THE EFFECT OF LONG TERM EXPOSURE TO ELEVATED TEMPERATURE ON STEAM LINE STEEL PROPERTIES

by

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Premature failure of pipes presents serious problem in the service of steam lines, produced of steel 14MoV63, developed for steam high temperature (540 °C) for at least 100,000 service hours. Experimental research with specimens, taken from virgin and used material (117,000 service hours), is performed for better understanding of the effect of long-term exposure to high temperature and high stresses on this steel properties. In addition to classical testing method (tensile test, impact toughness test), local approach to fracture is applied, offering detail analysis of changes caused in service. New designed extensometer is applied for measurement of contraction in the specimen root radius at elevated temperature. The differences between virgin and used steel properties, noticed in tensile test results, are described in better way by local approach method. The premature failure can not be attributed completely to revealed reduction in 14MoV63 steel properties after use and further research is necessary for complete explanation of premature in-service failure of pipes, produced of 14MoV63 steel.

Key words: fracture mechanics, local approach, ductile fracture, steam lines

Introduction

The development of 14MoV63 steel (DIN) for highly loaded steam pipelines in late seventies offered significant benefits compared to the steels of previous generations [1, 2]. It was very popular for steam lines design and construction due to increased steam parameters (temperature up to 540 °C and pressure as high 45 bar for service life of 100,000 operating hours), allowing reduced wall thickness of pipes.

However, frequent premature failures of steam lines produced of this steel, in some cases after only 30,000 service hours, imposed the requirement for retrofit of damaged steam pipelines. Typical examples are steam lines of thermoelectrical power plants in Greece [3] and in Germany [4]. This unexpected repair cost caused the application of 14MoV63 steel ambiguous and the designers prefer to replace it by other, highly alloyed steels (*e. g.* alloyed steel X12CrMoV1, according DIN, low alloyed steel 10CrMo9) for higher steam parameters. There is no clear explanation for failure occurrence, and steel producers claim that steel 14MoV63 is a proper one for intended application 2 . Better understanding of in-service behaviour of 14MoV63 steel can help in reducing forced shutdowns and to improve the reliability and service safety of thermoelectric power plants.

Experimental analysis is performed in order to get more insight in 14MoV63 steel properties decrease when exposed to elevated temperature for long term, corresponding to design service life. The rate of properties decrease and their level after long-term exposure to service temperature is of importance for the evaluation of residual life and for decision about next service of damaged pipes 5 .

The rate of properties decrease can be assessed comparing the data of new and used steel. In addition to microstructure, mechanical and creep properties, the resistance to fracture has to be analysed. New developed method of local approach to fracture 6, 7 can be applied for this purpose. The basic concept of local approach to fracture is to relate the local stresses and strains in considered component volume to the mechanical damage parameters, directly depended on material microstructure and fracture micromechanisms. The fracture parameters, so far developed and recommended by standards, such as stress intensity factor K_I or J integral, cannot confidently define and predict the behaviour of materials under external load in all conditions. Hence, a local approach to fracture is introduced as a promising one, developed in theoretical, experimental and numerical consideration of different stress concentration levels 8 . The purpose of applying the local approach is to define material characteristics in more accurate and less conservative way. This can be achieved by accurately determined stresses, strains and variables, which describe physical damage mechanisms in cracked material.

The specimens, produced from samples taken from new (virgin) and used of 14MoV63 steel have been simultaneously tested. Mechanical properties are evaluated by tensile and impact test. Resistance to fracture has been determined by local approach and analyzed for ductile fracture properties, that is dominant in considered case.

Experimental testing results

Material and specimen preparation

Specified chemical composition of 14MoV63 steel according to standard DIN 17175 is given in tab. 1. The mechanical properties, as prescribed by standard DIN 17175, are given in tab. 2.

