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Macro and Micromorphology of in Service Cracking and Fracture of Turbine Blades

Makro in mikromorfologija razpok in zlomov nastalih med obratovanjem turbinskih lopatic

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After the break down cracked and fractured blades were extracted from the turbine and the macro and micromorphology of cracks and fractures surface were investigated. Three modes of propagation were identified: stable propagation by HISC, stable propagation by HISC and fatigue and instable brittle and ductile propagation. The micromorphological characteristics of the different modes of propagation are explained.
Key words: Turbine blades, steel, cracking, fracture, corrosion, fatigue, microstructure.

Po zlomu so bile počene in zlomljene lopatice vzete iz turbine in bila je raziskana makro in mikromorfologija razpok in zlomov. Identificirani so trije mehanizmi širjenja: stabilno širjenje zaradi HISC, stabilno širjenje zaradi HISC in utrujenosti ter nestabilno krhko in duktilno širjenje. Opisane so mikromorfološke značilnosti posameznih načinov širjenja.
Ključne besede: Jeklo, turbinske lopatice, razpokanje, zlom, korozija, utrujenost, mikrostruktura.

1. Experimental work

The experimental work consisted of:
- examination of microstructure;
- analysis of impurities on cracks surfaces, and
- macro and micro examination on the cracks and fractures surface.

The data on the composition of the steels and mechanical properties will be reported later and will be considered in this paper only when necessary to explain better the findings relative to the microstructure and the aspect of the cracks and fractures surface.

The composition of all examined blades corresponded to that required for the martensitic stainless steel X21CrMoV 121 and also the mechanical properties sufficed the requirement of the buyer of the turbine. It should be noted that a very low notch toughness of 15 J was required. Four different cases of cracking and fracturing of the blades were identified on the basis of visual examination:- one case of cracking on the rounded trailing edge in the passage between the root and the blade;
- some cases of cracking in the first root grove mostly at a distance up to 50 mm from this edge **(fig. 1, 2 and 3)**, and
- fracture of precracked blade in the turbine in the first root grove with an initial crack **(fig. 4)** or without such crack **(fig. 5)**.

On some in service cracked blades the crack surface was opened for examination by bending in laboratory, generally after cooling in liquid nitrogen.

On the base of the macromorphology of the crack surface three types of in service crack propagation were identified:

- surface showing near the initial point no fatigue striations but with such striations on the remaining area of the crack **(fig. 2 and 6)**,
- surface of cracks without fatigue striations **(fig. 3)**, and
- surface with fatigue striations from the starting point of cracks propagation.

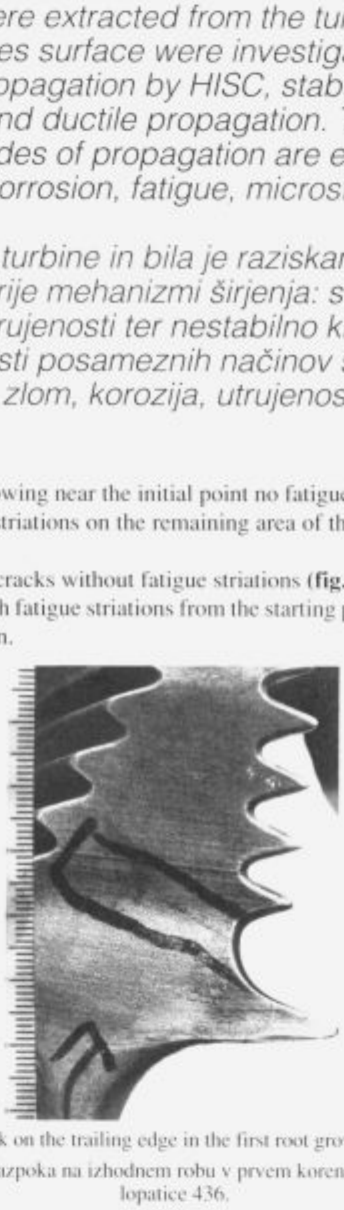

Figure 1: Crack on the trailing edge in the first root grove of blade 436.
Slika 1: Razpoka na izhodnem robu v prvem korenskem žlebu lopatice 436.

2. Micromorphology of cracks and fractures

Several form of propagation were observed on specimens cut from different parts of the fracture of blades and on laboratory

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Figure 2: Surface of a crack with areas with and without fatigue striations.

Slika 2: Površina razpoke z deli z in brez utrujenostnih brazd.

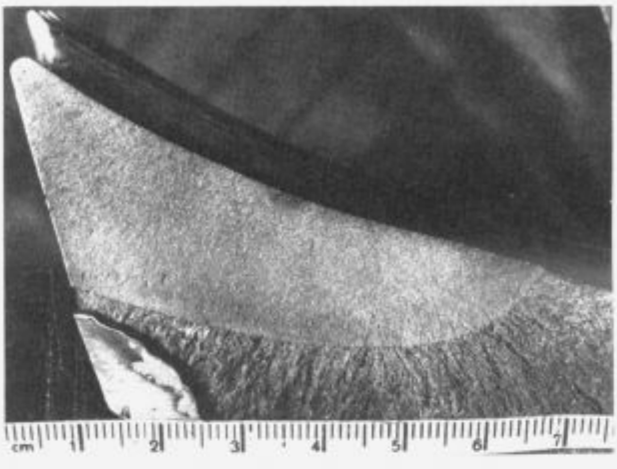

Figure 3: Surface of a crack without fatigue striations.

