RESIDUAL LIFE ASSESSMENT OF PIPELINE BEND BY A METALLOGRAPHIC MEASUREMENT OF CAVITATION DAMAGE-DETERMINATION OF THE “A” PARAMETER

D. MILANOVIĆ

"Janko Lisjak", Belgrade, Yugoslavia

V. ŠIJAČKI-ŽERAVČIĆ, A. MARKOVIĆ and RADOVIĆ

Faculty of Mechanical Engineering, Belgrade, Yugoslavia

ABSTRACT

Remaining life for power plant components in case of creep is estimated by applying various techniques, usually destructive, non-destructive or analytical. The non-destructive method occasionally applied consists in the determination of the metallographic parameter "A", i.e., a quantity that represents a grain boundary damage fraction relative to the total number of boundaries observed in the direction of main normal stress. Service life assessment of pipeline bend, operating under conditions of cca. 530°C temperature and 100MPa stress, has been carried out with the use of this method.

KEYWORDS

Fossil power plant, remaining service life, creep damages, method of "A" parameter

INTRODUCTION

Fossil power plant components, with emphasize on pipelines, are exposed to the high service temperatures were creep deformation mechanism is dominant beside other temperature-time dependent processes. These processes are the main cause of structure degradation, i.e., properties of pipeline steels that is leading to the damage and complete failure of components. Therefore, considering all problems connected with new plants building (economic difficulties) there is a great need for more precise residual life assessment prediction of plants components, especially those exposed to the high working parameters, which includes pipelines too. Two basic principles for residual life assessment of fossil power plants (and other constructions were similar steels are used) can be found in literature /1/:

(i) Method based on life fraction rule for creep consumed from the stress and temperature history connected with uniaxial stress rupture data for component material.

(ii) Method based on evolution of creep strain/creep damage accumulation of particular component through the dimension control, microstructural sampling or post-exposure testing.

Method (ii) is more complete than method (i) because scatter problem in the data or the material can be overcame. Besides, for the method (i) it is necessary to know mechanical and other properties of the material already in use, because all properties change during the exploitation. This kind of data can be obtained only by destructive testing, which can lead to some difficulties in the residual life assessment with method (i). On the other side, method (ii), for the steels in exploitation, requires understanding and quantitative knowledge of following process /1/:

- structural degradation leading to a continuos reduction in creep strength during service exposure
- intergranular creep cavitation

"A" parameter value /2/ represents quantitative measure for distribution of creep damage, and applied in creep-damage constitutive equation's /1,3,4/ it is giving the residual service life. It means that with the "A" parameter, as well as the calculated and experimental results of material density changes during creep damage /5/ or creep-damage results obtained by ultrasonic velocity investigation /6/, influence of the processes, which are defining the micro behavior of the material during the exploitation, are included in the model of macro behavior of the material, expressed by creep damage constitutive equations.

Method of "A" parameter, verified in this paper on two different power plant pipelines made of 0.5Cr0.5Mo0.25V steel that operates under 100 MPa stress and temperature about 530°C, values common for such installations.

THEORETICAL BASIS OF THE "A" PARAMETER METHOD

"A" parameter method is usually applied on the materials where the main cause for the brittle intergranular failure in the creep conditions is cavity nucleation on the grain boundaries, their growth and linkage into the cracks. Low alloyed ferritic pipeline steels belong to such group of materials. Therefore, it is necessary to know the constitutive equations of damage accumulation during creep, cavity growth, failure mechanism for the material.

Because power plant components are during their service life in the secondary creep stadium, where the creep rate is minimal and constant, equations for that period are used. Using formalism of continuum damage mechanics, following dependencies for creep rate damage accumulation rate are given:

$$\varepsilon = f(\sigma,\omega) \tag{1}$$

$$\omega = g(\sigma,\omega) \tag{2}$$

where σ is the stress, and ω ($0 \le \omega \le 1$) is the dimensionless parameter that is determining damage degree connected with the current damage processes. ω is introduced by Chachanov /7/ and Rabotnov /8/ model of creep damage, and enhanced by Cane /1/. For damage measurements to reflect $|t/t_f|$ (where tf is time to rupture) uniquely under variable loading patterns, two conditions have to be met /3/:

(a) There must be a single dominant damage mechanism through the ranges of stresses, temperatures and environments encountered in service;

(b) The damage rate equation given by eqn. (2) should be a separable function of σ and ω/9/.