Table 1. Chemical composition of 14MoV63 steel

DIN	C	Si	Mn	P_{max}	S_{max}	Cr	Mo	V
17175	0.10-0.18	0.15-0.35	0.30-0.60	0.035	0.035	0.30-0.60	0.50-0.65	0.25-0.35

Table 2. Mechanical properties of 14MoV63 steel at room temperature

Tensile strength R_m MPa	Yield strength R_e MPa	Longitudinal elongation A_l %	Transverse elongation A_t %	Longitudinal impact energy E_l J	Transverse impact energy E_t J
490-690	365	20	18	62	41

The samples of 14MoV63 steel were taken from virgin pipe and used pipe, withdrawn from service after above 117,000 service hours at 540 °C under pressure of 42 bar in steamline because of detected serious damage in elbows and welded joints. Because the wall thickness of virgin and used steels is not the same, the validity of results is proved by hardness measurement across the wall thickness and by metallography, indicating no significant difference.

Following specimens (fig. 1), had been taken from samples for:

- tensile testing – ST,
- impact toughness testing – FT,
- local approach to fracture testing, with notch root radius 2 mm – NT2, 4 mm – NT4, and 10 mm – NT10.
- *J* integral fracture toughness testing – SE(B), and
- *da*/*dN* – fatigue crack propagation assessment – FT.

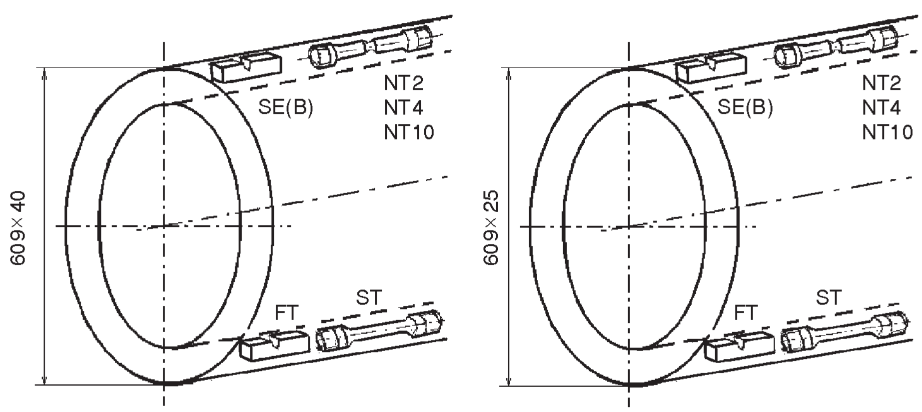

Figure 1. Samples and specimen position in virgin (left) and used pipes (right)

Crack behaviour will be analyzed in last two experiments (*J* integral fracture toughness and *da*/*dN* – fatigue crack propagation) as additional requirement, because final conclusion for premature failure of 14MoV63 steel could not be made based only on the results presented in this paper.

Chemical composition of tested material

The result of chemical analysis of tested samples is given in tab. 3. It is in accordance with specified values given in tab. 1. No significant difference is found in chemical elements content between virgin and used material.

Table 3. Chemical composition of 14MoV63 steel

Steel	C	Si	Mn	P_{max}	S_{max}	Cr	Mo	V
Virgin	0.13	0.20	0.36	0.014	0.021	0.55	0.51	0.28
Used	0.12	0.21	0.36	0.013	0.019	0.56	0.49	0.31

Tensile properties of virgin and used steels

Tensile properties of virgin and used 14MoV63 steels are determined by smooth standard specimens testing. Testing temperatures were 150 and 250 °C, selected as appropriate for next local approach testing. Mechanical properties at 150 °C are necessary as basic data for *J* integral determination. It is to be mentioned that for steels of this class tensile properties have similar values in the region from room temperature up to 150 °C. Higher temperature of 250 °C is selected for plastic analysis in local approach to fracture.

Typical plots, obtained in tensile testing, are presented in fig. 2. Corresponding values for tensile parameters, calculated from plots in fig. 2, are listed in tab. 4.

