# THERMAL FATIGUE OF STAINLESS STEELS

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# TEPELNÁ ÚNAVA KOROZIVZDORNÝCH OCELÍ

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**Abstract**

The paper is devoted to the study of initiation and propagation stages of thermal fatigue cracks in austenitic stainless steels subjected to repeated thermal shocks. This degradation process is typical very often for high temperature pressured water components. Two types of specimens were tested. The first one was equipped by the central hole and the second by the hole and two notches acting as stress concentrators. The surfaces of tested specimens were investigated after 1000, 3000 and 6000 thermal cycles. The temperature cycle has been chosen in the range from 100°C to 350°C, and 300°C, respectively. It was detected that partial fatigue cracks were spontaneously initiated in notches bottoms. Cracks were visible on free surface of the specimen even after 1000 cycles under loading. Thermal cracks were fractographically investigated and the mechanism of main crack formation has been revealed. Stress-strain analysis proves that stresses around notch root are sufficient to cause mechanical fatigue damage. For further improvement of stress-strain behavior of test specimens the numerical analysis of finite elements method is also needed. Comparing three tested steels no significant differences have been detected in their rezistivity to thermal fatigue. The circumstances that can cause thermal cracks initiation should be avoided in design of power plant station components. In existing plant components the risk of thermal fatigue cracking should be assessed and conditions necessary for the prevention of this degradation process should be clarified.

**Key words:** Stainless steel, thermal shock, thermal fatigue, fatigue crack, thermal cycle.

**Abstrakt**

Příspěvek je orientován na studium iniciačních stádií a stádií růstu únavových trhlin v austenitických korozivzdorných ocelích podrobených působení opakovaných teplotních šoků.

K tomuto degradačnímu procesu dochází nejčastěji u horkovodních tlakových komponent elektrárenských bloků. Byly testovány dva typy zkušebních těles kruhového tvaru opatřených centrálním otvorem a otvorem se dvěma vruby, které působily jako koncentrátory napětí. Povrch v okolí vrubů byl vyšetřován po 1000, 3000 a 6000 teplotních cyklech. Teplotní cyklus byl volen v rozmezí od 100°C do 350°C, resp. 300°C. Tepelné únavové trhliny iniciovaly v kořeni vrubu. Trhliny byly viditelné na volném povrchu vzorků až po 1000 zátěžných cyklech. Fraktografické šetření těchto trhlin objasnilo formování magistrální únavové trhliny. Napěťově – deformační analýza v okolí kořene vrubu prokázala, že napětí vyvolaná teplotním pnutím jsou dostatečná k iniciaci únavového poškození. Pro další zpřesnění znalostí o napěťově-deformačním chování zkušebních těles je nutné zpracovat i numerickou analýzu metodou konečných prvků. Porovnání testovaných ocelí neukazuje na žádné významné rozdíly v jejich odolnosti vůči tepelné únavě. Podmínkám, které mohou způsobit iniciaci tepelných trhlin, je nutné se vyhnout již při samotném návrhu konstrukčních částí nových elektrárenských bloků. U komponent stávajících elektráren musí být stanoveno riziko vzniku tepelné únavy a způsob, jakým lze vzniku tohoto degradačního procesu zabránit.

## 1. Introduction

Thermal shock is common damage process in power plant equipment involving water and steam. Thermal shocks often occur when low temperature fluid strikes an already hot surface. Another less common situation is where there is rapid depressurization in pressurized plant caused by sudden leaks or valve operations. Restraint of thermal expansion and contractions of a material as it is exposed to rapid changes in temperature results in strains and associated stresses in the material. If the changes in temperature are severe and the resulting strains are sufficient, local plastic deformation of the material will occur. Repeated application of this loading leads to rapid cracks initiation further propagating as low cycle fatigue cracks. Thermal fatigue cracking is very important life limiting failure mechanism of power plant pressure parts made from austenitic stainless steels.

This paper outlines results from an experimental investigation into thermal fatigue cracks in notched flat plate specimens equipped with central circular hole exposed to repeated thermal shocks. Obtained experimental results as the crack growth per cycle and evaluation of number of cycles leading to failure can be a useful guide for permissible crack size assessment and judgment of residual service life of the engineering parts exposed to thermal fatigue.

## 2. Experimental procedures

Gradient test were used to test the thermal fatigue. Internal tension in metal is induced by differentiating temperatures in the tested object which is either of a simple shape enabling the tension analysis, or is a model of an existing part, potentially marked with an initiation notch. In such case, thermal expansivity and thermal conductivity fully show their influence, as well as the shape of the specimen, its surface and surrounding environment. Despite various disadvantages [1-4], these tests are recommendable for mutual comparison of a greater number of materials.

