Toughness Properties up to Service Temperature (290 °C) for Different Thick Pressure Vessel Components in SA 508 C1.3

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ABSTRACT

A validation of fracture toughness characteristics, both in the transition zone and ductile regime was undertaken on specific PWR nuclear pressure vessel components : a nozzle and a steam generator tube plate. Dynamic fracture toughness results on specimens extracted from segregated zones were found conservatively predicted by the K_{IR} reference curve of the ASME Code based on the RT_{NDT} referencing procedure. The resistance against crack extension was characterized by the J-Δa resistance curve method. Compilation of J_{Ic} values and slopes dJ/da of the resistance curve originating from various forgings shows a close dependance with the CHARPY V notch upper shelf energy.

Up to 100°C a conservative J_{IC} value of 120 kJ/m^2 (K_{Jc} = 163 MPa$\sqrt{m}$) was assessed for the worst upper shelf energy material of 84 J exhibited on a high sulphur content (.015%) nozzle. A bilinear crack extension resistance curve was established up to 7 mm of stable crack growth.

At 250°C, a moderate decrease in J_{Ic} was observed for low loading rate tests. However, the main feature was a reduction in the slope of the tearing resistance curve when compared to the 100°C behavior.

1. INTRODUCTION

Pressure vessel components in Mn-Mo-Ni low alloy steel of Pressurized Water Reactor plants are cladded with austenitic stainless steel or nickel base alloy for avoiding excessive corrosion products in the primary circuit. The presence of segregated zones in the base metal associated with non adequate preheating and postheating temperatures may result in the formation of hydrogen induced underclad cracks. Two components were found to be affected in some circumstances by this type of defect : nozzles of the reactor vessel and tube plates of the steam generator.Fracture mechanics analyses were conducted to conservatively predict the fatigue crack growth evolution under in service loadings and to examine the crack stability at the end of life in emergency and faulted conditions.

Primordial importance was given to the inputs of material properties concerning especially fatigue crack growth rate and fracture toughness performance.Data were generated from actual cladded nozzle and tube plate selected in order to derive conservative design curves for application to all the products under consideration. Confident fatigue crack growth design curves were established and are reported elsewhere [1] while this paper presents the methodology used for assessing the fracture toughness in the transition and is mainly focussed on the description of the different steps followed to generate a conservative J-Δa resistance curve.

2. MATERIALS

Two reactor pressure vessel components in SA 508 Cl 3 steel were investigated for establishing conservative fracture toughness properties both in the fracture toughness transition range and in the ductile regime. These two components are obtained from large ingots where significant positive segregation occurs during solidification, mainly in the axial zone

The 600 mm thick tube plate is forged using an about 100 T weight ingot. Metallurgical examinations through the thickness indicate that segregated zones are located at the axial head side of the forging ;moreover gost lines (A segregates) are found in a circumferential zone at about one half radius distance from the axis of the tube plate (fig.1). Due to the decrease in quenching rate through the thickness, a noticeable reduction in fracture toughness transition properties occurs as a function of the distance of the quenched surface. Specimens were located in segregated zones at a convenient distance from the surface (fig. 1). The loading axis of the CT specimens was oriented in the circumferential direction, the crack extension direction being parallel to the short transverse orientation of the product and the crack tip located at about 175 mm from the surface, i.e. close to the quarter thickness(head side).

The investigated outlet nozzle was issued from a large 150 T weight ingot. In this case the axial segregated zone was eliminated by machining after forging. Six outlet nozzles of approximately 360 mm thickness were extracted from this forged ingot. The acceptance tests, including Drop Weight and CHARPY V notch impact tests are carried out on speciments located at 90 mm depth from the quenched surface. For the nozzle population under consideration the maximum sulfur content was .015%. In the transyerse direction, i.e.

the circomferential direction of the nozzle, the lowest CHARPY V impact energy at upper shelf corresponds to the maximum sulphur content : 84 J (10.5 daJ/cm^2).

Thus, the main problem was to evaluate the resistance against ductile fracture CT specimens were machined in an excess of the acceptance tests ring issued from the higher sulphur content nozzle. A transverse orientation was selected for CT specimens and additional CHARPY V specimens of identical orientation were simultaneously extracted for checking purpose.

The chemical compositions and mechanical properties of the two products in the investigated zones are respectively reported in Tables 1 and 2.

