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Research paper

METHODOLOGY OF DETERMINATION THE INFLUENCE OF CORROSION PIT ON DECREASE OF HYDRO TURBINE SHAFT FATIGUE LIFE

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Abstract: *This paper describes the influence of corrosion on stress concentration factor and crack initiation at shaft-flange transition section. The case study of hydraulic turbine shaft failure is used as the basis for this research.*
The quantification of the stress concentrators was accomplished by the usage of Theory of critical distances (TCD) in the prediction of high-cycle fatigue behavior in machine parts and systems. The stresses obtained by Finite Element Analysis, was used as an entry values for application of Theory of critical distances. The TCD represents a major extension of linear elastic fracture mechanics, allowing it to be used for short cracks as well as for stress concentrations of arbitrary geometry. Presented methodology is particular valid for machine parts of non-standard dimensions. The significance of results presented in this paper is that TCD and developed methodology can be used in preventing failures in power industry.

Key words: *fatigue, fracture, turbine shaft, Theory of Critical Distances*

1. INTRODUCTION

The most frequent causes of failure are defects such as pores or cracks introduced during manufacturing and inadequate design features which cause excessive stress concentration, such as sharp corners and other notch like type of stress raisers. In all such cases the common factor is high local stresses and also stress gradients, the stress decreasing with distance from the feature. One of the key points in failure analysis is the ability to make accurate predictions of the strength and fracture of materials in complex load-bearing structures. This task, the strength calculation of failed part, is also linked with the review of original designer approach in order to check hidden design errors. The majority of failures could be addressed to high-cycle fatigue [1, 2], and due to the fact that real engineering structures contain stress concentrations from which fatigue cracks frequently initiate, the prediction of the effect of stress concentrations on fatigue life and fatigue strength is of great importance.

Despite this, there is no commonly accepted set of standard methods for predicting the effect of notches, holes, joints, defects and other stress-raisers. This is not due to a shortage of theories and methodologies – there are, in fact, a multiplicity of methods to be found in the literature for the prediction of notch fatigue behavior. It is rather that the scientific community has not been able to decide which method, or methods, are most suitable, and under which circumstances [1, 3, 4]. The common point in all that theories the assumption that the relevant parameter is the stress averaged over some critical volume, but for convenience of calculation this has usually been simplified to the stress at one point (a given distance from the hot spot) or to the stress averaged over a line of given length. The origins of above stated are in work of Peterson and Neuber. Peterson considered that fatigue failure occurs when the stress at a constant distance beneath the surface equals the fatigue strength of the material [5] while Neuber related the stress concentration factor at the root of a sharp notch to the average stress over a certain critical distance [6].

Summary of the materials response under fatigue is presented by Suresh [7] where is clearly demonstrated that process of fatigue starts with the first cycle. The local regions of high stress promote the basic process of crack nucleation during high cycle fatigue. The damage progresses through mechanisms starting with crack nucleation, and the growth of micro structurally small cracks. Each mechanism is associated with a characteristic size or scale of magnitude, and each characteristic size has its own geometric complexity, constitutive law, and heterogeneity. Fatigue behavior cannot be fully understood and predicted without obtaining information about each of the characteristic sizes. According to the observations of Kitagawa and Takahashi [3], fatigue crack growth behavior of short cracks differs in a non-conservative manner from expectations based upon long crack behavior. Further contribution in understanding was done by El Haddad [8] who introduced an effective crack length to predict the propagation behavior of short cracks. In this formulation the effective crack length is equal to the crack length plus an amount *"l_0"*, which is related to the critical distance. This value *"l_0"* was stated by the authors as a characteristic of the material and the material condition accounting for the non-continuum behavior of very small cracks.

