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Procedia Structural Integrity 18 (2019) 385–390

Structural Integrity
Procedia

www.elsevier.com/locate/procedia

25th International Conference on Fracture and Structural Integrity

Integrity and Life Assessment Procedure for a Reactor

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Abstract

Integrity and life assessment of structural elements or structures subjected to variable loads is necessary in order to define the control interval and removal of damages that occurred during exploitation. Integrity and life assessment of a reactor was carried out with the previously performed welding technology qualification for new and exploited parent material sheets, made of Cr-Mo steel A-387 Gr. B, with a thickness 102 mm. Exploited parent material is the part of a reactor mantle which was in exploitation for over 40 years and is in the repair stage, i.e. its mantle is being replaced with the new material. Obtained test results and their analysis should provide a practical contribution to the assessment of exploitation conditions effects on the behaviour of parent material, welded joint components and the pressure vessel (reactor) used for exploitation at elevated temperatures, all for the purpose of integrity and life assessment of the structure, along with the revitalisation and work life extension of process equipment (reactor), made of steel used for exploitation at elevated temperatures.

Peer-review under responsibility of the Gruppo Italiano Frattura (IGF) ExCo.

Keywords: reactor; welded joint; crack; integrity; remaining life.

1. Introduction

The long period of exploitation of a pressure vessel-reactor (over 40 years), caused certain damages to the reactor mantle. The occurrence of these damages required a thorough examination of the reactor, as well as the repair of damaged parts. Reactor repairs included the replacing of the reactor mantle with a newly built-in material. The pressure vessel in question was made of low-alloyed Cr-Mo A-387 Gr. B according to ASTM standard with 0.8-1.15% Cr and 0.45-0.6% Mo. For the designed working parameters (p = 35 bar and t = 537 °C), the material falls into the area of tendency towards decarbonisation of surfaces in contact with hydrogen. Surface decarbonisation can result in reduced material strength. The reactor's structure is a vertical pressure vessel with a cylindrical mantle. Two deep lids were welded on the upper and lower part of the mantle, of the same quality as the mantle itself. The most important process of motor oil manufacturing takes place inside this reactor, and it involves the platforming, for the purpose of changing of the structure of hydrocarbon compounds and achieving of higher octane numbers. Welding procedure qualification for plates made of new and exploited PM was performed in accordance with standard SRPS EN ISO 15614-1, [1]. Tests not prescribed by this standard, which are necessary for remaining life and integrity assessment include working temperature tests (at 540°C),

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Peer-review under responsibility of the Gruppo Italiano Frattura (IGF) ExCo.
10.1016/j.prostr.2019.08.179

as well as additional tests of properties of new and exploited PM and welded joint components (weld metal - WM and heat affected zone – HAZ). Additional tests involved the determining of critical stress intensity factor K_{Ic}, critical crack length ac and fatigue crack growth parameters (da/dN i ΔK_{th}) of the PM, WM and HAZ, at room and working temperatures [2-4]. The goal of experimental research and measuring of stress and strain state was to assess the integrity and remaining life of the reactor, i.e. the prediction of remaining life in terms of exploitation conditions (working temperature and pressure), [2-7].

2. Test materials

Both exploited and new PM was steel A-387 Gr. B with thickness of 102 mm. Chemical composition and mechanical properties of the exploited and new PM are given in tables 1 and 2, [7].

Table 1. Chemical composition of exploited and new PM specimens

Specimen designation	% mas.							
	C	Si	Mn	P	S	Cr	Mo	Cu
E	0,15	0,31	0,56	0,007	0,006	0,89	0,47	0,027
N	0,13	0,23	0,46	0,009	0,006	0,85	0,51	0,035

Table 2. Mechanical properties of exploited and new PM specimens

Specimen designation	Yield stress, Rp0.2, MPa	Tensile strength, Rm, MPa	Elongation, A, %	Impact energy, J
E	320	450	34,0	155
N	325	495	35,0	165

Welding of steel sheets made of exploited and new PM was performed in two stages, according to the requirements given in the welding procedure specification:

- Root weld by E procedure, using a coated LINCOLN S1 19G electrode (AWS: E8018-B2), and
- Filling passes by submerged arc welding, with wire LINCOLN LNS 150 and powder LINCOLN P230.