### *2.1 Description of the equipment*

For thermal fatigue tests the test specimen took the shape of a disc with $\phi \leq 90$ mm, thickness of 1-2 mm with a central opening, Figure.1. The specimen was placed between two heating desks; free attachment of the specimen enabled its dilatation in the radial direction. The regulated temperature of the desks was approximately by 100 K higher than the maximum temperature in the central part of the specimen. The specimen's maximum and minimum temperatures $T_{MAX}$ and $T_{MIN}$ have been predefined in the temperature regulator that compares them concurrently with the actual temperature. Once $T_{MAX}$ is achieved, the temperature regulator opens the coolant inlet (liquid nitrogen, water, aqueous solution, etc.) that cools the central part of the specimen. Once the temperature drops to $T_{MIN}$, the coolant inlet is closed and another cooling and heating cycle begins. The evaluation is focused on the number of cycles before occurrence of a crack. The simultaneous execution enables the test performance within the temperature range from 200 K to 700 K i.e. from -70 °C to 430 °C; both the lowest and the highest temperature is infinitely optional within this range; creep does not significantly apply for usual types of corrosion steels at the highest temperature [1]. In addition to the loading of flat specimens, the equipment enables the application of additional tensile stress.

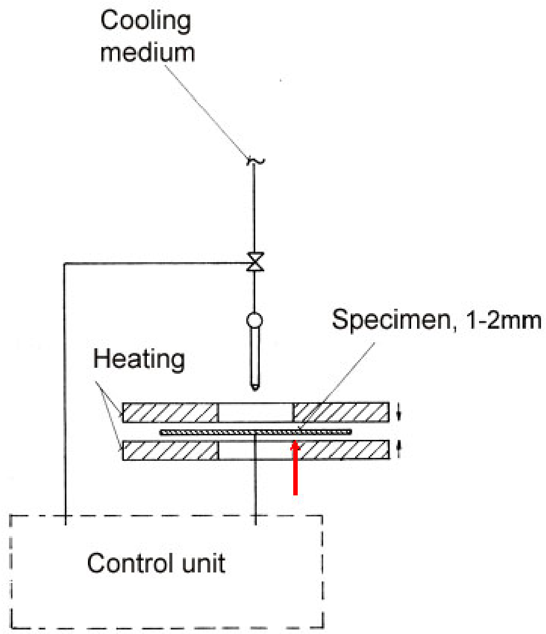



Fig.1 Scheme of thermal fatigue testing plant. The arrow shows the place where the specimen is fixed to the thermal desk. Specimen diameter is ϕ < 90 mm and uncovered part of the specimen is ϕ ≈ 20 mm.

*2.2 Testing material*

Austenitic stainless steels of 3 various qualities were used for thermal fatigue test, see Table 1. Thermal fatigue testing specimens were made of bars with diameter 35 mm; longitudinal axis of the bar was perpendicular to the surface of the testing disc. Two types of initiation notch were cut in the centre of the disc. For some of the experiments it had a shape of a circular hole with diameter 1 mm marked as Type K. This type of specimens has been prepared only from the material 3, i.e. 316 stainless steel and represents a greater part of the executed experiments. Also specimens with a more complex notch marked as type M were used (see Fig.2).

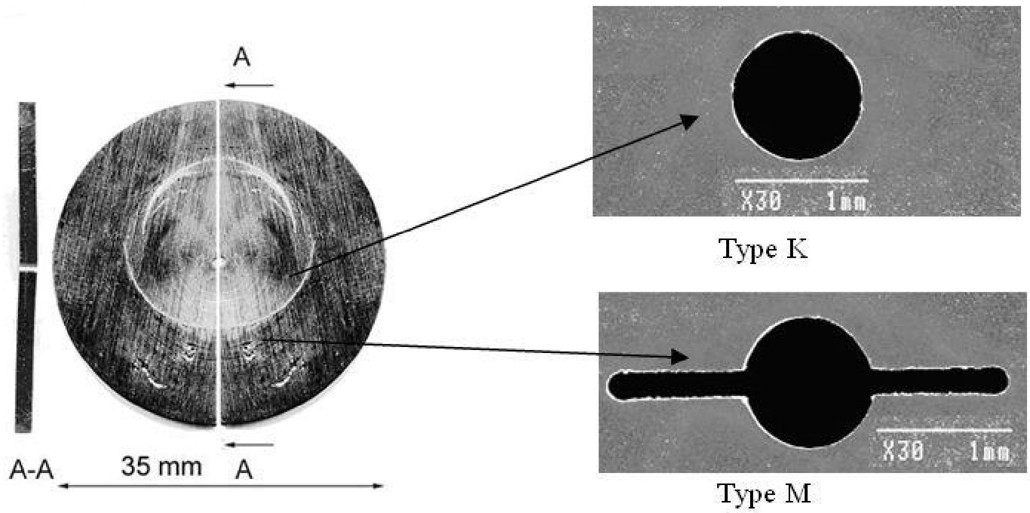



Fig.2 Appearance of the disc pattern for thermal fatigue tests. Thickness of the specimen is 1 – 2 mm. Detail of the initiation notch.