Deformation mechanism map /10/ presents that deformation mechanism include grain boundary diffusion area and dislocation creep area (low temperature power low creep) for power plant pipeline service parameters in intervals $10^{-3} < \sigma/G < 10^{-4}$ and $0.3 < T/Tm < 0.4$ for low alloy ferritic steels. Characteristic of these steels, including 0.5Cr0.5Mo0.25V, is that, at the same time, precipitation (secondary particles precipitation) and dispersion strengthening take place. Conservatism of prediction, because of difference between deformation rate for grain boundary diffusion $(\varepsilon \propto \sigma)$ and deformation rate of power low creep $(\varepsilon \propto \sigma^n)$, is giving advantage to the dominant mechanism, i.e.:

$$\varepsilon = B\sigma^n \tag{3}$$

where B and n are temperature dependent material constants.

Fracture-mechanism maps /10/ shows that rupture mechanism of metal can be applied for 0.5Cr0.5Mo0.25V steels in previously mentioned service conditions. For this map region, characteristic brittle intercrystal fine failure is caused by linking of cavities on grain boundaries, and with accepting it as a dominant mechanism, high conservative predictions are conceivable.

Cavity growth mechanism maps /12/ shows that low alloy heat resistant steels are characterized with possible following cavity growth mechanisms: source-controlled growth (limited by the availability of dislocation sources), diffusion controlled growth, continuum (plastic) growth and constrained growth (rapid cavitation is constrained by creep of the surrounding cavity-free regions). When cavities are large (near linkage), geometrically constrained growth pertains at stresses < 200 MPa /2,12/. It means that geometrically constrained growth, for power plant pipeline service conditions, is an upper bound to cavity growth and thus should lead to conservative life assessment. Mechanical model of constrained growth is given on Fig. 1 /2/ and it can explain "A" parameter appliance as a quantitative measure for distribution of creep damage in eqns. (1) and (3) instead ω parameter. It is obvious from Fig. 1 that normal stress on cavity boundaries must be decreased, and therefore normal stress on boundaries without cavities has to be increased. Reason for that is partial stress redistribution by normal stress acting on two bicrystalls simultaneously. This is unlikely because for the same deformation rate of damaged and undamaged bicrystall boundaries is the main cause for partial stress redistribution. Fig. 1b presents the case of total stress redistribution when cavity boundaries are completely destroyed.

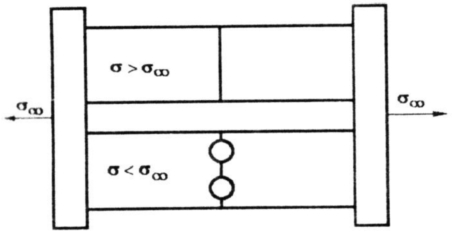


Fig. 1a. Partial stress redistribution

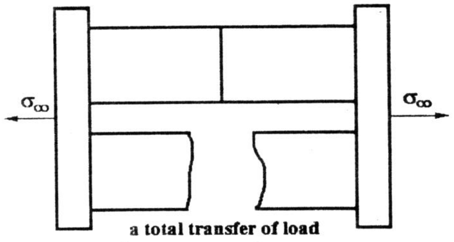


Fig. 1b. Total stress redistribution

According to the (1), (2) and (3) /1,2/, follows:

$$\varepsilon = \frac{B\sigma^n}{(1-A)^n} \tag{4}$$

$$A = \frac{C\sigma^\nu}{(1-A)^\eta} \tag{5}$$

where C, υ and η are material constants, and "A" parameter is:

$$A = \frac{\text{number of damaged boundaries through intersecting line}}{\text{total number of grain boundaries through intersecting line}} \tag{6}$$

where the intersecting line is following the direction of principle stress. It is obvious from (4) and (5), as well as theoretical basis, that conditions (a) and (b) have been fulfilled. Integrating above equations (4) and (5) under the constant stress and relevant constraints, a dimensionless equation relating "A" life fraction and λ is obtained /1,2/.