Chemical composition of the coated electrode LINCOLN S1 19G, and the wire LINCOLN LNS 150 according to the attest documentation is given in tab. 3, whereas their mechanical properties, also according to documentation, are given in tab. 4, [7].

Table 3. Chemical composition of additional welding materials

Filler material	% mas.						
	C	Si	Mn	P	S	Cr	Mo
LINCOLN Sl 19G	0,07	0,31	0,62	0,009	0,010	1,17	0,54
LINCOLN LNS 150	0,10	0,14	0,71	0,010	0,010	1,12	0,48

Table 4. Mechanical properties of filler materials

Filler material	Yield stress, Rp0,2, MPa	Tensile strength, Rm, MPa	Elongation, A, %	Impact energy, J at 20°C
LINCOLN Sl 19G	515	610	20	> 60
LINCOLN LNS 150	495	605	21	> 80

3. Integrity and remaining life of a reactor in exploitation

Even though loads with constant amplitudes are rarely encountered in practice, the largest number of experimental data in form of empirical law, $da/dN=f(\Delta K,R)$ is provided for these load variations. This means that the changes of ΔK during crack growth are incremental, in order to reduce the eventual interaction effect of loads to a minimum. Empirical law in given form is successful in describing crack growth for such conditions, whereas corresponding material constants C and m in its specific form $da/dN=C(\Delta K)^m$, i.e. Paris law, are adjusted to satisfy the experimental results. Due to this, such idealized conditions can be used for predicting of fatigue life of components subjected to loads with approximately constant values of ΔK and R range. Assuming the change is known, [10]:

$$\frac{da}{dN} = f\left(\Delta K, R\right), \text{ i.e. } dN = \frac{da}{f\left(\Delta K, R\right)} \tag{1}$$

Life is determined by integrating eq. 1:

$$\Delta N = \int_{a_0}^{a_d} \frac{da}{f(\Delta K, R)} \tag{2}$$

Since the function $f(\Delta K,R)$ is typically composite, the solution of this integral can be rarely determined in closed form, thus the integration must be carried out numerically. The simplest form of function $f(\Delta K,R)$ is the Paris model, thus expression 2 now becomes. [10]:

$$\Delta N = \frac{1}{C} \int_{a_0}^{a_d} \frac{da}{\left[Y\left(\frac{a}{W}\right) \Delta\sigma\sqrt{\pi a} \right]^m} \tag{3}$$

where ΔN is the number of cycles needed for crack growth, from initial crack length a_0 to critical length a_c. The correction factor $Y = Y(a/W)$ for a crack in a component is typically represented as a long polynomial or in table form, thus assuming that $\Delta\sigma$ = const. and that it does not depend on a, numerical integration imposes itself as the solution. Such integration is best solved using computers, although even without them the procedure is not unacceptably long. It should be pointed out that during the aforementioned linear integration procedures, positive retardation is not taken into account, thus the results obtained are conservative, from the safety standpoint.

In the case that the first approximation is adopted so that Y does not depend on crack length a, equation 3 can be written as:

$$\Delta N = \frac{1}{C\left[Y\Delta\sigma\sqrt{a} \right]^m} \int_{a_0}^{a_d} a^{-\frac{m}{2}} da \tag{4}$$

thus, after integration, the solution is obtained in closed form as:

$$\Delta N = \frac{1}{C\left[Y\Delta\sigma\sqrt{a} \right]^m} \cdot \frac{a_0^{\left(1-\frac{m}{2}\right)} - a_d^{\left(1-\frac{m}{2}\right)}}{\frac{m}{2} - 1} \tag{5}$$

It should be pointed out that this approximation leads to a non-conservative solution compared to solutions which take into account that $Y = Y(a)$ and which need to be determined using numerical methods [10].

Structural integrity and remaining life assessment of the reactor, for a nearly constant amplitude load, similar to loads in exploitation, i.e. the number of cycles necessary for crack growth from initial to critical length, is calculated using equation 5.

