CHANGES IN MICROSTRUCTURE OF TURBINE WHEEL MADE OF INCONEL 713 LC

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MIKROSTRUKTURNÍ ZMĚNY TURBÍNOVÉHO KOLA ZE SLITINY INCONEL 713 LC

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Abstrakt

V současné době je problematice životnosti turbínových lopatek a strukturní stabilitě Ni superslitin věnována celosvětová pozornost, neboť byl zaznamenán, zejména v posledních několika letech zvýšený počet selhání leteckých motorů. Během provozu jsou lopatky spalovacích turbín leteckých motorů vystaveny celé řadě degradačních vlivů, zejména pak vysokoteplotní korozi, únavovým procesům a creepu. V důsledku krátkodobého přetížení, např. během startů, přistávání, případně i dalších nepravidelností chodu proudového motoru dochází v souvislosti s maximy teplot a napětí k nevratným změnám v mikrostruktuře materiálu kol a jejich vlastností. Příspěvek je zaměřen na studium mikrostruktury turbínových kol z lité niklové superslitiny INCONEL 713 LC, u kterých bylo během zkušebního provozu zjištěno poškození lopatek.

Abstract

Since the record of aircraft engine failures has deteriorated in the recent years, the issues of turbine blade service life and those of structural stability of Ni-based superalloys have been treated worldwide. While in service the blades of gas turbines are exposed to a number of degrading influences, particularly to the high-temperature corrosion, fatigue processes and creep. In the periods of short-time overloading, e.g. during takeoffs, landings, or when experiencing other performance irregularities, the microstructure of the wheels undergoes irreversible changes in material and its properties induced by temperature and stress peaks. This paper aims to study the microstructure of turbine wheels made of INCONEL 713 LC, a Ni-based superalloy, and observed to develop blade damages throughout the test operation.

Key words: cast nickel alloys, turbine wheel blades, grain boundaries, cracks, scanning electron microscopy, microstructure

1. Introduction

The Ni-Cr-Al-based superalloys strengthened by the dispersion of coherent γ′ phase belong among the typical precipitation strengthened superalloys. When exposed to high temperatures and stresses, the particles of the strengthening γ′ phase can effectively restrain the movement of dislocations even at high temperatures, provided some preconditions are met. One precondition rests in a sufficient stability of the particles resulting from their coalescence, which makes the mean distance between them grow only very slowly under the creep conditions [1,3]. An ideal example is represented by particles coherent in relation to the matrix. Nevertheless, when the precipitation strengthened Ni-based superalloys are exposed to high temperatures, their structure coarsens and the γ′ precipitate partially assumes spherical shape; the intensity of this process depends on the exploitation temperature. The high temperature also causes the development of secondary carbides, particularly detrimental in the Inconel 713 type of alloys, as they deplete the matrix of important elements, e.g. Cr, thus deteriorating the corrosion resistance and refractory properties of the alloy. Last but not least the carbides, when developed within the matrix as a continuous layer at the grain boundaries, weaken the boundaries and bring about substantial degradation of the alloy properties [2,4,5].

2. Material and technique used in the experiments

The PBS a.s. Velká Bíteš plant received one used turbine wheel manufactured of Inconel 713LC (Figure 1) and one new wheel made of the same material. In the test operation the used wheel underwent 483 startups during 87 hours and 45 minutes; with the last cycle completed, the engine was inspected and the edge sections of blades on the tested wheel were found burnt.

Fig.1 Used turbine wheel

Sampling layout

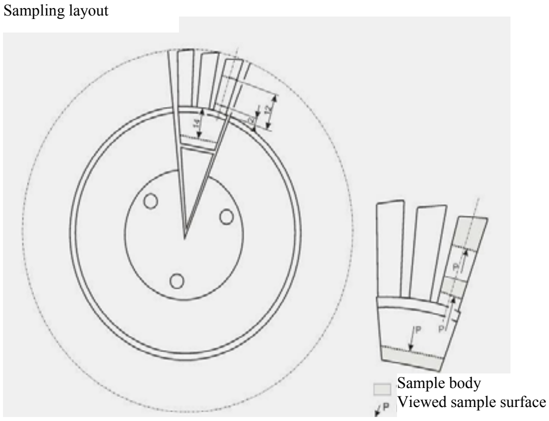

Fig.2 Sampling layout

The samples to be analyzed were taken from several blades and from the hub of the used and the new turbine wheels, as indicated on the Layout in Figure 2. The individual segments were cut using an electro-discharge cutter so that the structure of the samples remained unaffected by the cutting operation. The samples were prepared by the standard procedure and etched with the Kalling's etchant (2g $CuCl_2$, 40ml HCl, 60ml 95% of ethanol).