Table 1 Testing material

| Material | Quality mark | | | C | Cr | Ni | Mo | Ti |
|---|---|---|---|---|---|---|---|---|
| 1 | 304 | 17 241 | 1.4301 | 0,05 | 17,40 | 8,90 | 0,32 | 0,00 |
| 2 | 321 | 17 247 | 1.4541 | 0,03 | 16,91 | 9,40 | 0,10 | 0,22 |
| 3 | 316L | 17 345 | 1.4404 | 0,02 | 15,89 | 11,00 | 1,89 | 0,00 |

Heat treatment and mechanical properties of tested steels.

| Testing specimen | Type of steel | TZ | Re MPa | $R_M$ MPa | A,% | Z,% |
|---|---|---|---|---|---|---|
| 1-x | 304 | 1050°C/1h/water | 344 | 618 | 57 | 74 |
| 2-x | 321 | 1250°C /0,5h/water | 203 | 517 | 63 | 68 |
| 22-x | 321 | 1230°C /0,5h/oil+1050/1h/water | 235 | 525 | 61 | 71 |
| 3-x | 316 | 1050°C /1h/water | 305 | 558 | 57 | 73 |

## *2.3 The course of the thermal fatigue experiments*

After heat treatment and evaluation of mechanical and basic corrosion properties, the selected line of testing specimens prepared from materials marked as 1, 2, 22, 3 was exposed to 6000 thermal cycles. Testing specimens were evaluated after 1000, 3000 and 6000 cycles within the range of temperatures $T_{MAX}$ - $T_{MIN}$. The rate of change in temperature was approximately 100 $K.s^{-1}$ when specimen was cooled by a nozzle from one surface only and 25 $K.s^{-1}$ for full specimen volume heating – by convection. Heating cycles are summarised in Table 2.

Table 2 Conditions of the thermal fatigue experiments

| Test specimen | Temperature, °C | | Rate of the change in temperature, $K.s^{-1}$ | |
|---|---|---|---|---|
| | $T_{MAX}$ | $T_{MIN}$ | heating | cooling |
| MAT – 1 | 350 | 100 | 25 | - 100 |
| MAT – 2 | 300 | 100 | | |
| MAT – 3 | 420 | 80 | | |
| MAT – 4 | 250 | 80 | | |
| E.g. Material AISI 304 = 1, loading 300→100°C : marking 1-2 | | | | |

*2.4 Fractographic analysis*

After the thermal fatigue experiments, the specimens were depleted of the oxide layer by the electrochemical reduction of Li(s), by subsequent short-time (20 s) decontamination in a mixture of $HNO_3$ + HF (20+2 wt%). For visual evaluation the tested specimens were cleared in an ultrasonic cleaner and inspected with a light stereomicroscope JSM 840 A in the range of magnification from 20 up to 30 000×. Basic photographs of cracks visible on the free surface of testing specimens were taken during the inspection. The photographs were used for specification of the position and length of cuts that would weaken the remaining carrier intersection of the object so that it would be possible to open the formed fatigue cracks of size up to 100μm by finishing the static fraction. Considering the size of the evaluated objects (after being cut out, it is a rectangle with dimensions of app. 10 % of 20 mm) and lengths of the cracks (app 0.1 mm), preparation methodology was elaborated that enables opening of the fracture without damaging the fracture areas, Figure 3. Micro-morphology of the open fracture fronts was evaluated according to fractographic methodologies [5,6,7] with magnification of 30 up to 30 000x.

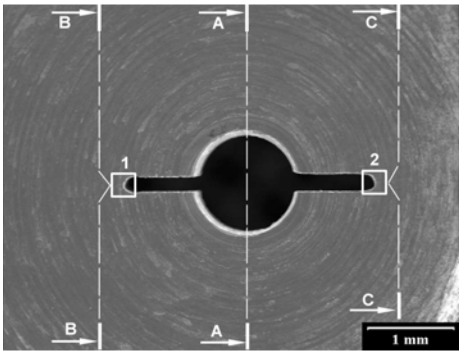



Fig.3 Detail of the part of specimens used for cracks preparation.