Input test parameters are the following:

- **Location of the potential crack**, i.e. whether it occurs in the PM, WM or the HAZ
- **Initial crack** is the crack which can be detected by external non-destructive test methods, and for the reactor in question, it must not exceed 5 mm in length.
- **Load variation in the reactor**, from the least favourable case, wherein the stress σ is close to yield stress $R_{p0.2}$ of the tested material (211 MPa), to the real working mode, i.e. the levels of maximum working stress for the reactor in question, measured using tensometry, in exploitation (46 MPa), [5,7].
- **Critical (allowed) crack length**, which was varied from 5 mm to critical crack length a_c, obtained by fracture mechanics parameters testing at working temperature of 540°C, for new and exploited PM, WM and HAZ, on both new and exploited PM sides.
- **Paris equation constants, *C* and *m*,** determined by fatigue crack growth parameter testing, at temperature of 540°C, for new and exploited PM, WM and HAZ, on new and exploited PM sides [4].
- **Coefficient *Y*, a geometric term,** which depends on the ratio of crack length and reactor PM thickness, and can be found in literature [2], for the case of a surface cracks and for different *a/W* ratios.

Results of remaining life assessment of the reactor, i.e. the number of cycles ΔN, are shown in tables 5 and 6 for new and exploited PM, table 7 for WM and tables 8 and 9 for HAZ, from new and exploited PM sides, while taking into account that reactors in exploitation are constantly subjected to variable loads.

Table 5. Remaining exploitation period-crack in the PM

Load case	Geometry term, *Y*	Stress range, $\Delta\sigma$, MPa	Assumed crack length, *a*, m	Initial crack length a_0, mm	Critical crack length, a_c, mm	Number of cycles, ΔN
I	5.58	211	0.01	5	41	160641
	6.01		0.02			46618
	6.45		0.03			20868
	6.91		0.041			10767
II	5.58	46	0.01	5	41	14149448
	6.01		0.02			4106189
	6.45		0.03			1838105
	6.91		0.041			948389

* Applies in the case of initial crack length of 5 mm.

In the case of a crack in the PM: C = 1.52 · 10-10. m = 2.94

Table 6. Remaining exploitation period-crack in the PM

Load case	Geometry term, *Y*	Stress range, $\Delta\sigma$, MPa	Assumed crack length, *a*, m	Initial crack length a_0, mm	Critical crack length, a_c, mm	Number of cycles, ΔN
I	5.58	211	0.01	5	29	20521
	6.01		0.02			9622
	6.21		0.025			7421
	6.41		0.029			6329
II	5.58	46	0.01	5	29	318383
	6.01		0.02			149276
	6.21		0.025			115128
	6.41		0.029			98199

* Applies in the case of initial crack length of 5 mm.

In the case of a crack in the PM: C = 1.48 · 10-8. m = 1.80

Table 7. Remaining exploitation period-crack in the WM

Load case	Geometry term, Y	Stress range, $\Delta\sigma$, MPa	Assumed crack length, a, m	Initial crack length a0, mm	Critical crack length, ac, mm	Number of cycles, ΔN
I	6.01	211	0.02	5	63.5	196096
	6.45		0.03			98731
	6.88		0.04			58520
	7.21		0.05			39320
	7.65		0.06			26957
	7.81		0.0635			23834
II	6.01	46	0.02	5	63.5	8972132
	6.45		0.03			4517323
	6.88		0.04			2677509
	7.21		0.05			1799030
	7.65		0.06			1233369
	7.81		0.0635			1090506

* Applies in the case of initial crack length of 5 mm.

In the case of a crack in the WM: C = 1.26 · 10-9. m = 2.51

Table 8. Remaining exploitation period-crack in the HAZ (new PM side)

Load case	Geometry term, Y	Stress range, Δσ, MPa	Assumed crack length, a, m	Initial crack length a0, mm	Critical crack length, ac, mm	Number of cycles, ΔN
I	5.58	211	0.01	5	32	70053
	6.01		0.02			24775
	6.45		0.03			12611
	6.51		0.032			11382
II	5.58	46	0.01	5	32	3015732
	6.01		0.02			1066565
	6.45		0.03			542903
	6.51		0.032			489975

* Applies in the case of initial crack length of 5 mm.