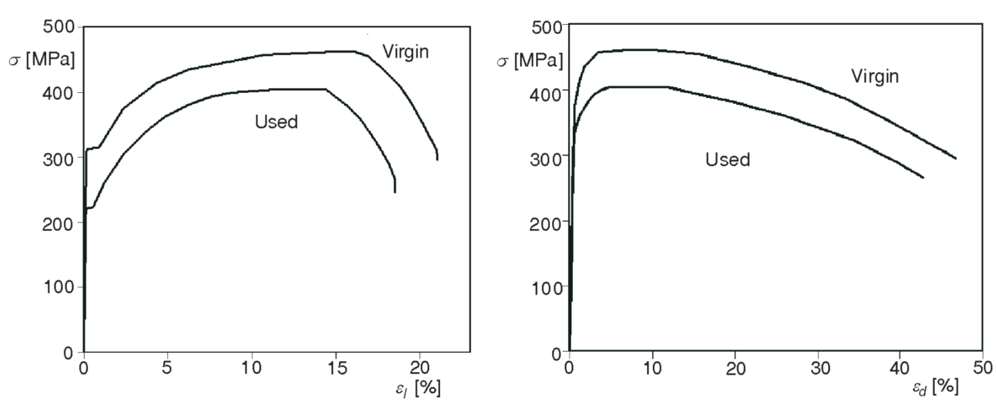

Figure 2. Typical stress – strain diagrams for virgin and used 14MoV63 steel; tensile test at 250 °C, stress – longitudinal strain (left), stress – diameter strain (right)

Table 4. Mechanical properties of virgin and used 14MoV63 steel at 150 and 250 °C

Steel	Temperature [°C]	Tensile strength R_m MPa	Yield stress R_e MPa	Longitudinal elongation A_l %	Transverse elongation A_t %	Young's modulus ε MPa
Virgin	150	490	338	20.6	44.8	198,000
Used	150	435	264	17.8	40.9	197,000
Virgin	250	480	318	21.0	46.7	194,000
Used	250	415	227	18.5	42.7	192,000

Long-term exposure to elevated temperature under operating stresses affects the tensile properties of steel 14MoV63, and this is expressed more in the yield stress than in tensile strength. At higher testing temperature (250 °C) the difference between yield stress and ultimate tensile strength is more expressed. The reduction in elongation is of the same level at both testing temperatures. In general, tensile properties of used steel are still not critical regarding next service.

Impact notch toughness

Using instrumented impact pendulum, it was possible to obtain the relationship force *vs.* time and to separate the energy, necessary for crack initiation from the energy for crack propagation. Typical diagrams are presented in fig. 3. Derived values for all tested specimens are tabulated in tab. 5.

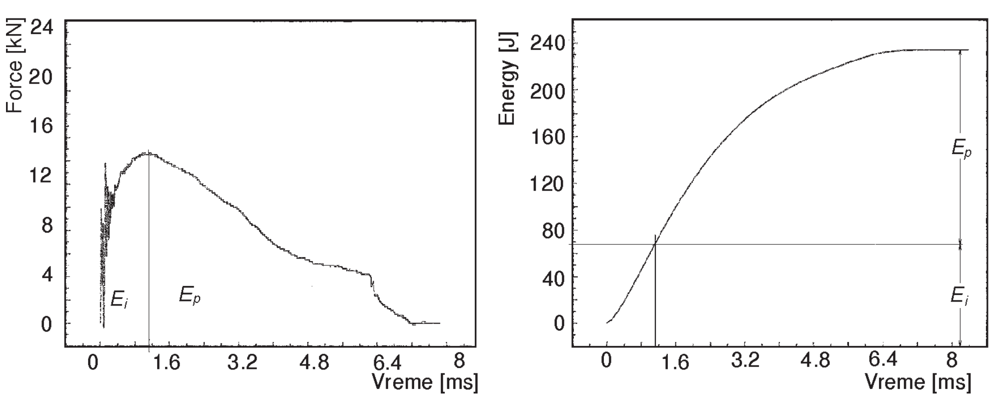

Figure 3. Typical relationships force *vs*. time (left) and energy *vs*. time (right) obtained in instrumented impact test (O-2, 150 °C)