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The theory of critical distances (TCD) as popularized by Taylor [9] attempts to predict the effect of notches and other stress concentration features by considering the stress field in the region close to the notch tip. This theory requires two parameters, a characteristic distance and a critical stress or strain characterizing failure. In one version of the critical distance theory, termed as the Point Method, the failure occurs when the stress becomes equal to the failure stress at a given distance from the notch root. In the other version of the critical distance theory, termed as the Line Method, the failure is assumed to occur when the stress becomes equal to the failure stress when computed as an average value over a line of given length. The background philosophy is lying behind the TCD is described as wish to observe engineering components rather than to test specimens. In practice this meant that we only considered predictive methods which could be applied to bodies of arbitrary shape and size, subjected to arbitrary loadings, containing stress concentration features of arbitrary geometry. This is achieved by measuring material behavior using test specimens containing notches rather than cracks (fatigue threshold ΔK_{th} and toughness Kc using sharp notches rather than pre-cracks) which avoids the difficulties and uncertainties of carrying out standard fracture mechanics tests. The second presumption of successful application of TCD is the existence of an accurate stress analysis of the machine part.

Methodology of application of TCD is as follows:

1. Generating stress–distance diagram such as fig.1 and read the necessary stress values from FEA; and
2. The second step is calculating the value of the critical distance.

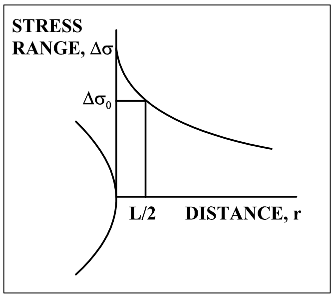


Fig.1. Schematic explanation of TCD point method

The result is that the critical distance for the point method is $L/2$, [1, 3, 4, 9], where:

$$L = \frac{1}{\pi}\left(\frac{\Delta K_{th}}{\Delta\sigma_0}\right)^2 \qquad (1)$$

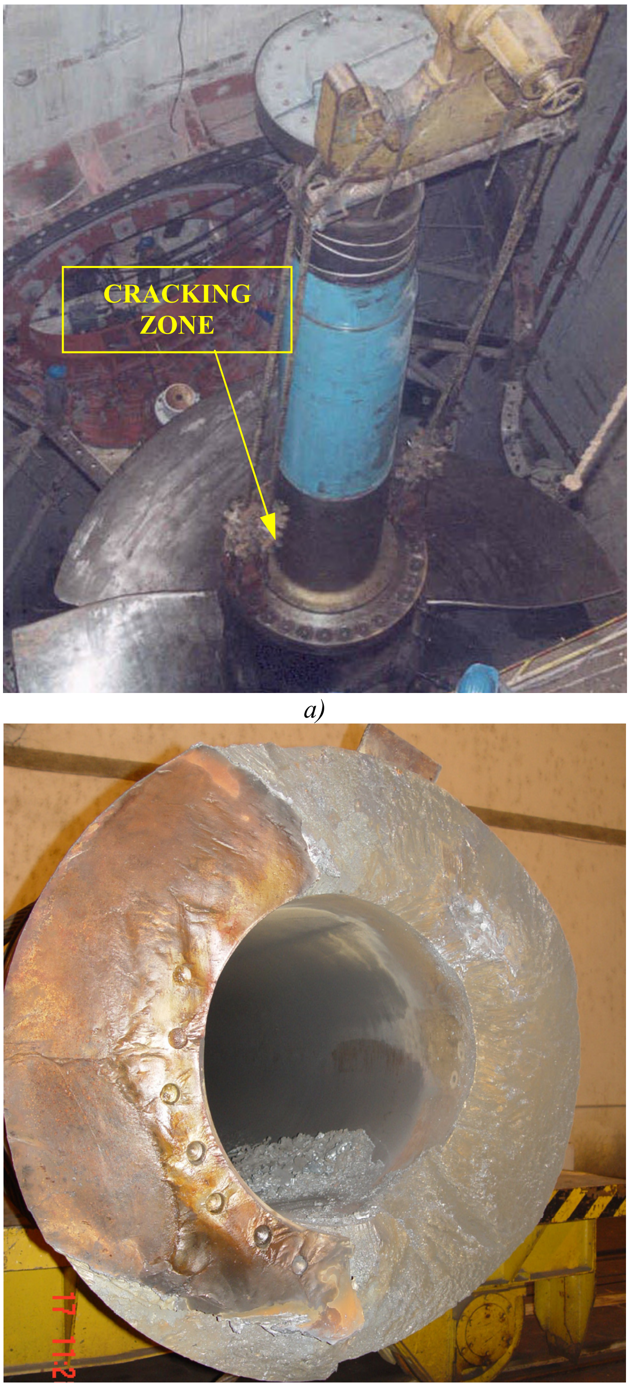
In this equation $\Delta\sigma_0$ is the fatigue limit of standard, unnotched specimens of the material, and ΔK_{th} is threshold stress intensity. The fact is that is often difficult to define the accurate fatigue limit, the stress range corresponding to a given number of cycles. The range from 1 to 10 million is generally used for determination of fatigue limit. It has been demonstrated by comparison with experimental data that the use of this value of $\Delta\sigma_0$ for L gives good predictions in many different materials, [9].