*2.5 Evaluation of specimens with a notch of Type K*

Specimens made of steel 1.4404 marked a material 3 with central circular notch, type K, were used for some of the experiments. However, during the experiment it was found out that in case of these specimens cracks are not initiated even after 3000 cycles of $T_{MAX}$ = 350°C and $T_{MIN}$ = 100°C. Deformation of the specimen in the central part was only identified as it is evident from Fig.4. For further evaluation of the thermal fatigue effect, the specimen with the central notch was cut and polished using usual metallographic procedures. The HVM 300 microhardness gradient was measured on the cut in the middle of the disc thickness. The distance was measured from the bottom of the notch. The distance among single indents was determined to be minimally 250 μm, i.e. more than a multiple of three of the indent's diagonal. Elevated values of microhardness were detected within the distance of 1.5 and 2 mm from the bottom of the notch on the cut of the disc that was exposed to the cyclic thermal fatigue, comparing the nominal average value, i.e. the value measured in a sufficient distance from the bottom of the notch To eliminate the effect of technology of specimen preparation, microhardness gradient was measured subsequently on the disc two times on not exposed specimen to thermal cycles. This state was identified as the starting point. Measurement conditions were identical with those of the preceding measurements, then in the middle of thickness and at a distance among single indents about 250 μm. No material changes were observed in this case, Fig.5. The Type K specimen was originally used for a simpler description of tension conditions of numerical modelling. However, considering the difficult initiation of cracks from this type of the notch, it has been stopped. This Type K specimen showed significant plastic reshaping and strengthening in the area where the specimen was cooled.

*2.6 Evaluation of notched Type M specimens*

Most of the experiments were performed on Type M specimens. The level of fatigue deformation of the tested specimens concerned was evaluated in three steps: after 1000 cycles, after 3000 cycles and after 6000 cycles of thermal loading. This evaluation focused on the surface micromorphology on both sides of tested specimens. Attention was drawn, in particular, on detection of cracks in the vicinity of bottoms of the sparked-out notches. Considering the first two steps, i.e. after 1000 and 3000 cycles only the tested specimen surface was observed. After 6000 thermal loading cycles the fractographic analysis of static initiated cracks was performed on some selected specimens. After the first set of 1000 cycles it was discovered that compared to the previous experiments [7] the disc specimens are getting deformed. The cooled surface has got bended and on the opposite side the surface became closed, Fig.4. The deformation resulted in closing of the initiation notch on the cooled side, and in opening on the un-cooled side of the specimen back, Fig.4 and 6.

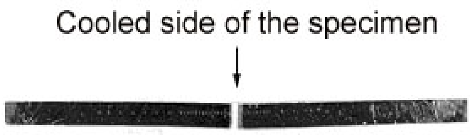
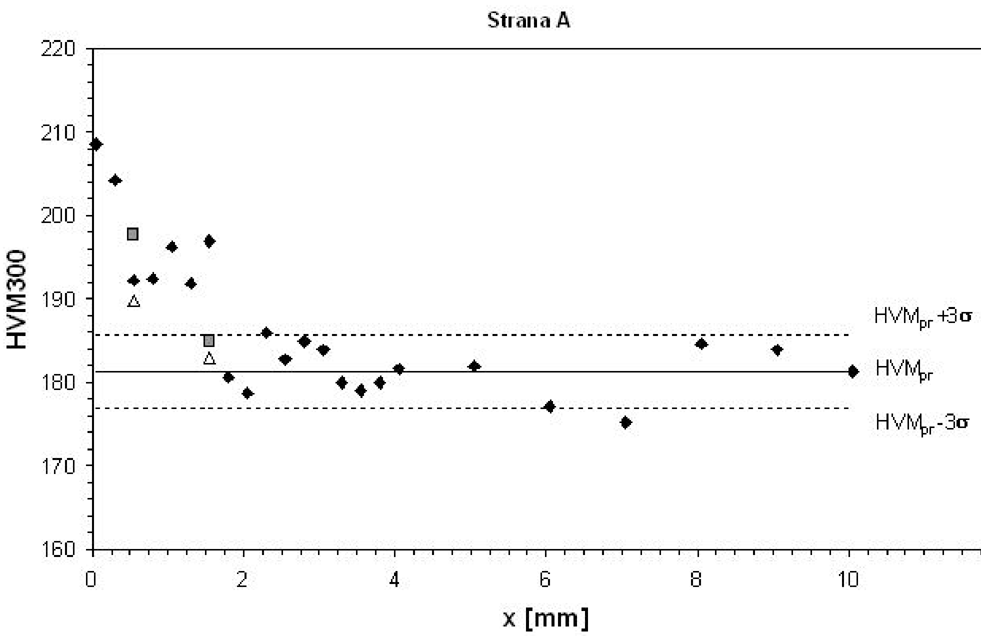
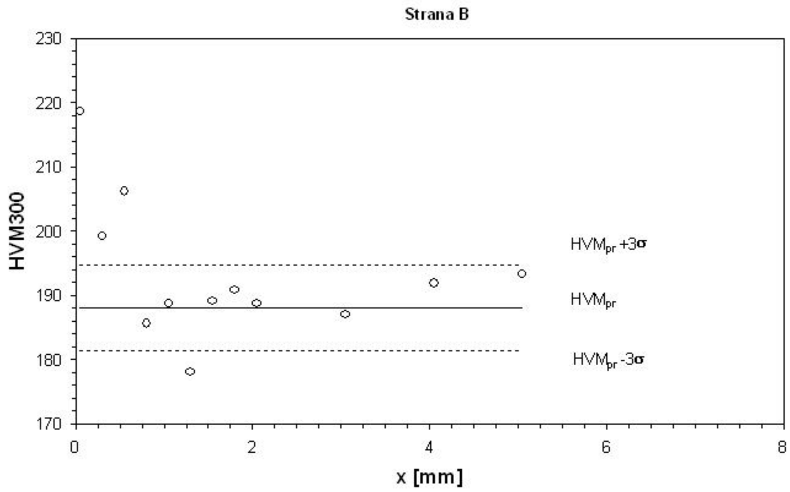



Fig.4 Deformation of the specimen after the heat fatigue experiment.





