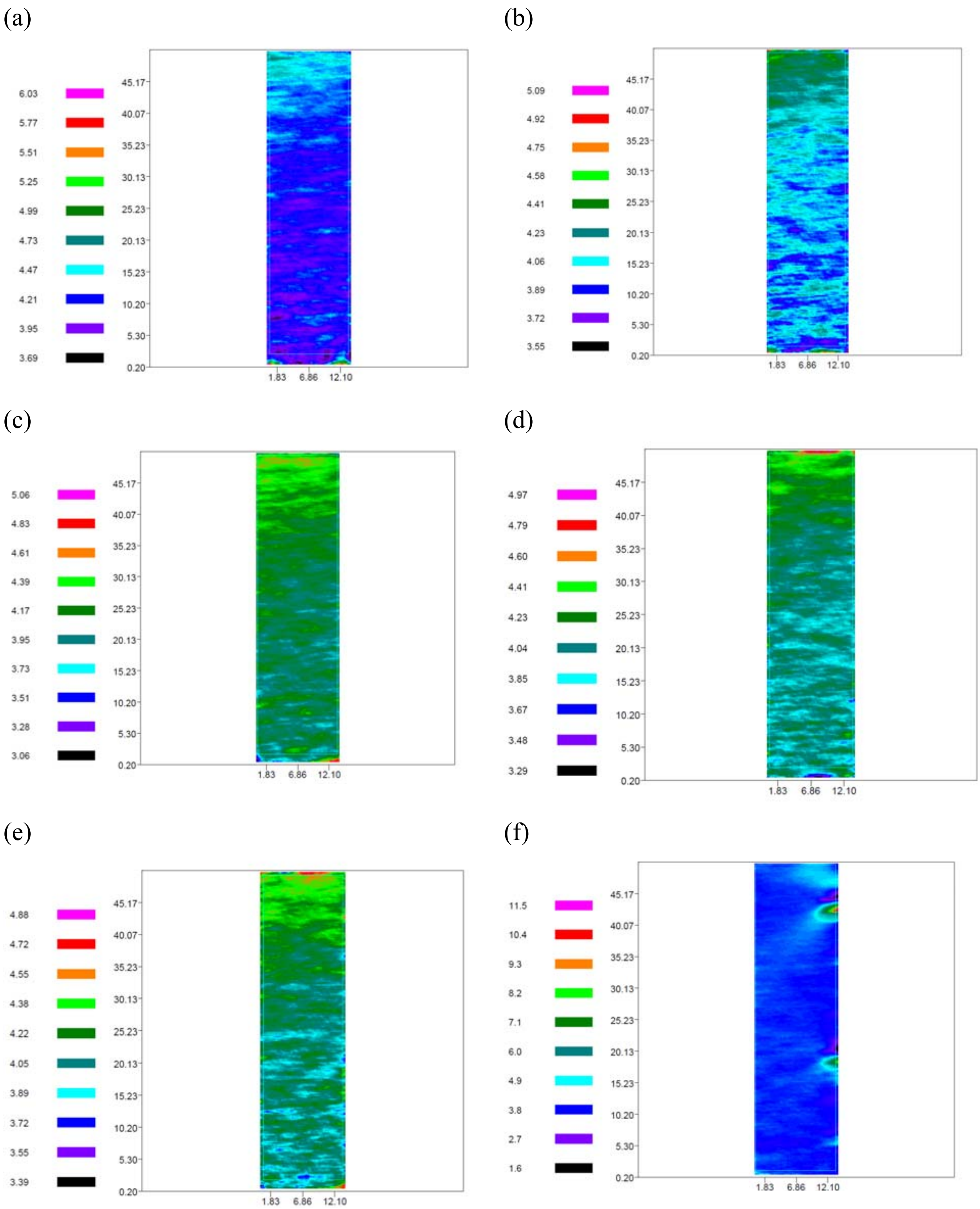

Fig. 5. Deformation map of sample surface for (a) 1 cycle (b) 10 001 cycle, (c) 20 001 cycle, (d) 30 001 cycle; (e) 40 001 cycle; (f) 50 001 cycle of fatigue test

Analysis of deformation map showed strain concentration in three areas (see fig. 5f), which acted as crack growth originator. One of the observed crack growth brought to sample rupture.

In table 1 a mean, minimum and maximum values of strain measured within gauge length after each load cycle are listed. Analysis of maximum strain values clearly shows effect of crack appearance during last measurements (after 50,000 cycles) and increase of strain as a result of coating cracking. In the case of upper crack (see fig. 5f), crack propagate into base material. This was confirmed by eddy-current measurements. Cracking of the aluminide layer precede sample decohesion, however, crack of the coating appears also in the area where base material was unimpaired.

Table 1. Strain values after established number of cycles

Measuring cycle	**Mean strain –** ε_{mean} **$*10^{-3}$**	**Min. strain** ε_{min} **$*10^{-3}$**	**Max. strain** ε_{max} **$*10^{-3}$**
1 cykl	4.245	3.782	4.863
10 001	4.096	3.708	4.583
20 001	4.143	3.721	4.616
30 001	4.113	3.68	4.69
40 001	4.155	3.71	4.61
50 001	4.194	1.97	10.93

During stoppage of loading cycles, when ESPI measurements were made, simultaneously eddy – current measurements on sample surface were conduced to detect material discontinuities. In fig. 6 the change observed in ET signal caused by discontinuities is shown. Fig. 6a shows signal of reference sample with incision depth of 0.1, 0.2, 0.5 and 1 mm. In fig. 6b and 6c a signal indicated on discontinuities on surface after 50 000 loading cycles on unloaded and loaded sample are shown respectively. The comparative analysis of signals provide information about crack depth in the range from 0.1 to 0.2 mm, which is more than the layer thickness.