The another good example for application of TCD is presented by Chattopadhyay [10]

2. EXPERIMENTAL PROCEDURE

The problem of quantifying the influence of stress raiser is the problem that could be used in failure analysis. In order to check the usability of TCD in real case study instead of laboratory specimens, we chose to re-examine failure of hydro turbine shaft [11].

Briefly, failure analysis of hydro-turbine shaft, fig 2, shows that there is a zone from shaft-to-flange transition radius i.e. the width of the maximum stress zone, obtained by the Finite element analysis, strongly correlates with the width of the zone determined by non-destructive inspection, fig 3.



a)

b)

Fig.2. a) turbine shaft with runner during assembling in the bulb, b) fractured surface

The main conclusions of shaft failure analysis, fig. 2a), was that the combination of several factors leads to failure:

- Inappropriate corrosion protection in the zone of critical radius and lack of procedures of renewing corrosion protection of turbine shaft.
- Corrosion, i.e. corrosion fatigue due to leakage of river water through the sealing box.

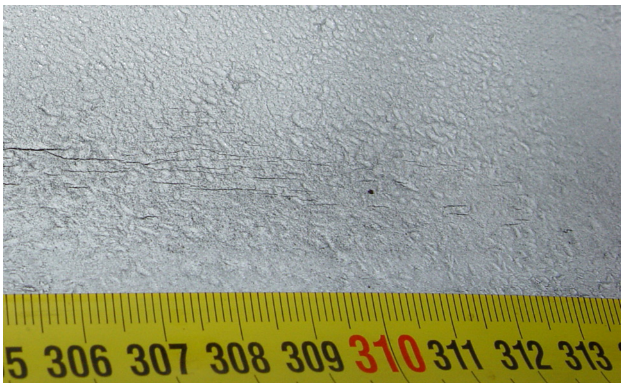


Fig.3. Corrosion cracks at shaft to flange radius

The results of basic mechanical properties for turbine shaft steel casting is given at the Table 1 and the results for fatigue properties of 20GSL is given at Table 2.

Table 1. Average and required mechanical properties at room temperature of the 20GSL steel casting, [12]

	Average values	Required (GOST 977) - min. values
Yield strength (MPa)	310	294
Tensile strength (MPa)	509	540
Elongation, in 2 in. (%)	17.6	18
Reduction of area (%)	35.2	30
Brinell hardness HB	153	-
Charpy-V notch, +20°C (J)	74.4	23.4