First, the changes in microstructure were observed with Olympus GX71, an optical microscope, and later on they were analyzed with PHILIPS XL 30 EDAX, a scanning electron microscope (SEM) using the acceleration voltage of 20 kV. The analysis relied on the technique of secondary and recoiled electrons. The chemical composition of the tested samples was investigated by an outside service provider by means of the LECO 2000 spectrometer; for the results see Table 1.

Table 1 Chemical composition of the tested samples

Element	Cr	Mo	Zr	Nb	Mn	Fe	Cu	S	Ni
Content [wt. %]	11,7	4,44	0,1	2,05	<0,05	<0,01	<0,05	<0,004	base
Element	C	B	Ti	Al	Ta	Co	Si	P	
Content [wt. %]	0,04	0,01	0,75	6,41	<0,05	<0,05	<0,05	<0,004	

3. Results

To arrive at an objective assessment of the structural changes experienced by the turbine wheel during the test operation, the structures being compared were those of samples taken from the used and the new wheels made of material from the same heat (Y 22). Under the optical microscope, and especially under the scanning electron microscope, we have observed a substantial volume of secondary carbides developed throughout the test operation at the grain boundaries in the form of continuous chains (Figure 3 and Figure 4) leading to the loss of strength at the grain boundaries and to major degradation of the material properties.

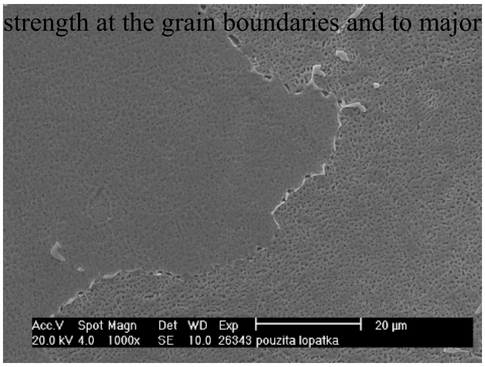

Fig.3 Microstructure, the used blade, central section, SEM, 1000x

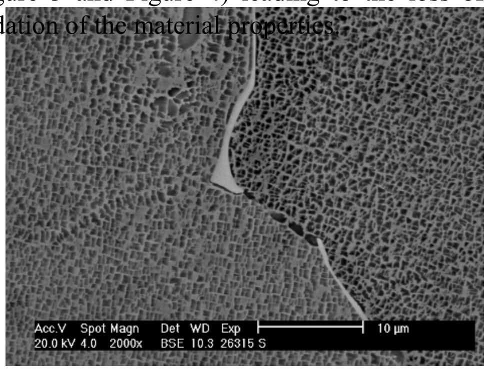

Fig.4 Secondary carbides, the hub of the used wheel, SEM, 2000x

The morphology of the γ' strengthening phase was observed with SEM and the structure of blades in the used turbine wheel was found substantially changed; the changes progressed from the hub towards the blade tips, which were destroyed by burning. The wider section of the blades (closer to the hub) exhibited some isolated γ' phase precipitates in the γ matrix and an enhanced volume of the eutectic (Figure 5). At the central section of the blades the high temperatures gradually and with ever increasing intensity dissolved the γ'precipitates (Figure 6), thus giving rise to an oversaturated solid solution. Towards the tip - where the blade is thinnest and exposed to the highest temperatures - the strengthening γ′ phase particles were already fully dissolved in the solid solution (Figure 7). Since this section of the blade was cooled faster, no new γ′ phase particles were developed here as witnessed by the conspicuous discoloration of the blade surface. The structure at the thin end of the blades exhibited just very small areas of secondary carbides, at some places surrounded by still partially undissolved and coarsened γ′ phase precipitates (Figure 8).