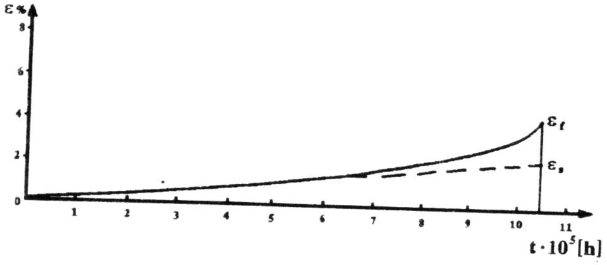
$$(1-A)=\left(1-\frac{t}{t_f}\right)^{\frac{\lambda-1}{n\lambda}} \qquad (7)$$

where λ is:

$$\lambda=\frac{\varepsilon_f-\varepsilon_p}{\varepsilon_s}\approx\frac{\varepsilon_f}{\varepsilon_s} \qquad (8)$$

Substraction of deformation ε_p in a primary creep is permitted because it is negligible for low alloyed heat resistant ferritic steels. Transforming equation (7) and solving for residual lifetime t_{res} in function of previous exploitation period t_{exp}, following expression is obtained /2/:

$$t_{res}=t_{exp}\left\{\frac{1}{\left[1-(1-A)^{\frac{\lambda-1}{n\lambda}}\right]}-1\right\} \qquad (9)$$



14MoV63 (DIN 17 175)

σ=108 MPa, τ=530°C

$$\varepsilon=\frac{\varepsilon_f-\varepsilon_p}{\varepsilon_s}\approx\frac{\varepsilon_f}{\varepsilon_s}=1.68$$

Fig. 2. Determination of λ coefficient from creep curve

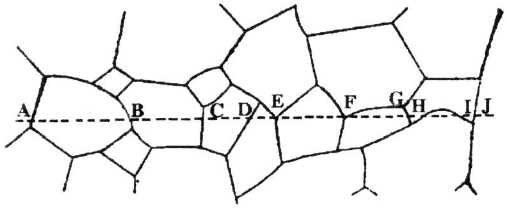
This expression is providing residual service life, and input parameters are "A", λ and n parameters. Determination of "A" parameter is directly from replicas, or from specimens (possible differences are negligible /2/), while coefficient λ is measured from creep curve for investigated material, Fig. 2. Value of n is provided from literature or from experimental measurements.

DETERMINATION OF "A" PARAMETER

According to the equation (6) "A" parameter is determined by counting grain boundaries with cavities orthogonal to the line parallel to the principal stress direction, followed by division of amount of boundaries from that direction with acquired amount of boundaries with cavities, Fig. 3. Therefore, basis for application of this method is determination of damage on the grain boundaries. Measurement of "A" parameter is made under magnification of 500 times so the need for the precise damage defining (which are not so clearly visible at smaller magnification) and sufficient number of grain boundaries (at least 400 for accurate results /2/) is fulfilled.

Principles for determination of "A" parameter are well explained in literature /2/. It is important to mention that, from the aspect of "A" parameter, boundaries with one cavity and boundaries with several linked cavities or microcrack are equal. Influence of n and λ coefficients, from the aspect of the "A" parameter significance on residual service life, is shown on Fig. 4. Value of λ=1.68 is calculated from the creep curve of 0.5Cr0.5Mo0.25V steel under the σ=108MPa and τ=535°C, what is appropriate for pipeline service conditions. Value for n=6 is taken from literature /10/.

If there is no accurate data, values of n=3 and λ=1.5 /2/ can be chosen for equation parameters, resulting in more conservative predictions, but still appropriate for pipeline service parameters. It is visible from Fig. 4 that increase of λ leads to the more conservative predictions (bigger curve slope), while n increase induces less conservative predictions (smaller curve slope).



Damaged boundaries: A, B, C, E

Undamaged boundaries: D, F, G, H, I, J

$$n_p=4,\quad n_u=6,\quad A=\frac{n_p}{n_p+n_u}=0.4$$

----------- Traverse line in σ_1 direction

Fig. 3. Determination of "A" parameter

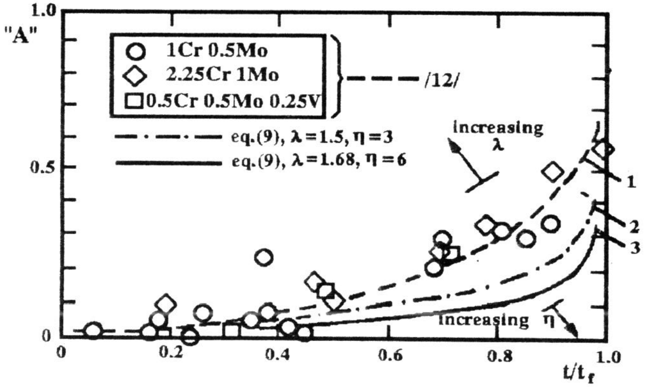


Fig. 4. Influence of n and λ parameter on "A" parameter curve via t/t_f

EXPERIMENT

"A" parameter method was inquired on the specimen surfaces prepared for metallography of two different pipeline components (bend and a straight part) which were manufactured from the same material, 0.5Cr0.5Mo0.25V (14MoV6.3 DIN17175).