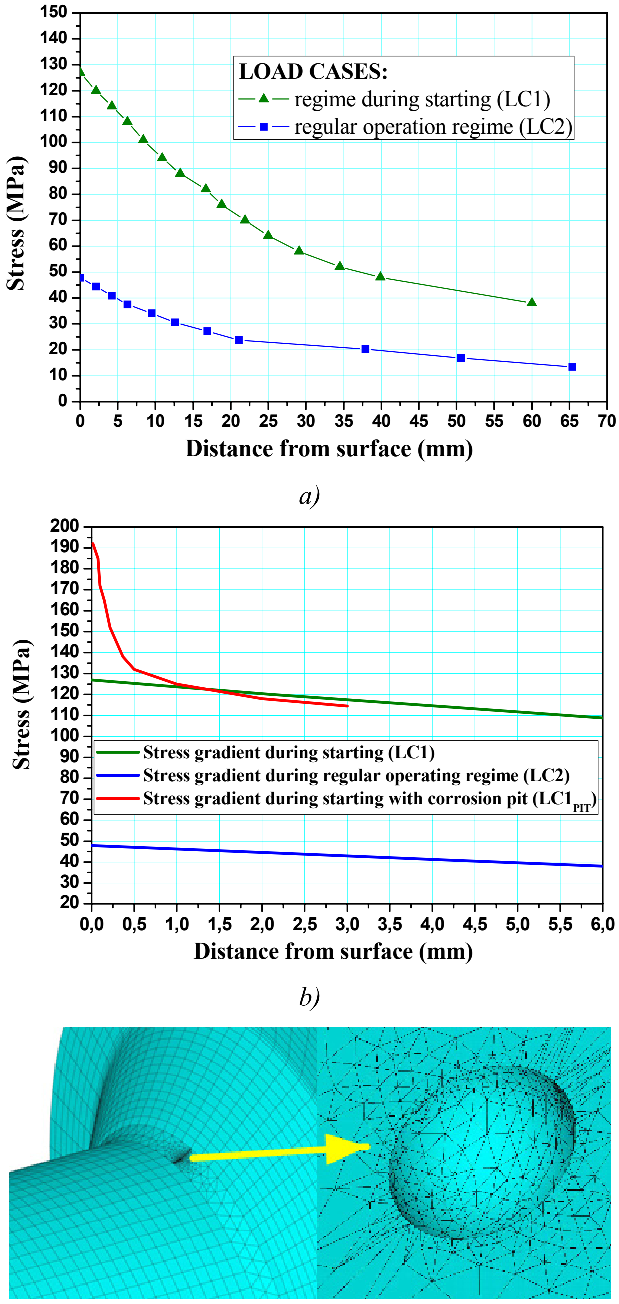
Table 2. Average and reference fatigue values of the 20GSL flange steel casting, [13]

	Average values	Reference values	
Fatigue limit S_{FL} (MPa)	168	on air 225	in water 140

As an integral part of failure analysis, the finite element analysis of turbine shaft was performed under various conditions [14, 15]. The major conclusion was that stress gradient during start up and regular regime had no influence on crack initiation, fig. 4a) and fig. 4b). But the simulation of corrosion pits with diameter of 600 μm, fig. 4c) during start up regime revealed that the stresses under corrosion pit at distance $L/2$ was above the values of fatigue strength of unnotched specimens tested in water. The values of K_t (stress concentration factor) obtained by FEM analysis was, for the case of LC1 (regime during starting) the 3,97 and for case LC2 (regular operation regime) 2,057. The value of K_t on corrosion pit on radius, Fig 4c) was 5,97.