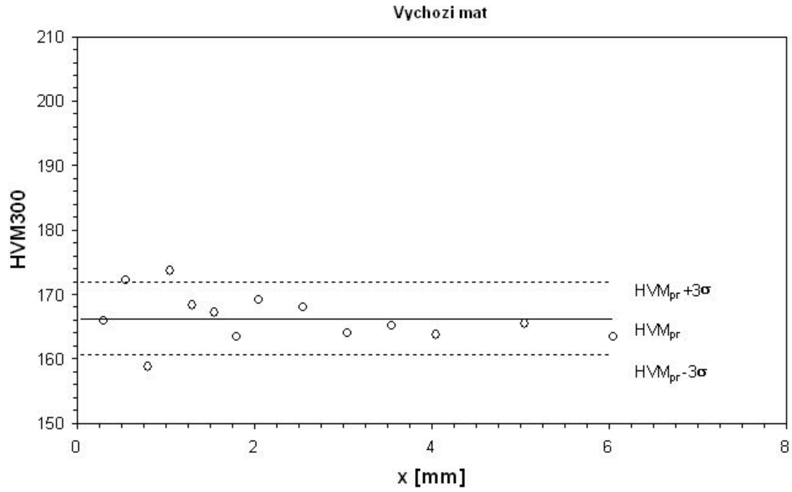
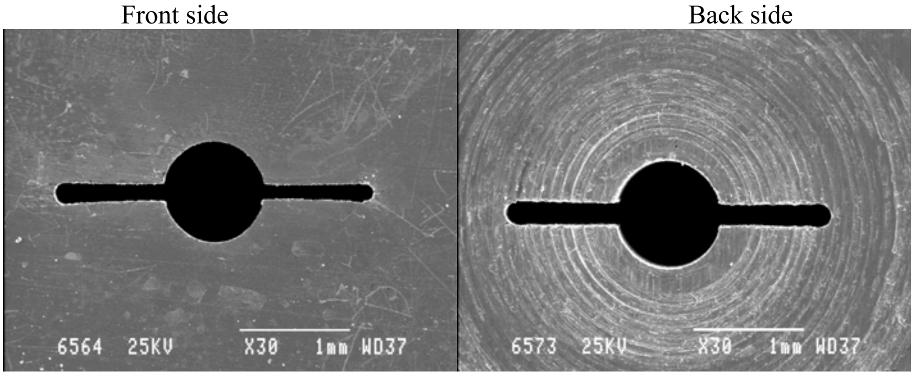
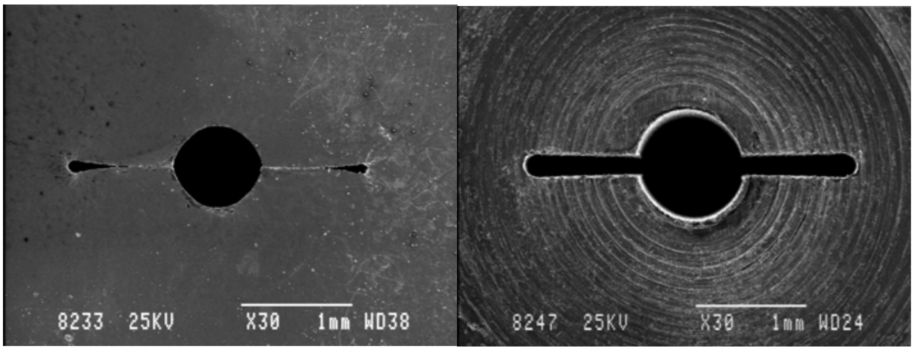




Fig.5 Change of microhardness in the vicinity of the initiation notch of K type specimen and sides A and B after 3000 thermal cycles, position 0 mm corresponds to bottom of the notch (material 3).