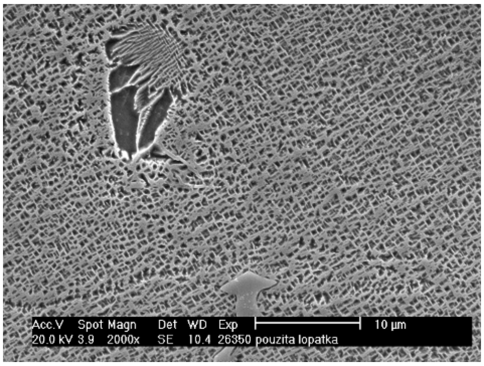

Fig.5 Precipitates γ′ in γ matrix; the used blade; closer to the hub; SEM, 2000x

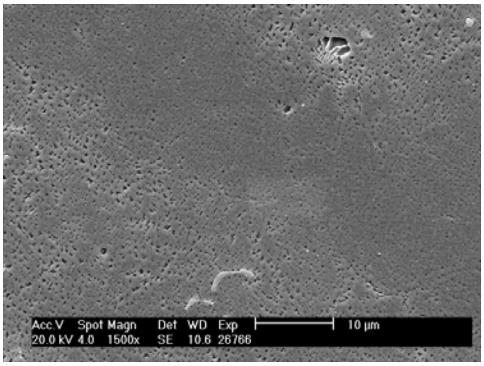

Fig.6 Partially dissolved precipitates; the used blade; central section; SEM, 2000x

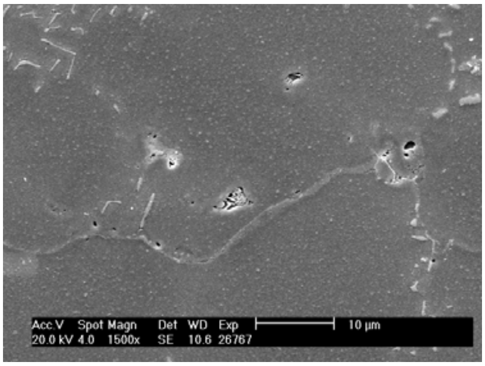

Fig.7 Dissolved γ′ precipitates; the used blade; edge section; SEM, 2000x

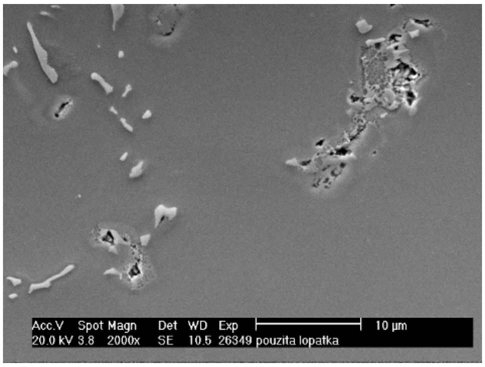

Fig.8 Partially undissolved γ′ precipitates around the secondary carbides; edge; SEM, 2000x

The SEM observations have proven true the hypothesis that the initiation and propagation of cracks in the alloy structure are closely related to the secondary carbides developed at the grain boundaries (Figure 9 and Figure 10), where the cracks were revealed most often. The EDS microanalysis performed on various sections of the used wheel blades proved that the chemical compositions were identical.

In contrast to the blade samples, the samples taken from the used wheel hub showed no major changes in the morphology of the strengthening γ′ phase precipitates, but the structure was found, once again, to contain secondary carbides developed at the grain boundaries (Figure 11 and Figure 12). The EDS microanalysis disclosed that the secondary carbides developed consisted mainly of Nb, or possibly of Ti and Cr.