Bend. This pipeline component was partially fractured by intercrystal crack propagation during creep and there were all processes of creep cavitation mentioned in theoretical basis of "A" parameter method. The cause for bend failure was local dimension inaccurance (smaller wall thickness then designed) during manufacturing. "A" parameter was calculated for positions given on Fig. 5, and three structural areas from those positions are given on Fig. 6a,b and c. Gathered values are shown in Table 1 and graphically represented on Fig. 7.

Straight part of pipeline. Fracture through the wall thickness (≈ 25mm) was consequence of material softening because of base poverty, what was the outcome of mistakes in pipeline material manufacturing /13/. This fracture shouldn't behave under the conditions met in theoretical basis of "A" parameter (only "A" parameter based on creep cavitation mechanism can be found in literature), because mechanisms of dislocations interactions with structural components are different in case of softened and precipitately hardened base. Therefore we can't consider anymore that same deformation mechanisms are applied as a common case for $\frac{1}{2}\mathrm{Cr}\frac{1}{2}\mathrm{Mo}\frac{1}{4}\mathrm{V}$ steel. "A" parameter was measured on positions 1-7, and obtained results are presented in Table 1. Some characteristic structures are shown on Figs. 8.

Table 1.

Position	1	2	3	4	5	6	7
Distance from crack tip (mm)	5	7	9	16	24	34	38
Bend "A" parameter	0.48	0.39	0.37	0.29	0.28	0.19	0.16
Straight part "A"parameter	0.49	0.48	0.48	0.47	0.48	0.47	0.46
Bend t/t_f	0.99	0.99	0.99	0.99	0.99	0.95	0.92
Straight part t/t_f	0.99	0.99	0.99	0.99	0.99	0.99	0.99

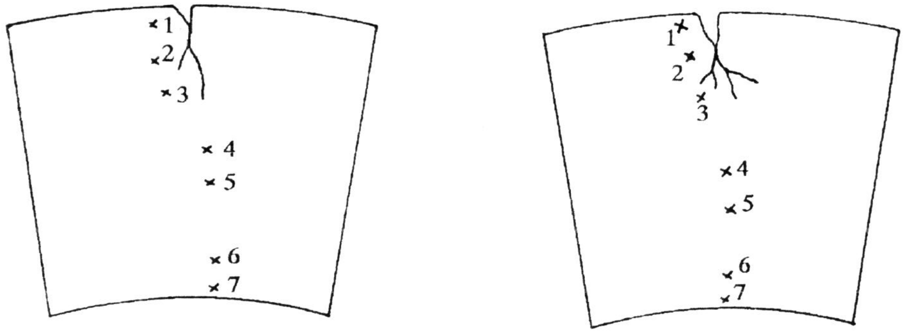


Fig. 5. Macro view a) of bend part with position for "A" parameter measurements
b) of straight part with position for "A" parameter measurements

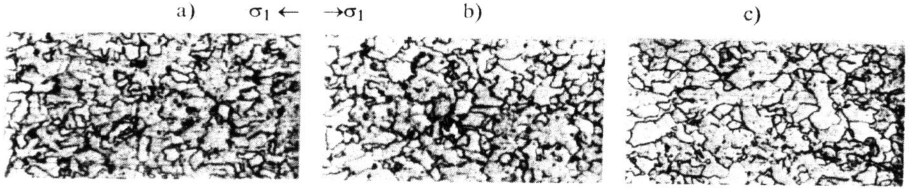
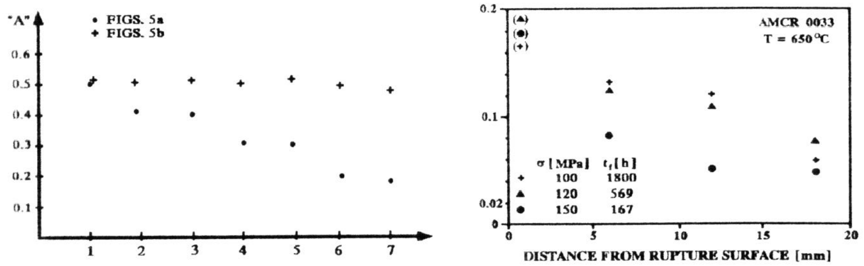


Fig. 6. Structures on ruptured bend in positions: a) 3; b) 5; c) 7



a) b)

Fig. 7. a) "A" parameter independence of the position points
b) "A" parameter measured on austenitic steel /6/