Table 5. Impact notch toughness of virgin (N) and used (O) 14MoV63 steels

Specimen	Testing temperature [°C]	Energy		
		Total E [J]	for crack initiation E_i [J]	for crack propagation E_p [J]
N-1	20	193	74	119
N-2	20	148	72	76
O-1	20	102	66	36
O-2	20	102	77	25
N-1	150	230	67	163
N-2	150	241	64	177
N-3	150	227	57	170
O-1	150	235	65	170
O-2	150	235	68	167
O-3	150	216	54	162

Impact toughness is almost the same for virgin and used steel when tested at 150 °C (tab. 5). Reduction in impact energy at room temperature is expressed only in crack propagation energy, not in crack initiation energy.

Again, as in the case of tensile properties, the reduction in impact toughness is not critical. There is no reduction in impact energy of used steel when testing at 150 °C.

Determination of local approach parameters

Local approach to fracture defined parameters, which describe brittle fracture (cleavage) and ductile fracture (tearing) 9 . Determination of these parameters is based on theoretical, experimental and numerical procedures, proposed by ESIS 7 . In considered case only ductile fracture is of importance because steel is exposed to high temperature.

Theoretical basis of local approach to fracture

Process of ductile fracture initiation is developing through three independent stages:

- void formation due to presence of inclusions;
- void growth, and
- void coalescence 10 .

Voids are formed inside the inclusions or at the boundary inclusion surface during material loading under critical normal stress. These voids are caused by breaking of links, connecting matrix and particles (inclusions and second phase particles). Next stage in ductile fracture development is growth of voids and it is considered as most important. The growth of formed voids is depended on the effect of the external load, which produces additional plastic strain and affects hydrostatic stress component. These affects further growth of voids and eventual coalescence of nearer voids.

Several model are proposed for description of ductile fracture. One of the most frequently applied is the model of Rice and Tracey [11], in which the growth of insulated void in a volume is considered, as presented by the expression:

$$\ln \frac{R}{R_0} \quad 0.283 \exp \frac{3\sigma_m}{2\sigma_{eq}} \, d\varepsilon_{eq}^{p} \tag{1}$$

Here, R/R_0 is void growth rate, R – stands for actual void size, R_0 – for initial void size. Void growth rate can be determined integrating right side from initial value of equivalent deformation to its actual value ε_{eq}^{p}, for each point of calculated values of hydrostatic pressure σ_m and equivalent stress σ_{eq}.

This model takes into consideration stress triaxiality given by ratio of hydrostatic stress σ_m and von Mises equivalent stress σ_{eq}, given by components of stress tensor σ_{ij}:

$$\sigma_m \quad \frac{\sigma_{rr} \quad \sigma_{\theta\theta} \quad \sigma_{zz}}{3} \quad \frac{\sigma_{11} \quad \sigma_{22} \quad \sigma_{33}}{3} \tag{2}$$

$$\sigma_{eq} \quad \sqrt{\frac{1}{2}[(\sigma_{11} \quad \sigma_{22})^2 \quad (\sigma_{22} \quad \sigma_{33})^2 \quad (\sigma_{33} \quad \sigma_{11})^2]} \tag{3}$$

Experimental analysis of notched specimens for local approach to fracture

Design of tensile specimen for experimental analysis is given in fig. 4. Specimens are produced with notch radius r = 10, 4, and 2 mm. In this way triaxiality effect is taken into account, that means the critical void growth, in this way determined local approach parameter, does not depend on geometry. By testing at elevated temperature, in this case 250 °C, ductile fracture is dominant, indicating that in

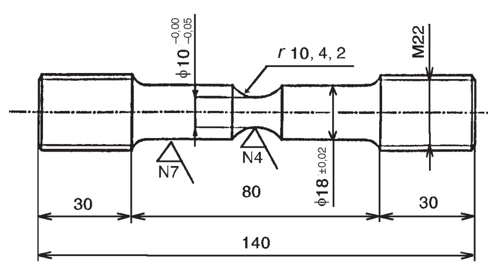

Figure 4. Design of specimen for experimental analysis of local approach to fracture

this case calculated critical void growth does not depend on temperature 9 . For next calculation by FE method true stress – true strain curve has been applied, obtained at the temperature for which calculation is performed. Strain parameter in this case is contraction of the diameter in specimen notch root.