3. DISCUSSION AND CONCLUSIONS

Presented case study is another confirmation, the applicability range of TCD as a method that combines properties of material and geometrical features of engineering component is very wide. Compared with standard models, which are not generally used to predict cracking processes because they are not well adapted to deal with stress singularities, the TCD can be used as a complementary methodology to modern damage mechanics. On fig. 5 the comparative stress gradients from tension as result of axial hydraulic force during starting regime (F_a=5542.65·10^3 N) without corrosion pit and with corrosion pit are presented.



a)

b)

c)

Fig.4. a) Stress gradients on r = 80 mm radius over two regimes b) Stress gradients over two regimes, c) Simulated corrosion pit with 600 µm diameter on transition radius

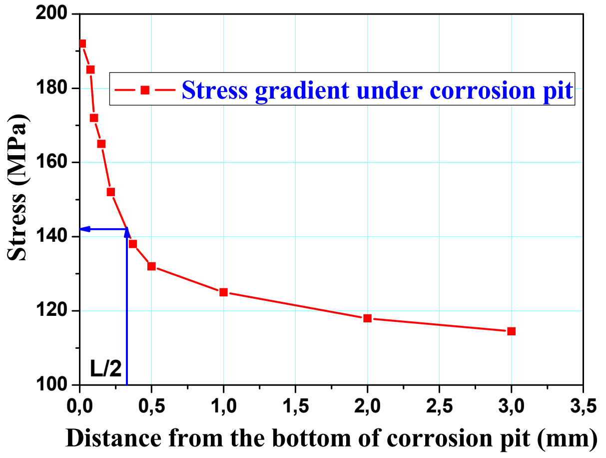
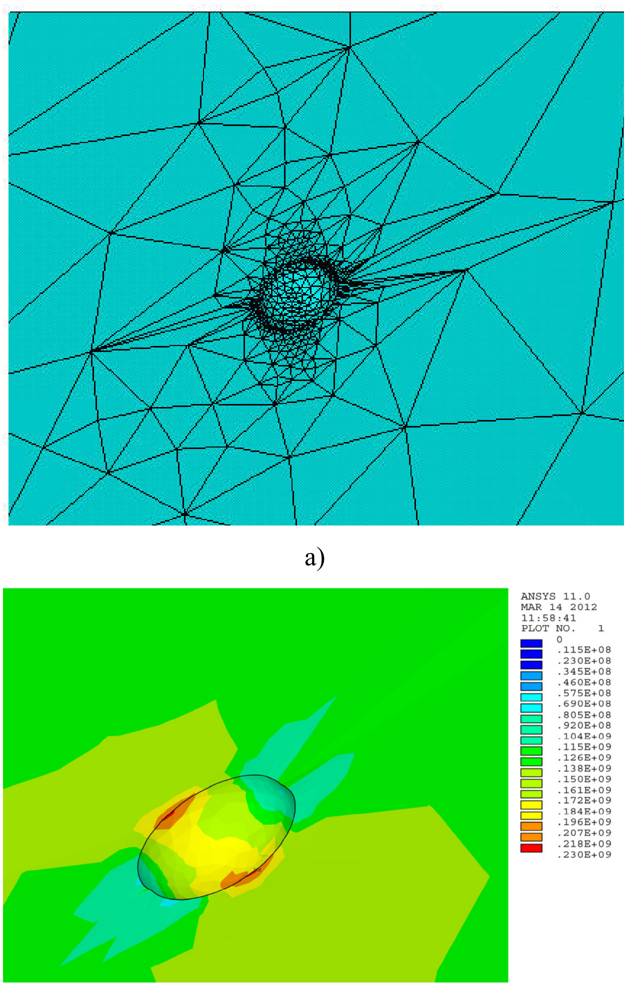


Fig.5. Stress gradient under the corrosion pit

The obtained numerical results for stress state in critical zone shows maximum Von Mises equivalent stress of $\sigma_{eqv\text{-}max}$=230 MPa, fig. 6.



a)

b)

Fig.6. a) Meshing arround the simulated pit

b) Equivalent stresses in the zone of corrosion crack

Combined stress coefficient factor for the corrosion pit on the radius is: $K_{t(sum)} = K_{t(radius)} \cdot K_{t(pit)} = 3{,}97 \cdot 5{,}97 = 23{,}7$ which is extremely high value. Another interesting viewpoint regarding influence of corrosion pit on premature failure is presented on fig. 7.