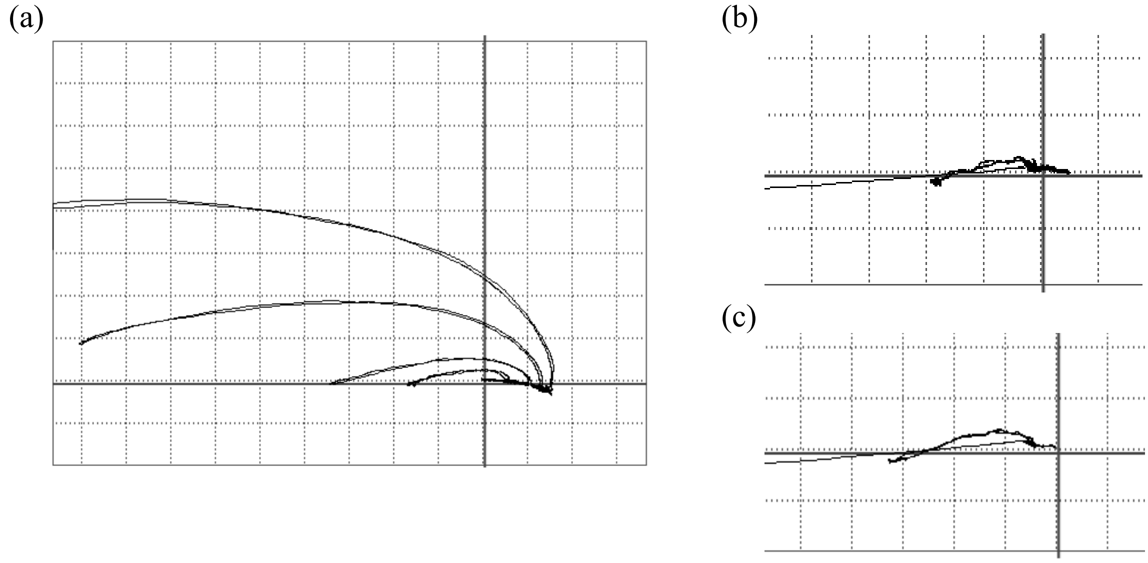

Fig. 6. ET signal changes indicated by discontinuities on the reference sample (a), in the unloaded (b) and loaded (b) sample after 50,000 cycles

The depth of the identified cracks with the use of ET method allows to assume that it is dominant area of crack development leading to sample rupture. No other cracks were identified, however ET method allows for detection of surface discontinuities not less than 20 microns, which is a coating thickness value for this experiment.

Numerous cracks of aluminide layer were formed during fatigue test. This was confirmed by results of fractographic observations of sample surface conducted on fractured sample. These results are shown in fig. 7. The aluminide coating thickness was also confirmed.

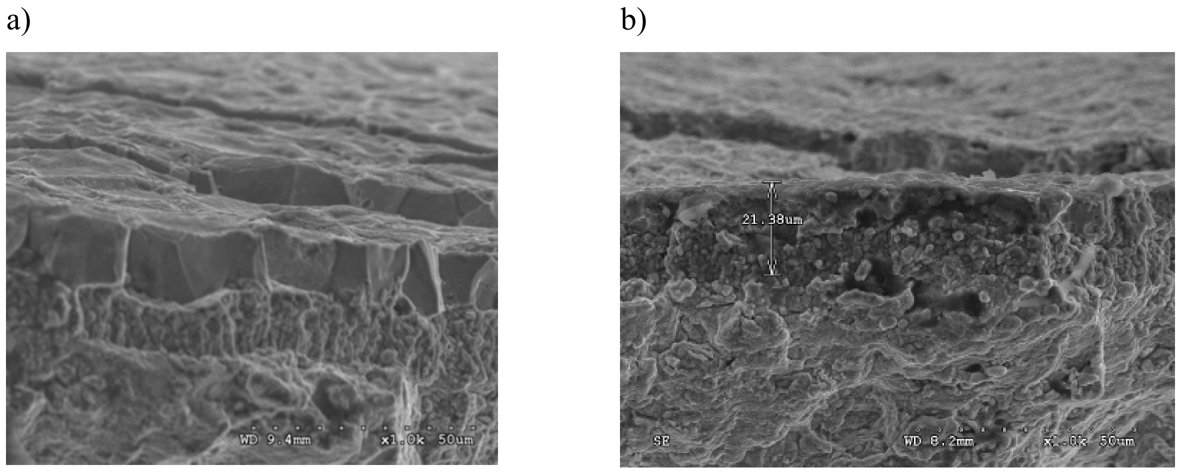

Fig. 7. Image of sample fractured sample surface, visible nickel alloy base with aluminide coating

CONCLUSIONS

Obtained results confirmed possibility of effective detection of fatigue cracks in the diffusion layer on the nickel alloy using non-destructive techniques before the sample rupture. It allow to determine the fatigue resistance of diffusion layer in the form of number of cycles causing crack formation and its identification with the use of distortion map (ESPI system) and location of deformation.

Future application in investigation and optimization of heat resistant layers applied on elements from nickel alloys working at temperature exceeding 1000 °C is predicted. Cracking of heat resistant layer locally reduces the heat resistance of detail and, behaving as a notch, reduces its strength.

Use of non – destructive techniques, described in presented paper, enables thoroughly investigation of cracking phenomena occurring during cycling loading of sample and estimation of heat – resistance coating efficiency.

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