Slika 3: Površina razpoke brez utrujenostnih brazd.

Figure 4: Fracture of the blade 447 extracted from the disc after the break down. The initial crack is on the left side.

Slika 4: Prelom lopatice 447, ki je bila iz turbine vzeta po havariji. Začetna razpoka je na levi strani.

Figure 5: Fracture of the blade 379 extracted from the disc after the break down.

Slika 5: Prelom lopatice 379, ki je bila vzeta iz turbine po havariji.

Figure 6: Surface of the crack on the blade on fig. 4.

Slika 6: Površina razpoke na lopatici na sl. 4.

specimens. In order to make the matter easier to follow the fracture micromorphology is described separately for different areas: initial point, stable propagation and brutal (instant) rupture on laboratory specimens and in the turbine.

2.1. Initial point of cracking and stable propagation

Generally, the surface of cracks near the initial point was covered with corrosion products and also after a very careful cleaning it was rarely possible to find at SEM observation reliable details, which would characterize the mechanism of initiation. An exception was the specimen in **fig. 7**, where several crack initials with a perfectly clean surface were found. Near the tip of the pitting with a size of appr. 0,25 mm the fracture surface is brittle trans and intergranular (**fig. 8**) without fatigue striations. The micromorphology of the transgranular surface is featherlike and similar to that reported frequently for high strength steels with a martensitic microstructure and with an increased content of hydrogen. This suggests that in presence of the pitting the nucleation of the crack was induced by the overcharging of the steel with hydrogen produced by the corrosion process at the tip of the pitting. A similar detail of micromorphology of fracture surface near the nucleation point was observed also on the blade 436 (**fig. 9**). It shows mixed propagation and small contamination with corrosion products, visible more clearly on the intergranular surface. On the clean part of cracks surface without striations near the border of the brutal fracture the micromorphology was similar as in **fig. 8** and **9** and it showed mixed trans and intergranular propagation with the featherlike surface of transgranular cleavage (**fig. 10**).

Figure 7: Fracture initials on blade 450.

Slika 7: Začetki preloma na lopatici 450.

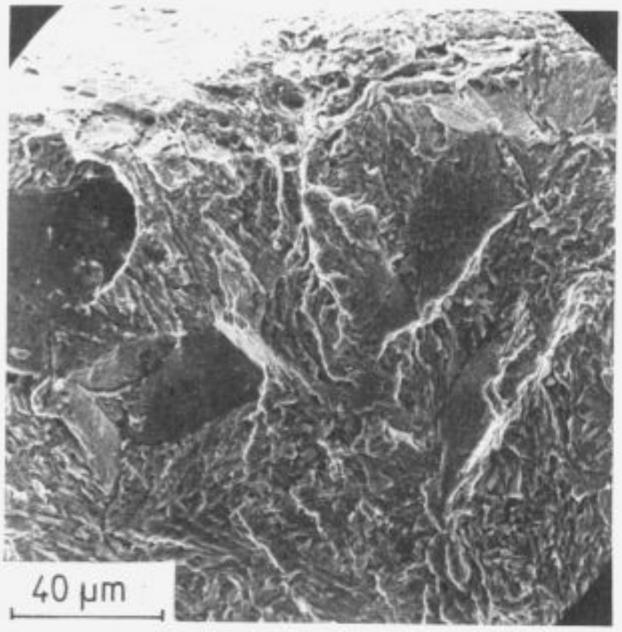

Figure 8: Surface of one of the cracks in fig. 13 near the bottom of the pitting.

Slika 8: Površina ene od razpok na sl. 13 ob dnu zajede.

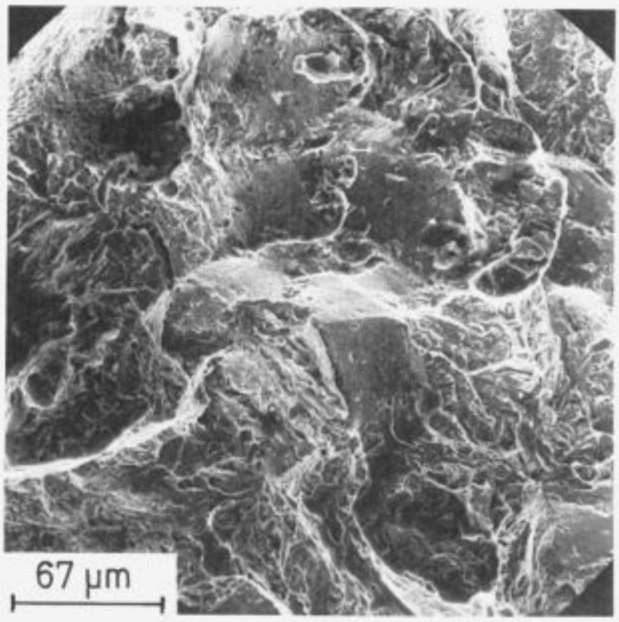

Figure 10: Surface of the crack in fig. 3 near the border line of the brutal rupture of the blade.