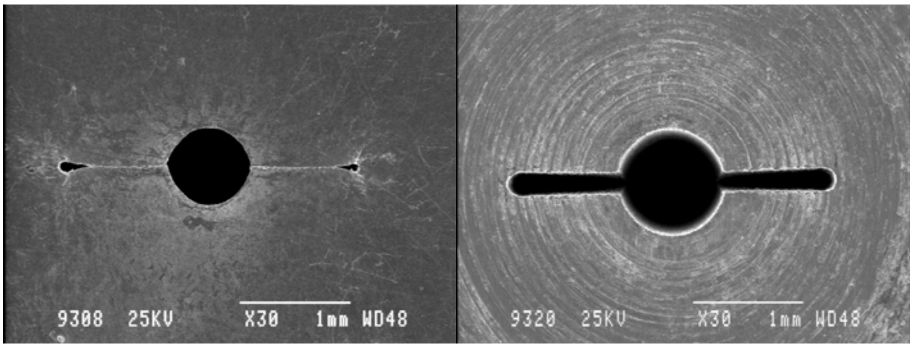
Front side Back side




1000 cycles

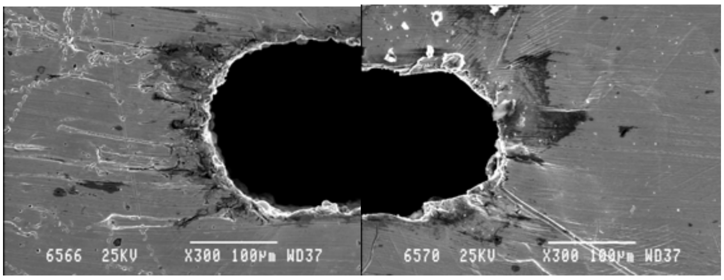



3000 cycles

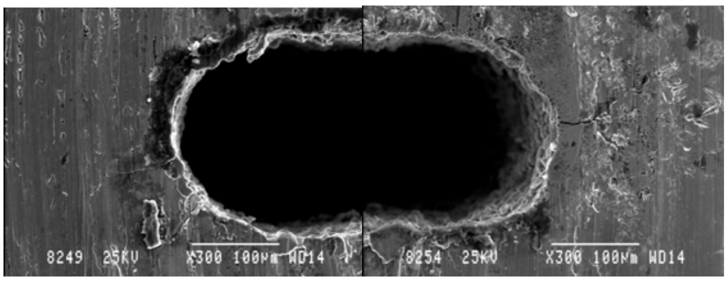



6000 cycles

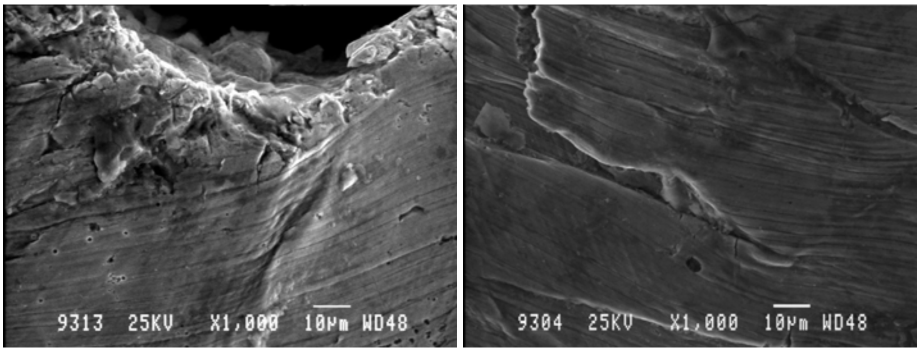
Fig.6 Deformation of the surface of test specimens that occurred during the thermal cycling in the range of temperatures of 350→ 100°C (material 1.4301).




1000 cycles




3000 cycles




6000 cycles

Fig.7 Micromorphology of the surface of test specimen 1-1 (350→ 100°C) in the vicinity of the notch bottom (material 1.4301).