Using the records load *vs*. diameter contraction, fig. 5, true stress *vs*. true strain relationships can be determined for new and used steel, tested at 250 °C (fig. 6). In this way obtained curves will be compared with corresponding curves, obtained by FEM calculation. The reduction in strength and plasticity of used steel is visible. True stress reduction ($\Delta\sigma_F$) is the greatest for notch radius 2 mm, and reduction in plasticity ($\Delta\varepsilon_F$) is most expressed for notch radius 10 mm, indicating that stress concentration is involved in local approach method.

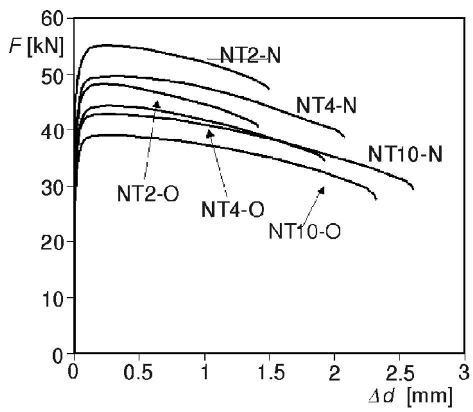

Figure 5. Load (F) *vs*. contraction of notch root diameter (Δd), for virgin (N) and used (O) steel, with notch radius 2 mm (NT2), 4 mm (NT4), and 10 mm (NT10)

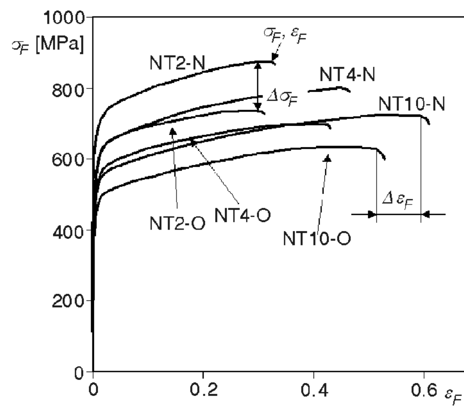

Figure 6. True stress (σ_F) *vs*. true strain (ε_F) relationships for virgin (N) and used (O) steel specimens, with notch radius 2 mm (NT2), 4 mm (NT4), and 10 mm (NT10)

This can be explained by fracture mechanics approach because for plane strain condition critical triaxiality is achieved, and this corresponds to notch root radius 2 mm. Used steel properties degradation produce faster void activation, followed by faster occurrence of critical growth rate and material fracture. For plane stress case, dominated for lower triaxiality level (notch root radius 10 mm), the influence of strain is dominant. In order to obtain an average result, critical void growth should be determined for all three specimen geometries (r = 2, 4, and 10 mm) 7 .

Calculation of local approach parameters

In order to determine void growth rate R/R_0 according to eq. (1), for ductile fracture parameters calculation, equivalent uniaxial strain $\bar{\varepsilon}_F$ and true stress $\bar{\sigma}_F$ values are required, defined as:

$$\bar{\varepsilon}_F = 2\ln\frac{d_0}{d_F} \tag{4}$$

and

$$\bar{\sigma}_F = \frac{4F_F}{\pi d_F^2} \tag{5}$$

The initial value of diameter in root radius, d_0, and its final value, d_F, as well as fracture load, F_F, can be obtained in tensile testing of notched round bar specimens, presented in fig. 7.