Slika 10: Površina razpoke na sl. 3 ob meji z nasilnim zlomom.

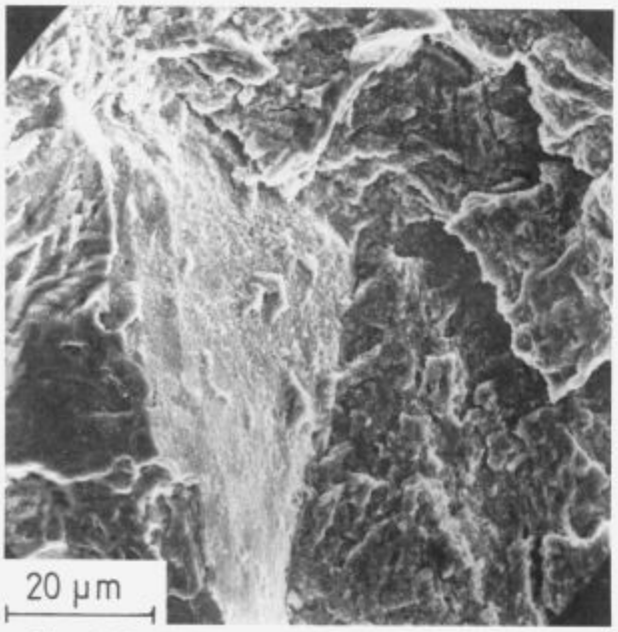

Figure 9: Detail of the crack surface without fatigue striations.

Slika 9: Detajl površine razpoke brez utrujenostnih brazd.

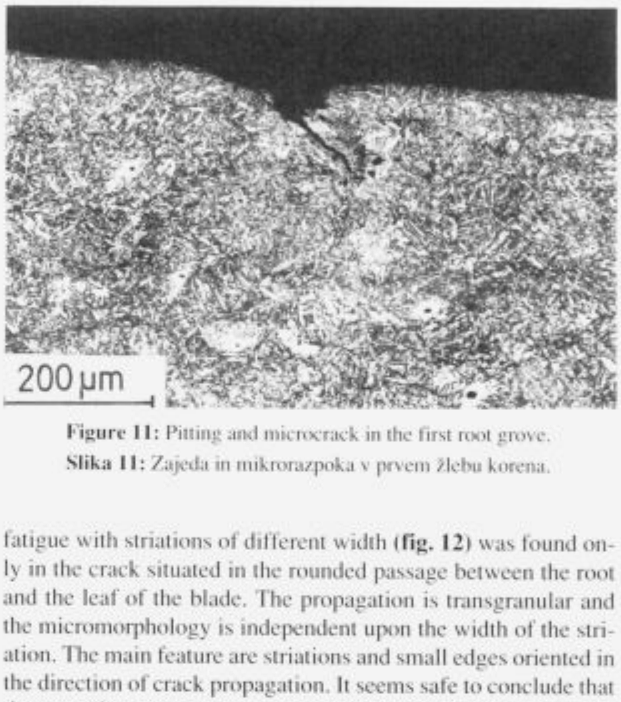

Figure 11: Pitting and microcrack in the first root grove.

Slika 11: Zajeda in mikrorazpoka v prvem žlebu korena.

Corrosion pits were the initials of all the cracks in the first grove of the root, also pitting as small as 0,05 mm **(fig. 11)**.

In all cases when the cleaning was sufficient to reveal details the surface of cracks without fatigue striations showed a micromorphology similar to that in **fig. 10**, thus brittle trans and intergranular propagation.

Fatigue striations were found on crack surface of several blades at various distance from the starting point on the surface. That shows that two mechanisms of stable propagation were active in the growth of cracks. Consequently, on cracks surface two different micromorphologies of propagation were found. Pure fatigue with striations of different width **(fig. 12)** was found only in the crack situated in the rounded passage between the root and the leaf of the blade. The propagation is transgranular and the micromorphology is independent upon the width of the striation. The main feature are striations and small edges oriented in the direction of crack propagation. It seems safe to conclude that the cause for propagation was the amplitude of fatigue stress and that large striations represent the operation of the turbine in range of critical number of revolutions. Also the width of the narrowest striation is considerable (0,01 mm) and indicates to a relatively high amplitude of dynamic stress. In the second case the crack surface showed by macroscopic observation an apparent pure fatigue propagation. By appropriate magnification is SEM a mixed micromorphology was observed **(fig. 13)**. It consisted of groups of steps and microcracks orthogonal to the direction of propagation alternated with wider bands where the surface indicates a specific mechanism of transgranular propagation. Microridges parallel to the direction of the propagation of cracks trespassed sheafs of steps and microcracks orthogonal to the direction of propagation. The conclusion is that the crack propagated in conditions when corrosion and fatigue prevailed alternatively, thus a propagation by fatigue corrosion.