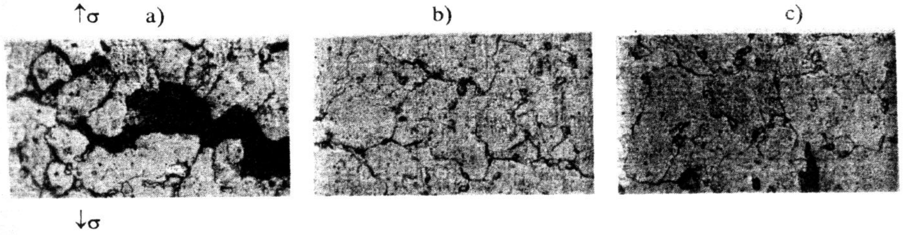


Fig. 8. Structures on straight pipe in positions: a) 3; b) 5; c) 7

DISCUSSION

"A" parameter method, as one of the latest in a row of non-destructive methods for residual service life, require more testing in purpose of validation of this method. In order to improve the accuracy and increase the confidence of such methods there is a need for more studies, involving, where possible, monitoring of damage and crack development. Results of "A" parameter determination on pipelines presented in this paper are in complete agreement with theoretical basis of "A" parameter. Considering that in investigated case "A" parameter was determined on already exploited material, in the direction of crack propagation but through the wall thickness, basic approach was that 0.5Cr0.5Mo0.25V steel had different degrees of damage on dissimilar distances from crack. Furthermore, prediction of proper failure degree and different values of remaining service life can be correlated (results of that are shown in Table 1) and compared with experimental values of estimated service life Fig.4 /12/. In case of ruptured bend, failure occurred because of:

a) decrease of precipitation and dispersion strengthening influence due to the dynamic recovery and
b) total loss of precipitation and dispersion strengthening due to structural degradation in service under creep conditions.

Assessment of "A" parameter, described in this paper, on a straight part of pipeline, we believe that it is a first attempt of such kind in practice and literature, according to different structural degradation mechanism on creep cavity degradation. In case of straight part of pipeline, failure occurred because of:

a) thermal softening of matrix caused by loss of alloying elements in solid solution;

b) carbide coagulation and separation by the grain boundaries;
c) insufficiency of precipitation and dispersion strengthening at the beginning of service.

Diagram based on real values (curve 3 $n=6$, $l=1.68$) and recommended diragram from ref. /2/ (curve 2 $n=3$, $l=1.5$) gave higher values than experimental ones from ref. 12 (curve 1) as shown on Fig. 4. From economical point of view, curve 1 is the most beneficial because it predicts that part of pipeline can be in service longer than it is predicted by curves 2 and 3. However, curve 3 gave the most conservative prediction of remaining service life, what is, from the point of reliability, the most beneficial. Figs. 7a. and 7b. present the parallel in order of data distribution of "A" parameter values, on different distances from crack tip, with values from ref. /6/, where the values of "A" parameter are determined on austenitic stainless steel. Parallel can be clearly seen, from values of bend failure (marked by circles) with values from Fig. 7b. It means that, exponential creep law, constrained cavity growth and brittle intercrystal fine failure due to cavitation by grain boundaries mechanisms, are properly established. On the other hand, presenting of straight part pipeline data, which failured due to matrix softening, show expected equalization of results through the thickness of tube wall. This conclusion illustrates objectivity of "A" parameter method, in the remaining life assesment, because matrix softening of straight pipeline is taking place through the complete wall thickness, which happened due to unproper thermal treatment in steel manufacturing.

CONCLUSIONS

1. The results of this study validates constrained cavity growth model. The cavity number, on single grain boundary, is less on the fractured specimen due to matrix softening then to the fractured specimen due to material creep exhaustion. That confirms conservative prediction that single cavity perform stress redistribution on uncavitated grain boundaries in the same way as more cavities or microcracks in the grain boundaries.
2. Value redistribution of "A" parameter, with increasing distances from crack tip, show conservativity of creep and destruction mechanisms proposition.
3. "A" parameter model predicted cavity damage growth, in conservative way. Curve 3 presented on Fig.4 gives most realistc predictions for residual life assesment for 14MoV63 steel.
4. Curves 1, 2 and 3 on Fig.4, show that there has to be standard procedure for determination of n and l for every material.
5. "A" parameter is only non-destructive method which could be applied to real or mathematical steel structure model (modeling by stochastic geometry) /14/. It requires development of standard methods for "A" parameter determination.

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