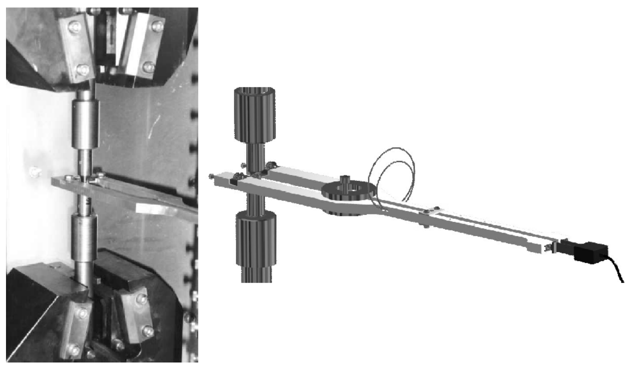

Figure 7. Diametric extensometer (measuring range 10 mm, accuracy 0.01%, applicable up to the temperature +600 °C); elevated temperature cabinet with prepared specimen (left), design of extensometer (right)

The calculation is carried out using a post-processor program [7]. The cavity growth rate R/R_0 is calculated in each mesh element using the equivalent uniaxial strain and true stress averaged values of the strains and stresses, respectively, over the Gauss points. Critical cavity growth rate $(R/R_0)_c$ can be obtained by replacing von Mises equivalent stress, σ_{eq}, eq. (2), and triaxial stress state, σ_m, eq. (3), which represents hydrostatic stress. This can be explained as follows: true stress – true strain curves obtained by testing the specimens with three different notch root radii, are compared with corresponding curves, obtained by FEM analysis. When sufficient agreement between two sets of curves [7] is achieved, critical void growth rate can be calculated according eq. (1). The hydrostatic stress σ_m value is determined from maximum normal stress components, obtained in a finite element critical node, positioned in the minimum cross-section of specimen axes. It is marked by CN (centre node) in fig. 8. Von Mises equivalent stress σ_{eq} is calculated in the same node.

FEM calculation is performed by elastic-plastic analysis in NASTRAN software, using 3D elements. Upper specimen half is modeled as a wedge element, with angle of 5°, corresponding to 1/72 part of upper specimen part. This affects the shape of

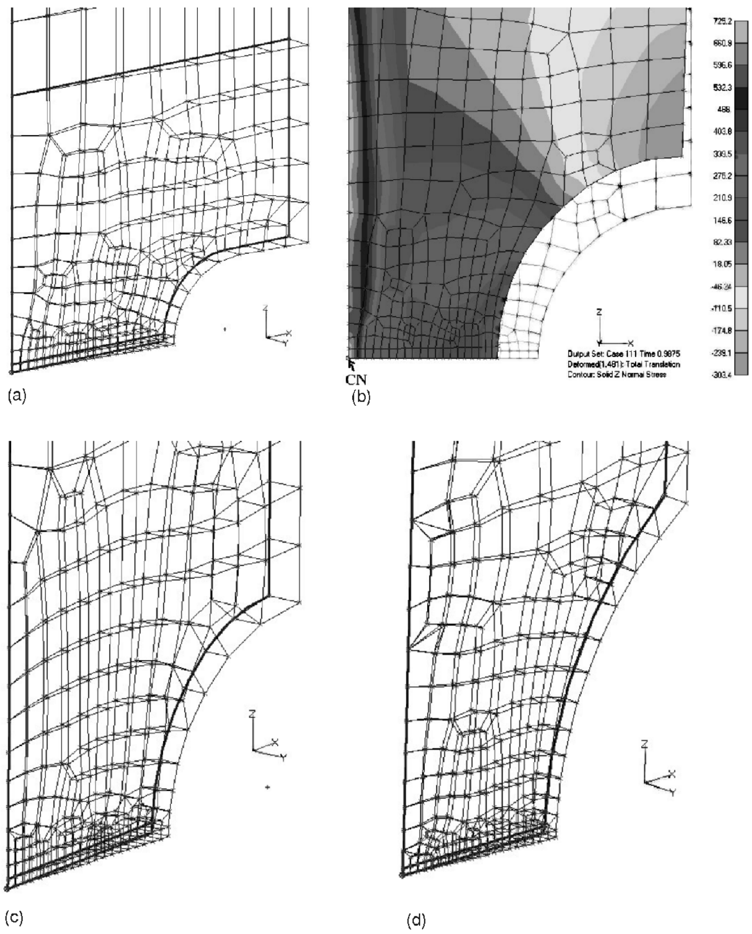

Figure 8. Notched tensile specimen mesh; (a) mesh for notch root radius $r = 2$ mm, (b) stress distribution for $r = 4$ mm, (c) mesh for $r = 4$ mm, and (d) mesh for $r = 10$ mm

finite elements mesh, producing wedge type elements around axes, and the other elements are of brick type.