As already shown, all the findings indicate that the initials of cracking in the first grove of the root were corrosion pits, also pits as small as 0,05 mm (**fig. 11**). The steel at the top of the pits was charged with hydrogen, that decreased it fracture toughness and cracks with mixed trans and intergranular propagation were

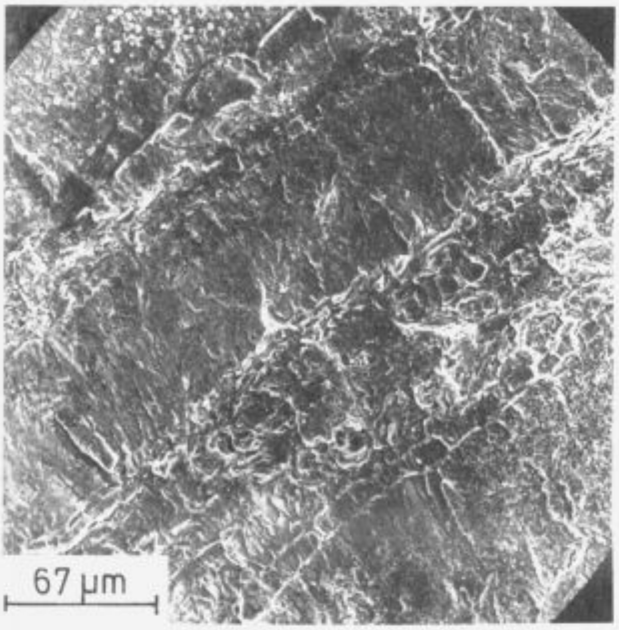

Figure 12: Surface of the fatigue crack in the rounded area of the transition from the root to leaf of the blade.

Slika 12: Površina utrujenostne razpoke na zaobljenem prehodu iz korena v list lopatice.

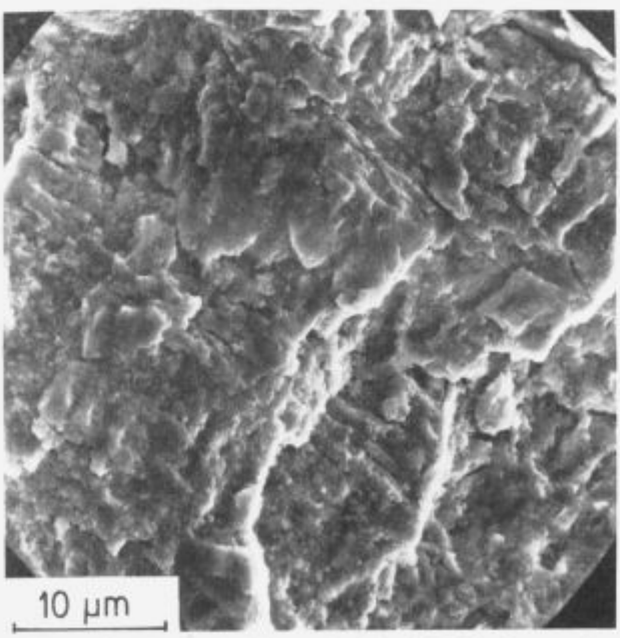

Figure 13: Microdetail of the crack surface in fig. 2 in the area of fatigue striations.

Slika 13: Mikrodetajl površine razpoke na sliki 2 na področju utrujenostnih brazd.

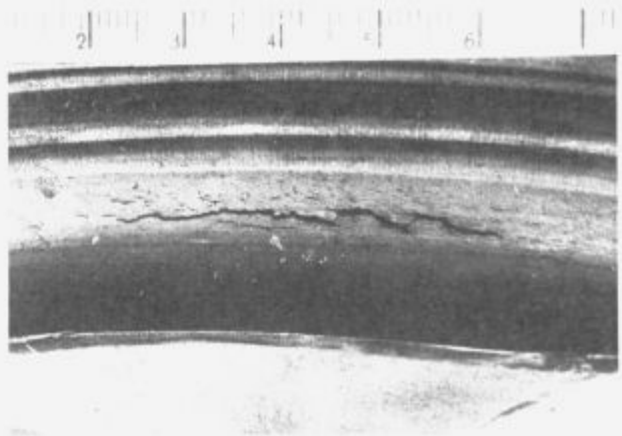

Figure 14: Step like crack on the working side in the first root grove. Blade 435.

Slika 14: Stopničasta razpoka na delovni površini v prvem korenskem žlebu. Lopatica 435.