4. Conclusions

When exposed to high temperature, the structure of the used turbine wheel developed a large volume of secondary carbides lining in chains the grain boundaries. The boundary strength was thus substantially reduced and the strength reduction, in synergy with the service-induced vibrations and strong centrifugal forces, initiated crack growth in the affected areas. The individual cracks have been developing until they critically deteriorated the cross-section strength of the turbine wheel blades, then a part of a blade separated and destroyed the remaining blades of the wheel. This conclusion is supported by the shape and appearance of the fractured surfaces of the blades with the bent tips of some of the damaged blades. The structure of the blades was found to contain an increased volume of the eutectic, a fact also indicative of the high temperatures at work.

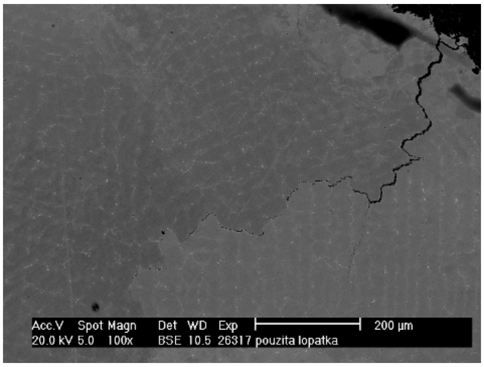

Fig.9 Crack at the grain boundary; the used blade; SEM, 100x

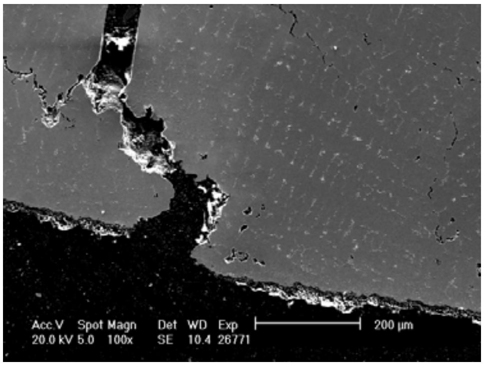

Fig.10 The crack detail; the used blade, SEM, 100x

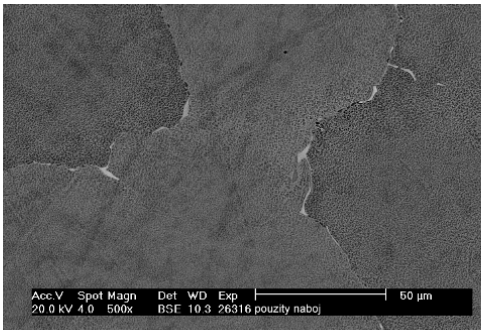

Fig.11 Secondary carbides at the grain boundary; the used wheel hub; SEM, 500x

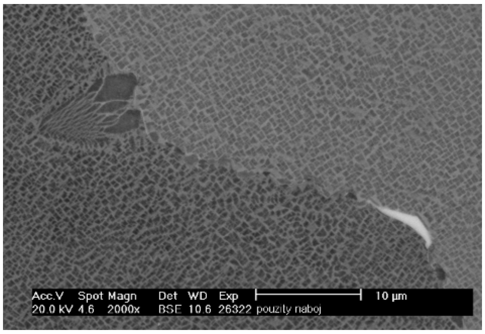

Fig.12 Microstructure, the used wheel hub, SEM, 2000x

Another major change in structure rested in the gradual dissolution of the individual precipitates of the strengthening γ' phase by the action of high operational temperatures. As the distance from the hub towards the blade tips increased, the volume proportion of the individual precipitates diminished and the fast rate of cooling created an oversaturated solid solution that merged with the secondary carbides into a uniform mass. This phenomenon, once more, causes degradation, since the capability of the strengthening γ' phase precipitates to restrain the dislocation movement and thus to prevent creep damage was minimized, particularly at the tips of the damaged turbine wheel blades.

On the outside surface of the blades, where the leading edge blends into the hub, we have disclosed flaking scales of the material, caused by the joint action of the operational temperature and the cyclic loading of the turbine wheel blades.

The structural examination of sample taken from the damaged wheel hub showed no substantial changes in the γ' phase precipitate morphology, but, here too, the secondary carbides were observed to develop at the grain boundaries.

This paper and the one entitled Heterogeneity of Inconel 713LC rely on the same experimental materials.

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