Calculated local criterion is material characteristic, representing local stress state, which corresponds to critical void growth and next unstable fracture. This material characteristic is a convenient form, directly applicable in FEM calculation. That means, when high stress level is found in a structure and void growth rate R/R_0 is verified, at the critical $(R/R_0)_c$ level, failure of structure can be expected. From engineering point of view this verification should be performed for maximum load, *e. g.* for ultimate tensile strength, $(R/R_0)_m$. This should be the indication for critical behaviour of a structure.

Five specimens of virgin and of used steel and each geometry had been tested for determination of values of critical void growth rate R/R_0 vaules and void growth rate R/R_0, corresponding to ultimate tensile strength. Critical value of void growth rate, corresponding to final fracture, is designed by subscript *c*, and the value of void growth rate, corresponding to maximum loading, *e. g.* to ultimate tensile strength, is designed by subscript *m*. For presentation of these results only average values are used, because the large number of tested specimens. In tab. 6 three columns are used to present average values of measurement of five specimen, taken from virgin (N) and used steel (O) for three geometries (notch root radius 10 mm, 4 mm, and 2 mm). Last three columns present final average values of critical void growth rate $(R/R_0)_c$ and void growth rate $(R/R_0)_m$, corresponding to maximum load (ultimate tensile strength). Solution of eq. 1 produces $\ln(R/R_0)$, and in this form values of void growth rate R/R_0 start from 1, because $\ln(R/R_0)= 0$. For this reason the values $R/R_0 - 1$ should be used in comparison of obtained results.

The bearing capacity of steel is exhausted when maximum load is reached, *e. g.* for ultimate tensile strength. For that, this value of void growth rate $(R/R_0)_m$, is relevant and should be taken for comparison, and not critical value defined in local approach, $(R/R_0)_c$. This is also the explanation in difference for the values $(R/R_0)_c$ and $(R/R_0)_m$ in tab. 6.

Table 6. Value of void growth rate for final fracture $(R/R_0)_c$ and maximum load $(R/R_0)_m$

Specimen	Average values for 5 specimens				Final average values			
	$\ln(R/R_0)_c$	$\ln(R/R_0)_m$	$(R/R_0)_c$	$(R/R_0)_m$	$\ln(R/R_0)_c$	$\ln(R/R_0)_m$	$(R/R_0)_c$	$(R/R_0)_m$
10N	0.6136	0.0792	1.8470	1.0824				
4N	0.5467	0.0751	1.7275	1.0780	0.5131	0.0734	1.68	1.08
2N	0.3790	0.0659	1.4609	1.0682				
10O	0.5612	0.0742	1.7670	1.0770				
4O	0.4855	0.0702	1.6250	1.0727	0.4526	0.0688	1.59	1.07
2O	0.3112	0.0621	1.3650	1.0641				

Analysis of results

Tensile properties of used steel are reduces compared to corresponding values of virgin steel for both testing temperatures (150 and 250 °C), as given in tab. 4. This reduction percentage is expressed in tab. 7. Tensile properties reduction is more expressed at higher testing temperature (250 °C). The reduction is most expressed for yield stress.

Table 7. Reduction of tensile properties of used steel compared to the values of virgin steel

Temperature t °C	Ultimate tensile strength R_m [%]	Yield stress R_e [%]	Longitudinal elongation A_l [%]	Transverse elongation A_t [%]
150	11.2	22	14	8.71
250	13.5	29	12	8.77

Impact toughness is not convenient parameter for comparison, because there is no significant differences in values for virgin and used steel at room temperature, and at 150 °C, as it is given in tab. 5. Nil ductility transition temperature for this steel is above room temperature, and this explains significantly higher values of impact toughness at 150 °C.