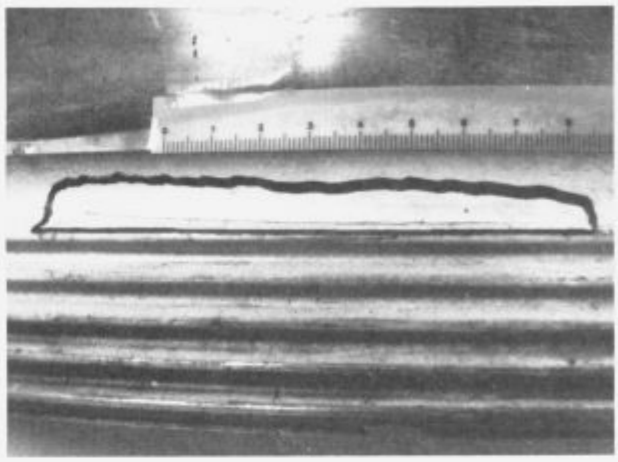

Figure 15: Straight crack on the working side in the first root grove of blade 411.

Slika 15: Ravna razpoka na delovni strani v prvem korenskem žlebu lopatice 411.

initiated because of static or dynamic stresses. The initiation took place either on several points and single microcracks coalesced in a steplike macrocrack (**fig. 14**) or in one point and the microcrack did grow in a harline slightly curved macrocrack (**fig. 15**). If the corrosion process was continued, the crack continued to propagate by the same mechanism and a crack surface without striations was obtained. If the intensity of corrosion was diminished or the corrosion was stopped, the propagation continued by sufficient stress amplitude in conditions of pure fatigue.

In **ref. 1** it is reported that the enrichment of impurities in the first drops of condensate could reach several orders of magnitude. The presence of pittings in the first grove of the root shows that the first drops of contaminated condensate appeared in this area of the blade, where the static and dynamic stress made them particularly harmful. The presence of pittings demonstrates naturally also a poor quality of boiler water, at least in some periods of the work of the power station.

2.2. Brutal fracture

This type of fracture was obtained in three different ways:
– in service,

– on laboratory specimens and
– by bending of cracked blades in laboratory.

Brutal in service fracture was observed on blades 379, 434, 442 and 447. **Fig. 16** shows the micromorphology of the fracture in area I on blade 379 fractured without precrack and shown in **fig. 5**. The micromorphology shows a quasi ductile propagation under shearing stress with very rare intercrystalline details. In area II of the same blade the micromorphology is identical. In area III, where the propagation occurred in conditions of plane strain (1), the micromorphology is brittle, mixed trans and intergranular **(fig. 17)**. Virtually identical was the micromorphology of the fracture of blade 434, which failed in service probably at the same time and in similar stress conditions. Also the micromorphology of the brutal fracture of blades 442 **(fig. 4)** and 447, two blades broken in service or during the break down and precracked in the first grove of the root is similar as that in area III of blade 379.

On notch toughness specimens the more intercrystalline brittle propagation was found the lower was the value of notch toughness. By a level of 70 J and more the propagation was ductile **(fig. 18)** with mostly small dimples, which indicate that only a thin layer of metal both sides of the crack lips was deformed

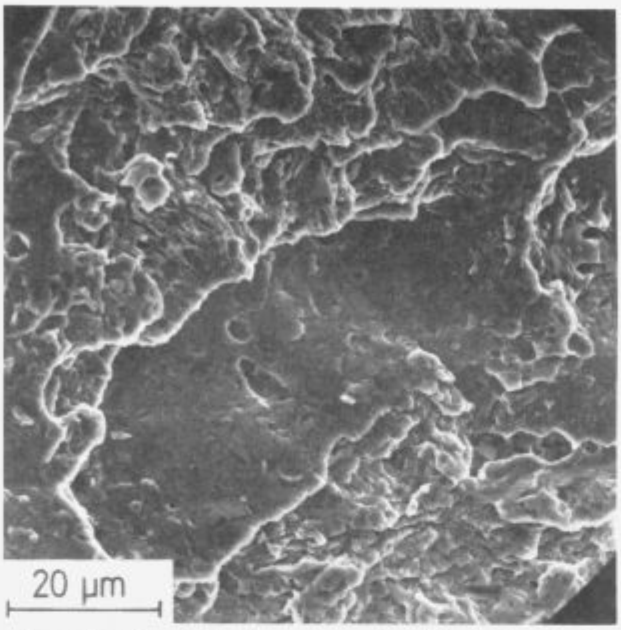

Figure 16: Microdetail of the rupture surface of the blade on fig. 5 in area I.

Slika 16: Mikrodetajl površine preloma lopatice na sl. 5 v področju I.