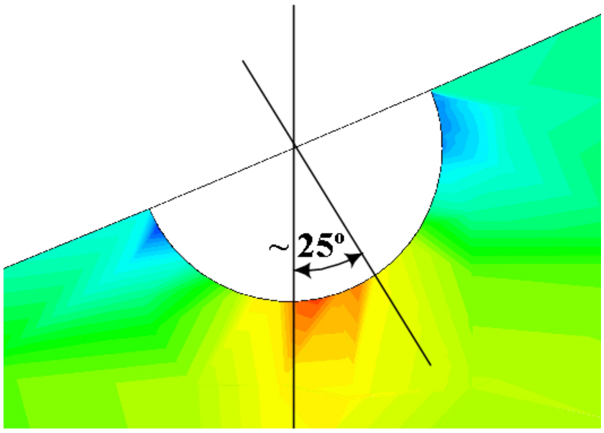


Fig.7. Matching of angle of fatigue fracture (through-thickness crack) and the angle obtained by FEM simulation of corrosion pit

On the fig. 6, it is possible to see that the angle between perpendicular axis of the shaft and the axis drawn on the half of the corrosion pit is approximate equal to the angle of 25 degrees. This value is almost identical to the slope of fractured surface presented at the fig. 2.

By using the eq. (1) we obtained the value of L = 0,7 and this value corresponds to material by available literature data for similar cast steels and particularly with microstructure, fig. 8 of turbine shaft material. The microstructure of the material is the cast ferrite-pearlite one, with oxide type non-metallic inclusions and with minimal participation of dendrite structure. This inhomogeneity of microstructure also explains the formation of "pits" on transition radius.

The comparisons between stress concentration factors and stress states obtained by Finite Element Analysis and analytical stress calculations that used the Peterson's elastic stress concentration factor charts for conventional values of fillet shaft's transition radii led to conclusion that analytical approach was not suitable for calculation of load capacity of such turbine shaft with flange [15]. In cases like the presented one, only FEA analysis is valid an the use of "classic" analytical approach can lead to the inaccurate results and wrong conclusions.

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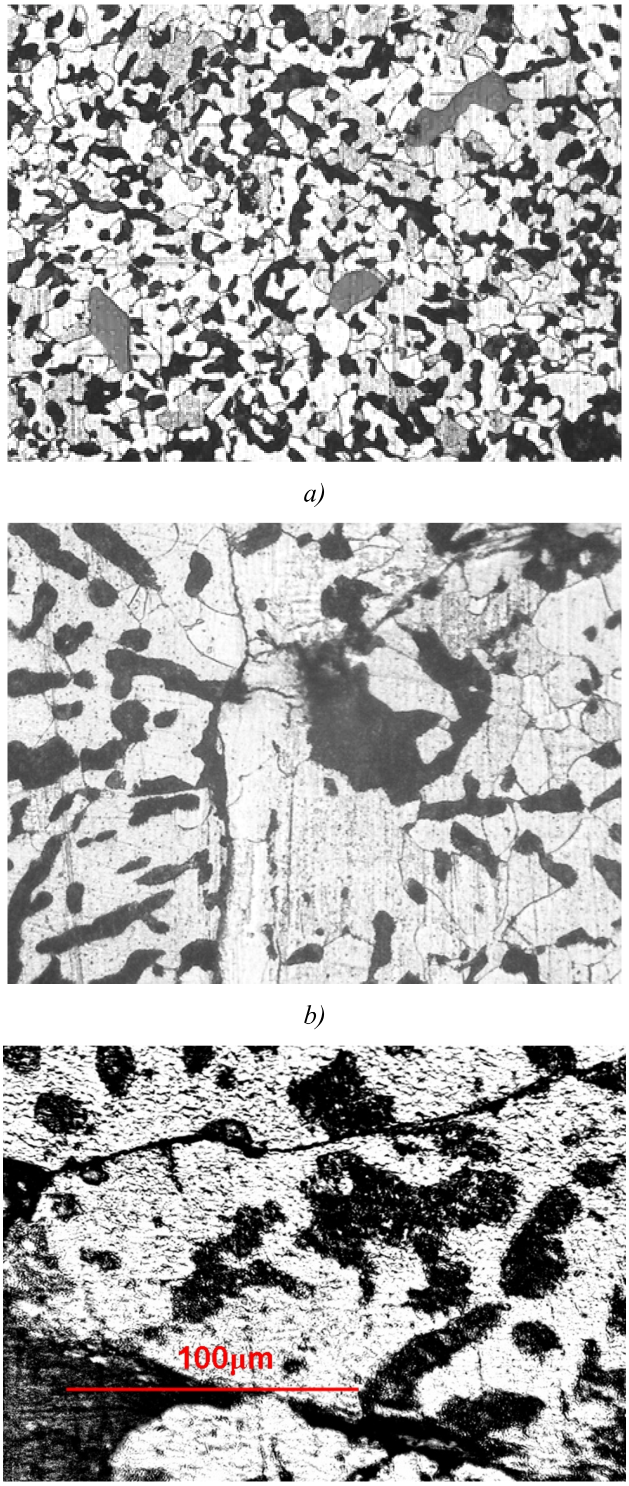
The presented research points out the new trend in stress concentration factor calculation. This procedure is particularly suitable and important for machine parts with non-standard geometry and specific operating conditions.