Percentage in void growth rate R/R_0 reduction is presented in tab. 8 for final fracture and for maximum load values. As it is already said, for the proper analysis of steel degradation, the value corresponding to maximum load should be used, *e. g.* $(R/R_0)_m - 1$.

Table 8. Reduction of void growth rate R/R_0 for used steel

$\ln(R/R_0)_c$ [%]	$\ln(R/R_0)_m$ [%]	$(R/R_0)c$ [%]	$(R/R_0)_m$ [%]	$(R/R_0)_c - 1$ [%]	$(R/R_0)m - 1$ [%]
11.8	6.3	5.5	0.5	13.7	6.5

Comparison of properties degradation at 250 °C shows that the reduction is more expressed for tensile strength R_m (13.5%, tab. 7), than for corresponding void growth rate $(R/R_0)_m$, given through $(R/R_0)_m - 1$, (6.5%, tab. 8). This is the indication of conservatism of classical approach. In addition, ductile fracture criterion, applied in local approach, is directly applicable in FE method, defining limit stress value in a structure.

Conclusion

Required accordance of records, obtained by notched specimens tensile testing, and of diagrams, obtained by FEM analysis, is a prerequisite for calculation of local criterion for ductile fracture. In this way material's characteristics, precisely describing material properties, are available for modern computational methods, such as FEM.

Described properties of local approach to fracture enabled more precise evaluation of degradation of steel 14MoV63 properties after long-term exposure to elevated temperature. Obtained results have shown that maximum load in tensile test of notched specimens, not the value at final fracture, is a proper one for the comparison of virgin and used steel properties. The reduction in void growth rate capacity, obtained in performed experiment is only 6.5%, whereas expressed in term of tensile strength is 13.5%, and finally, expressed through yield stress is as high as 39%.

It is possible to conclude that considered steel can be used for next service, although specified service life is spent, under condition to prescribe proper in-service inspection. The economical benefit could be significant. Anyhow, further development in local approach to fracture is necessary for its practical application.

Nomenclature

A_l – longitudinal elongation, [%]
A_t – transverse elongation, [%]
d_F – initial diameter value in noth root, [mm]
d_0 – final diameter value in noth root, [mm]
E – Young's modulus, [GPa]
E_i – impact energy for crack initiation, [J]
E_l – longitudinal impact energy, [J]
E_p – impact energy for crack propagation, [J]
E_t – transverse impact energy, [J]
F – load, [kN]
F_F – fracture load, [kN]
J – path independent J integral, [kJ/m^2]
K_I – stress intensity factor, [MPa·m$^{1/2}$]
R – actual cavity radius, eq. (1), [μm]
r – notch root radius, [mm]
R_e – yield stress, [MPa]
R_m – ultimate tensile strength, [MPa]
R_0 – initial cavity radius, [μm]
$(R/R_0)_c$ – critical value of cavity growth rate
$(R/R_0)_m$ – relevant value of cavity growth rate
t – time, [s]

Greek symbols

Δd – reduction of notch root diameter, [mm]
$\Delta\varepsilon_F$ – reduction in plasticity
$\Delta\sigma_F$ – true stress reduction, [MPa
ε_d – diameter strain
ε_{eq}^p – equivalent strain, [%]
ε_F – true strain, [%]
$\bar{\varepsilon}_F$ – average fracture strain, [%]
ε_l – longitudinal strain
σ – conventional engineering stress [MPa]
σ_{eq} – Von Mises equivalent stress, [MPa]
σ_F – true stress, [MPa]
$\bar{\sigma}_F$ – average fracture stress, [MPa]
σ_m – hydrostatic stress, [MPa]

$\sigma_{rr}, \sigma_{\theta\theta}$,
σ_{zz} – maximum principal stress – polar co-ordinate system, [MPa]
σ_{11}, σ_{22},
σ_{33} – maximum principal stress, [MPa]

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