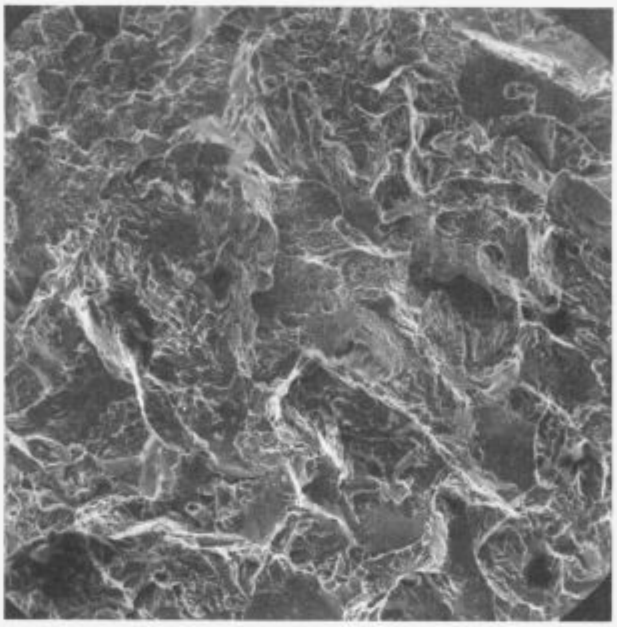

Figure 17: Microdetail of the rupture surface of the blade on fig. 5 in area III.

Slika 17: Mikrodetajl površine preloma lopatice na sl. 5 v področju III.

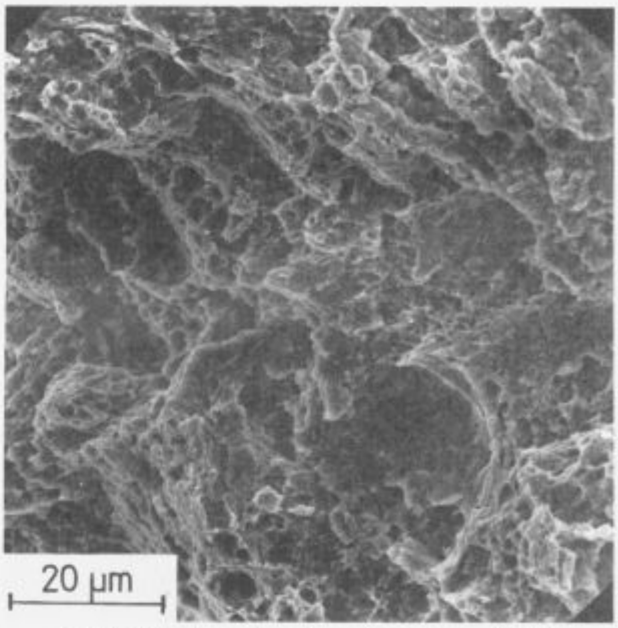

Figure 18: Fracture surface by a notch toughness of 110 J.

Slika 18: Prelomna površina pri zarezni žilavosti 110 J.

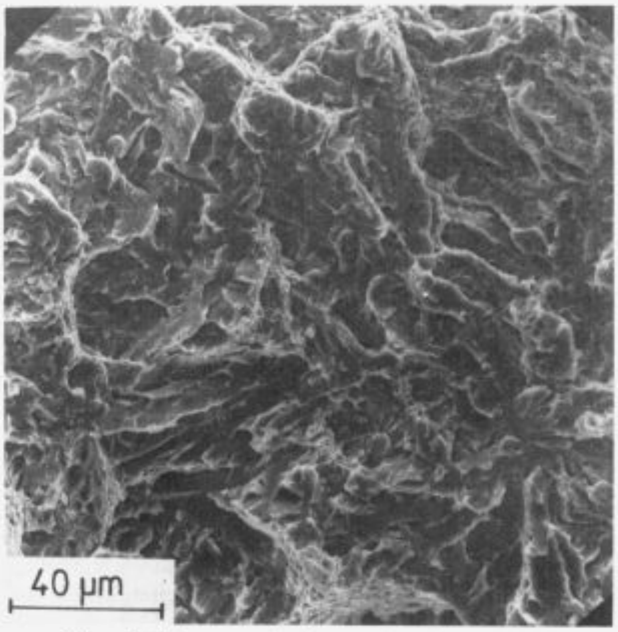

Figure 19: Fracture surface by a notch toughness of 52 J.

Slika 19: Prelomna površina pri zarezni žilavosti 52 J.

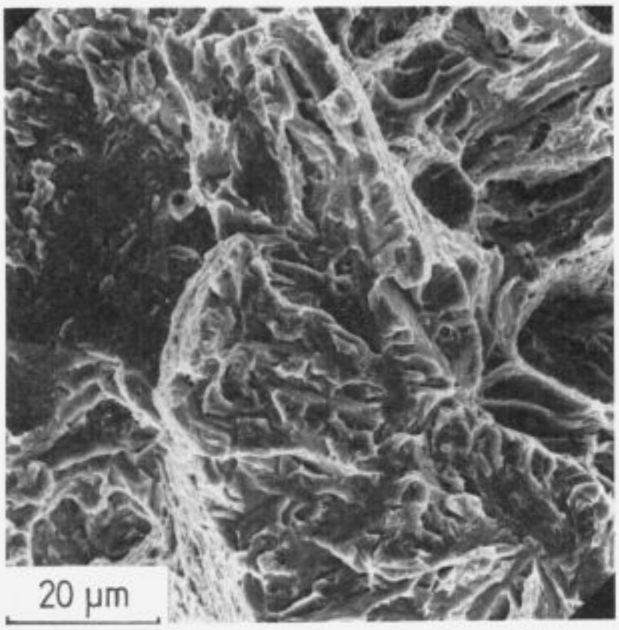

Figure 20: Fracture surface by a notch toughness of 35 J.
Slika 20: Prelomna površina pri zarezni žilavosti 35 J.