In the case of a crack in the HAZ from the new PM side: C = 9.61 · 10-10. m = 2.47

Table 9. Remaining exploitation period-crack in the HAZ (exploited PM side)

Load case	Geometry term, Y	Stress range, Δσ, MPa	Assumed crack length, a, m	Initial crack length a0, mm	Critical crack length, ac, mm	Number of cycles, ΔN
I	5.58	211	0.01	5	27	17470
	6.01		0.02			6554
	6.21		0.025			4682
	6.39		0.027			4005
II	5.58	46	0.01	5	27	607655
	6.01		0.02			227949
	6.21		0.025			162859
	6.39		0.027			139303

* Applies in the case of initial crack length of 5 mm.

In the case of a crack in the HAZ from the exploited PM side: C = 5.5 · 10-9. m = 2.33

4. Discussion

Results shown in tables 5-9 indicate that the remaining work life of the reactor, i.e. the number of cycles ΔN until critical crack length is achieved, depends on:

- Assumed crack length a;
- Allowed stress range, $\Delta\sigma$, and
- Crack initiation location

The greater the assumed crack length and the range of allowed stress, the lower the number of cycles until the potential catastrophe and uncontrolled failure. Under the assumed working loads (stresses), equal to yield stress in exploitation conditions ($R_{p0.2}$ = 211 MPa), the number of cycles needed to reach critical crack length is very low, tables 5-9. This was expected, having in mind that this is low-cycle fatigue, i.e. the acting loads are close to yield stress value, [5,7].

In the case when the assumed work load is real, i.e. the load determined by tensometry of the reactor, with a magnitude of 46 MPa, the number of cycles needed to reach critical crack length is considerably greater, since the stress levels are lower. However, despite the lower stresses, it is still above the fatigue threshold stress, $\Delta K_{th},$ and thus, assumed crack growth happens anyway, [3,7].

Furthermore, in this analysis, the location of the potential crack was also taken into account, in terms of whether it occurred in the PM, WM or HAZ. Additionally, the effect of exploitation time was analysed, i.e. it was determined whether the crack occurs in the new or exploited PM or HAZ from the new or exploited PM sides. The effects of heterogeneity of the structure of welded joint components is directly reflected on the fatigue crack growth rate, da/dN, i.e. it is directly related to certain Paris equation parameters, coefficient *C* and exponent *m*.

Based on tables 5-9, for the case of real load of 46 MPa, it can be seen that:

In the case that the initial crack (with a length of 5 mm) in the new PM reaches the critical length of 41 mm, the exploitation period is 25.7 years, whereas the period required for the initial crack of the same length in the exploited PM to reach the length of 29 mm is 4.6 years.

In the case that the initial crack (5 mm) in the WM reaches the critical length of 63.5 mm, the exploitation period is 29.6 years.

For cracks with initial length of 5 mm in the HAZ on the new PM side, the critical length is 32 mm, and the exploitation period is 21.4 years. For the case of the same crack in the exploited PM side HAZ, the critical length is 27 mm, and the exploitation period is 4.1 years.

5. Conclusion

Since structural safety is assessed based on the weakest structure component, it can be seen that in the case of real load of 46 MPa, and for the case where the crack had an initial length of 5 mm, which increased to a critical length of 27 mm, the exploitation period is 4.1 years, for the exploited PM side HAZ. Such conclusion necessitates a permanent control of the reactor work technological process, along with the NDT control of all critical locations of the reactor, including the PM.

Obtained test results represent a practical contribution to exploitation conditions effects on structural integrity and remaining life of pressure vessels (reactors) used for working at elevated temperatures.

6. Acknowledgement

Parts of this research were supported by the Ministry of Sciences and Technology of Republic of Serbia through Mathematical Institute SANU Belgrade Grant OI 174001 and OI 174004.

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