a)

b)

c)

Fig.8. Microstructure of flange material
a). Cast, ferrite-pearlite microstructure, x 200, 5% nital
b). Micro cracks emanating from shrinkage, x 500,
c) The relative siye of microcracks
5% nital

For this particular type of turbine shafts, another researcher gain the similar conclusions regarding crack initiations on transition radius [16, 17, 18]. Metallurgical approach in failure analysis, by matching appearance of cracks, presented on fig. 9, by literature [19, 20, 21] now is extended by calculation which is more direct proof in cases like this one.

The significance of TCD in novel, better design of machine parts, lays in fact that the value of L is obtained combining the material parameters such as $\Delta\sigma_0$ (the fatigue limit of standard, unnotched specimens of the material), and ΔK_{th} (fatigue threshold stress intensity) with the stress gradient of particular stress raiser. The range of applicability of this methodology is very wide. Although the theoretical background of the TCD is complex the use itself of TCD is simple as presented.

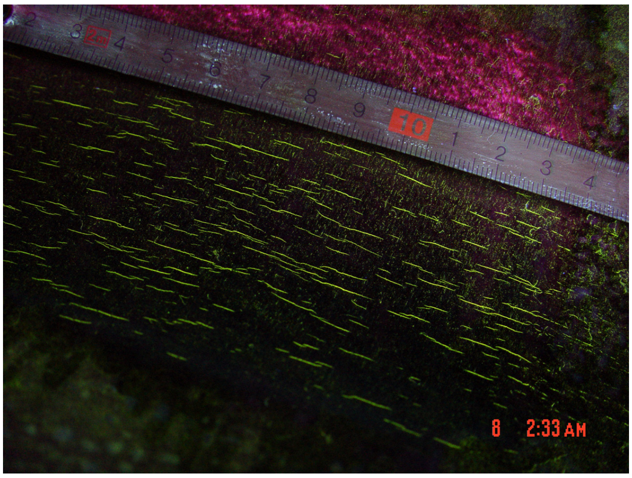


Fig.9. Fine cracks in the critical zone of shaft-flange transition zone, found by magnetic particle testing after fine grinding.

From above presented, it is confirmed it is again confirmed and documented that TCD methodology has significant potential in quantification of any type of stress raiser influence on decrease of machine parts fatigue life. The next step and the challenge for TCD is the calculation the number of cycles when a crack will occur on arbitrary geometry of machine part.

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