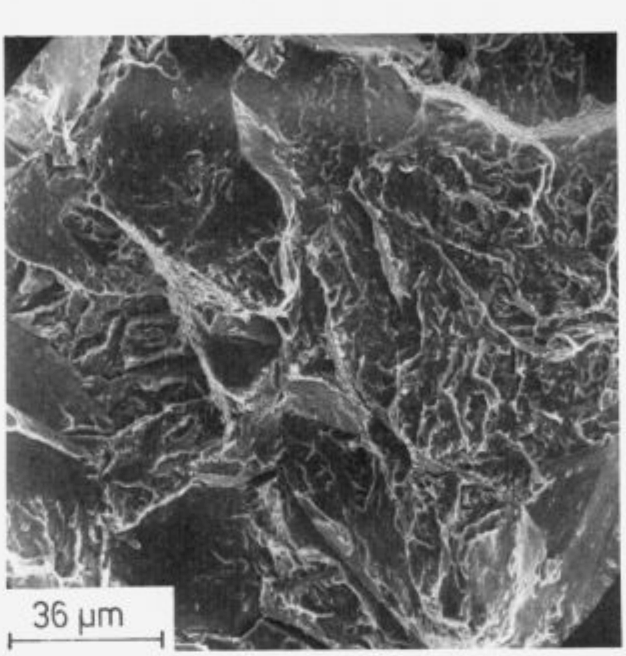

Figure 21: Fracture surface by a notch toughness of 22 J.
Slika 21: Prelomna površina pri zarezni žilavosti 22 J.

during the formation of the voids. Below a toughness of 60 J the surface shows a quasi brittle propagation with frequent areas of propagation through martensite platelets lying in the plane of the fracture and rare ductile details **(fig. 19)**. By a notch toughness of 34 J in a similar transcrystalline matrix intergranular facets are found **(fig. 20)** and by a notch toughness of 24 J the intergranular brittle propagation predominated **(fig. 21)**. It seems thus that the diminution of toughness below a level of appr. 35 J is connected to an increasing part of intergranular brittle crack propagation. The micromorphology of fracture toughness and of notch toughness specimens of the same steel was virtually identical.

3. Contamination of crack surface and mechanism of stable crack propagation

On some of the cracked blades broken by bending in laboratory small relatively clean areas of crack surface were obtained. On two such surfaces, one with and the second without fatigue striations the presence of some elements was determined with surface scanning in a SEM equipped with two wavelength dispersive spectrometers. Because of the uneven surface no quantitative analysis was possible, therefore the results given in **table 1** have only a comparative value. It seems logical to conclude that all the analysed elements were present on the crack surface as compounds, since all of them could not reach the crack surface as pure elements. It is assumed also, considering the traces of corrosion on the surface of the blades, that sulphur and chlorine are present in form of sulphate rsp. chloride which in water solution strongly increase the corrosivity of the droplets in the first area of steam condensation (2, 3, 4). The very great difference in the level of contamination offers a logical support for the following explanation of the difference in the process of stable crack propagation and the resulting difference in the morphology of the surface of cracks.

Table 1: Results of the analysis of crack surfaces.
Tabela 1: Rezultati analize površine prelomov.

Blade No.	Mode of crack propagation	Element, mg/cm^2					
		Cl	Na	Ca	Si	S	Cl+S
435	without fat. str.	47.7	48.4	55.6	112	50.2	97.9
436	with fat. str.	1.6	0.17	5.2	12.4	0.19	1.79

Chloride ions break the passive layer on the surface on the blade, cause a rapid local process of corrosion and pittings are formed because the cathodic area is much greater than the anodic area. On the bottom of the pittings the condition for the initiation of cracks are present: an aggressive solution, small active tip, great passive lateral surface as well as brittle steel charged in hydrogen produced at the tip by the corrosion process through the following electrochemical reactions: $M \rightarrow M^{+} = e$, and

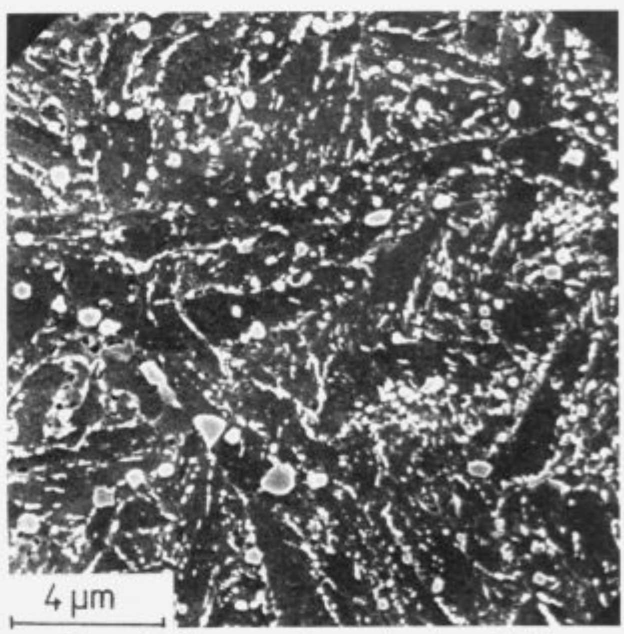

Figure 22: Microstructure by a notch toughness of 110 J.
Slika 22: Mikrostruktura pri zarezni žilavosti 110 J.