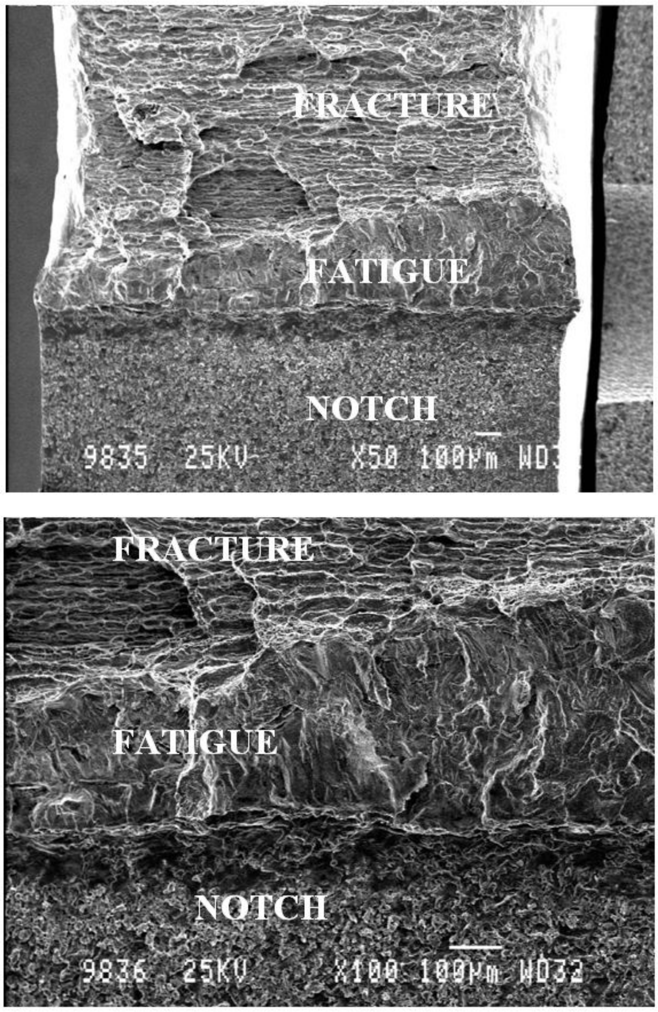
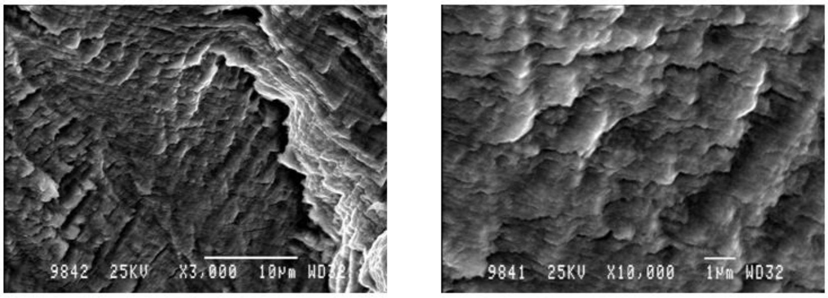
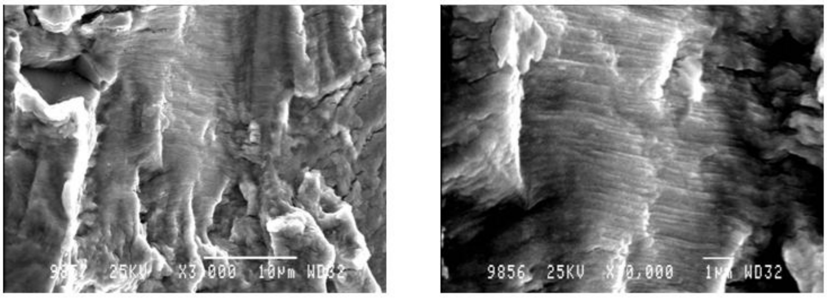


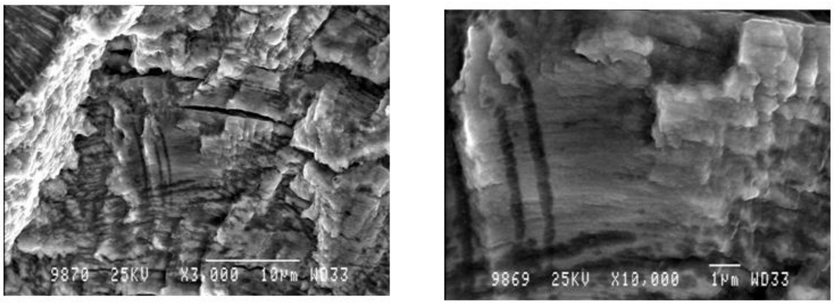

Fig.8 Character of the micromorphology of a fatigue crack face that was opened by final static fracture of the test specimen 1-1 (350→100°C, material 1.4301).




specimen 1-1



specimen 2-1




Specimen 22-1

Fig.9 Appearance of the fracture micromorphology after 6000 cycles of 350→100°C (specimen 1-1: mat. 1 / 1.4301 and specimens 2-1, 22-1: mat.2 / 1.4541).

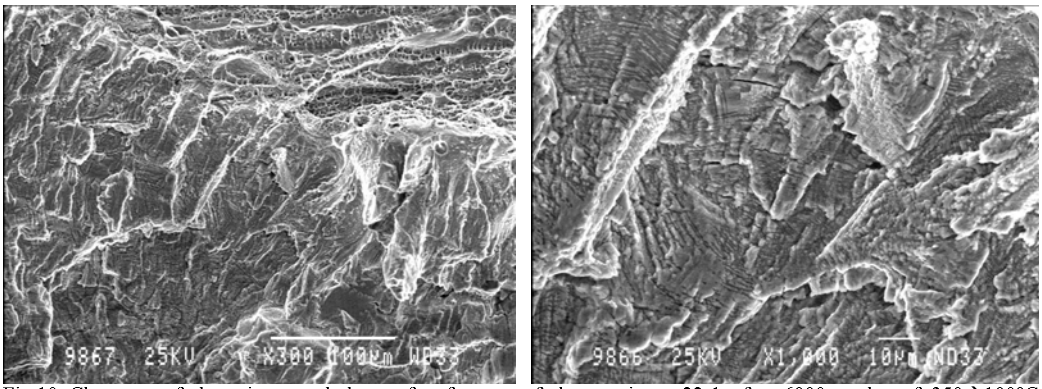


Fig.10 Character of the micromorphology of a fracture of the specimen 22-1 after 6000 cycles of 350→100°C (material 2: 1.4541).