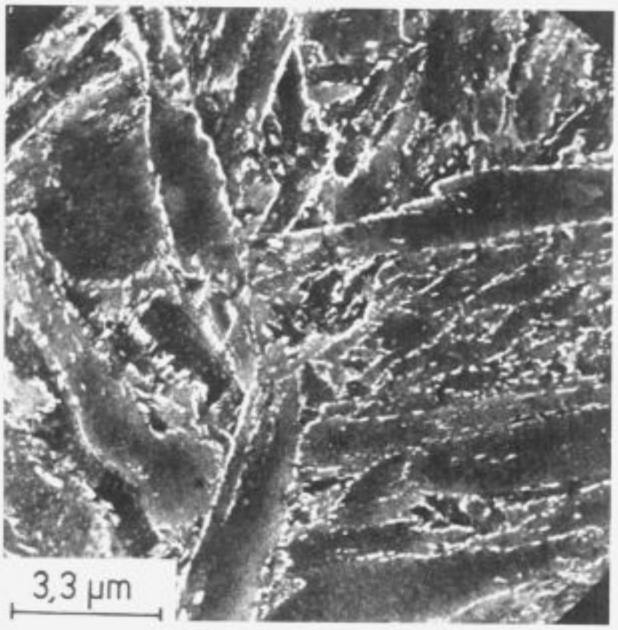

Figure 23: Microstructure by a notch toughness of 35 J.
Slika 23: Mikrostruktura pri zarezni žilavosti 35 J.

$M^+Cl^- + H_2O = MOH + Cl^- + H^+$. Metal chloride produces through hydrolysis metal hydroxide as deposit on the crack surface and ions of hydrogen and chloride. The formation of acid in the pitts lowers the pH value, produces hydrogen ions which promote the hydrogen induced stress cracking (HISC). In references 2, 3 and 4 the brittle cracking of martensitic stainless steel in the presence of a corrosion process which generates hydrogen ions in cathodic areas is confirmed. Typical features of this type of cracking are non branched cracks, which were found in all the blades cracked in the first grove of the root, while in case of stress corrosion cracking the cracks are branched. Hydrogen in interstitial solution segregates to areas of tensile stress concentration, lowers the ductility and the fracture toughness of the steel and causes a mixed trans and intergranular brittle fracture.

4. Microstructure and notch toughness

The examination in optical microscope did not show significant differences in microstructure of the steel, while the observation in SEM was more instructive. In all cases the microstructure consisted of tempered mostly acicular martensite. By observation in SEM it was possibly to connect partly the microstructure, especially the size and distribution of tempered carbide particles, to the notch toughness. By high notch toughness the carbide particles are coarse and the habitus of martensite poorly marked **(fig. 22)**. By intermediate toughness level the particles of carbide are smaller, frequently aligned along grain boundaries and along martensite platetels, and the habitus of martensite is well marked **(fig. 23)**. By a very low notch toughness of 20 J the microstructure is similar. A careful evaluation indicates that the difference in notch toughness and the increasing part of intergranular fracture can not be explained only in terms of microstructure. The tempering temperature required for a high limit of elasticity for this type of steel is in the range of reversible intergranular segregation of some elements, especially phosphorus (5). It seems thus that the intergranular fracture by low toughness is partly due also to the brittleness produced by intergranular segregation. This conclusion is confirmed by the fact that frequently intergranular facets are perfectly smooth **(fig. 21)**, thus typical for intergranular brittleness produced by reversible intergranular segregation (5).

Conclusions

In the paper the results of the investigation of the cracks and fractures surface of turbine blades are presented.

On the base of the cracks macro and micromorphology three mechanisms of stable crack propagation were established:
– mixed inter and transgranular propagation by HISC and
– transgranular propagation by corrosion fatigue, and
– transgranular propagation by fatigue.

In the first two cases cracks started on corrosion pits as small as 0,05 mm. Brutal fracture in turbine and in laboratory occurred by mixed brittle trans and intergranular propagation. On the initial part of the in turbine rupture of the blades without crack the fracture was ductile, in the second area the propagation was brittle trans- and intergranular while the fracture of precracked blades was completely brittle. The lowering of the notch toughness of the steel below appr. 35 J is characterised by an increasing part of intergranular fracture with a smooth surface suggesting that the steel brittleness was connected to the microstructure as well as to an intergranular segregation of phosphorus.

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