## 3. Summary – results of qualitative fractographic evaluation

It was detected that partial fatigue cracks were spontaneously initiated in notches bottoms. Cracks were visible on free surface of the specimen even after 1000 cycles under loading. Considering the results of previous documents it cannot be ruled out that the fatigue cracks in the testing specimens were initiated practically in the first phases of cyclic load.

No major defects or inhomogeneities that might substantially affect the time to cracks initiation were detected in the initiation area. Continuous growth and coalescence of partial microcracks gives rise to a main crack, Fig.9 and 10.

The micromorphology of the crack faces is characterised by occurrence of striation patches and transversal microcracks.

The maximum length of fatigue cracks was evaluated in terms of orientation measured as a distance from the bottom of the initiation notch. Having compared the measured values we can see that no significant differences have been detected among the tested materials. More significant effect was shown only for the maximum temperature of heating during the loading, Table 3.

Table 3 Depth of the intruding fatigue crack from the bottom of the initiation notch

| Testing specimen | Material | $T_{MAX}$ / $T_{MIN}$, °C | Length of the fatigue crack, μm |
|---|---|---|---|
| 1-1 | 1.4301 | 350 / 100 | 450 |
| 2-1 | 1.4541 | 350 / 100 | 500 |
| 22-1 | | 350 / 100 | 450 |
| 22-1 | | 300 / 100 | 350 |

Cracks propagated practically only by means of striation mechanism during the loading. The involvement of other intrusive mechanisms may be deemed irrelevant.

No material differences were detected among the tested types of steels neither in terms of the character of the initiation areas nor in terms of the character of the fracture area micromorphology, i.e. in the mechanism of fatigue intrusion.

## 4. Thermal shock stress-strain analysis

The circumstances that can cause thermal cracks initiation should be avoided in design of power plant station components. In existing plant components the risk of thermal fatigue cracking should be assessed and conditions necessary for the prevention of this degradation process should be clarified. Risk of thermal fatigue occurrence judgment demands stress – strain analysis around stress concentrators during thermal shock. The maximum thermal stress amplitude generated during a thermal shock $\Delta T = T_{MAX} - T_{MIN}$ can be calculated by the following relationship

$$\sigma_{aMAX} = \frac{\alpha_0 E \Delta T}{2(1-\nu)} k_f \quad (1)$$

where $\alpha_0$ is the coefficient of thermal expansion, $E$ is the Young´s modulus of elasticity, ν is Poisson´s ratio and $k_f$ is the stress concentration factor caused by geometrical discontinuities. Stress concentration factor can include also the influence of local stress concentrators such as machining works, and its maximum value for a severe notch is about $k_f = 5.0$. Values of $k_f$ less than $k_f = 5.0$ to be justified using numerical Finite Elements Method (FEM). Stress concentration factor of rounded notch is very close to the value of $k_f = 3.0$.

The generation of thermal shock fatigue cracks is indicated if the maximum thermal stress amplitude $\sigma_{a\mathrm{MAX}}$ exceeds the allowable design stress amplitude $\sigma_a$. The allowable design stress amplitude for a given number of cycles may be taken from the Wöhler curve. Using eq.(1) for a given number of cycles $N_f$ the maximum stress amplitude $\sigma_{a\mathrm{MAX}}$ ($N_f$) received from the Wöhler curve is useful for calculation of the maximum magnitude of thermal shock $\Delta T_{\mathrm{MAX}}$. This value as it is evident from transposed eq.(1),

$$\Delta T_{MAX} = \frac{2(1-\nu)}{\alpha_0 E} \frac{\sigma_{aMAX}(N_f)}{k_f} \tag{2}$$

with increasing number of cycles diminishes. Inserting typical values of variables for austenitic steel in the right side of eq.(1), $E$ = 200 GPa, $\nu$ = 0.3, $\alpha_0 = 17.10^{-6}$ and $k_f \cong 3.0\text{-}3.5$ depending on damage stage, there is for experimental $\Delta T_{\max}$ = 330 °C, $\sigma_{a\mathrm{MAX}}$ = 240-280 MPa. The strong dependence of the maximum thermal stress amplitude on the stress concentration factor $k_f$ needs numerical calculation of stress state around the notch using finite elements method.

## 5. Conclusions

Specific conditions prevailing in power plant equipment (heat transfer and thermal cycling) can lead to various mechanisms of materials deterioration. The dominant degradation processes of stainless steels, which occur under the heat transfer and thermal cycling was identified to be thermal fatigue.

## Acknowledgements

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