3. TESTING METHODOLOGY

3.1. Dynamic tests

Dynamic fracture tests were conducted using 25 mm thick CT specimens. The loading rate obtained on the servo-hydraulic testing device was close to $3.10^4 MPa\sqrt{m}.s^{-1}$. The specimen design allows the measurement of the displacement of the crack faces in the loading axis. The load-displacement curve was continuously recorded during the tests. Moreover a high-frequency AC potential drop method derived from a system described elsewhere [2] was used for detecting crack initiation. When the load-displacement diagram cannot be interpreted in accordance with the standard procedure of ASTM E 399 the J initiation value at cleavage instability or at ductile initiation event is calculated using the MERKLE-CORTEN formulation [3] .

3.2. J-Δa resistance curve

The J-Δa resistance curve method was adopted to characterize the resistance against ductile crack extension [4]. 50 mm thick CT specimens (a/W $\simeq$ 0.6) where used for all tests conducted following the heat tinting technique. In some circumstances, the specimens were 25% side grooved. The specimens are immerged in an oil bath heated at the required temperature.

After unloading and subsequent heat tinting, the specimens are broken at liquid nitrogen temperature and the crack extension is finally measured in 9 points of the crack front.

4. DYNAMIC FRACTURE TOUGHNESS TRANSITION CURVE

The dynamic tests were performed on the 25 mm thick CT specimens extracted from the segregated zones of the tube plate at temperatures T ranging from - 10°C to + 80°C. Results are reported in figure 2 versus the parameter T-RT_{NDT} (RT_{NDT} = -10 or -15°C for this material). Scanning Electron Microscope examinations, corroborated by the type of load displacement and potential curves, show that for temperatures up to T - RT_{NDT} = 50°C the initiation is controlled by a pure cleavage mechanism, while at higher temperatures small ductile crack extensions occur before cleavage instability. At T - RT_{NDT} = + 100°C one of the specimens tested does not exhibit cleavage at all and one of the value reported is related to

the dynamic ductile initiation value.

The main conclusion illustrated in figure 2 is that all data were found superior to the values expected from the K_{IR} reference curve of ASME Code [5] . Consequently, the referencing procedure based on the RT_{NDT} can be applied to segregated material even at large distances from the quenched surface or acceptance test location. In fact, the maximum length of the crack calculated at the end of life was widely inferior to the quarter thickness location which improves the conservatism of the approach.

For the nozzles, it was demonstrated that the minimum temperature TCV for which each CHARPY V notch specimen of a set of three provides at least 68 J of fracture energy was 33°C for the product of higher sulphur content (.015%).

The highest Nil Ductility Transition Temperature (NDTT) observed for the population was -2°C. According to the definition of the ASME Code [5] a conservative upper bound of the RT_{NDT} of nozzles which were originating for the same vendor,was fixed at 0°C. As the segregated level was inferior to those encountered in tube plates it was reconized that the K_{Ic} , K_{Ia} reference curves should be directly obtained using a RT_{NDT} of 0°C on the basis of the previous conclusion concerning the applicability of the referencing procedure in segregated zones.

5. J-Δa CRACK EXTENSION DATA

The J-Δa resistance curves of the selected tube plate and of the high sulphur level nozzle were established at a temperature of + 100°C (fig. 3 and 4).

The CT specimens of the tube plate were non side grooved resulting in a higher crack extension Δa_{max} at the center of the specimen than near the surfaces. While the presence of side grooves straighten the crack front propagation for the CT in nozzle material, the propagation was observed to be heterogeneous and local high crack extensions were observed. In this case a mean value of these localized propagations was adopted for the Δa_{max} definition. As illustrated in figures 3 and 4, the use of Δa_{max} in place of Δa_g for defining the crack extension induces a high conservatism in the J-Δa resistance curve mainly on the slope of the tearing curve.

J_{Ic} values at crack growth initiation were respectively found to be 190 kJ/m^2 and 140 kJ/m^2 for the tube plate and the nozzle. However, a small discrepency was found when checking the CHARPY V upper shelf energy at the CT specimen location. The value of 95 J was higher than the 84 J reported from the acceptance tests. This fact attributed to material variability is further taken into account.

6. METHOD FOR DERIVING A CONSERVATIVE RESISTANCE CURVE

The method is first based on the strong correlation established between CHARPY V upper shelf energy (USE) and two parameters of the resistance curve : the initiation value J_{Ic}

and the slope dJ/da of the resistance line of stable tearing. The extension of the resistance curve to high crack growth values was further accomplished using a bilinear approximation for describing the shape of the resistance curve.

6.1. Effect of sulphur content on CHARPY V upper shelf energy (USE)

It is well known that the content and the shape of manganese sulphide inclusions have a strong influence on the CHARPY V upper shelf energy (USE) level of specimens of transverse orientation relative to the major forging direction. The correlation between the USE and the sulphur content for the specific case of nozzles is illustrated in fig. 5. The lowest value observed on a .015%S nozzle was 84 J (10.5 daJ/cm^2).

6.2. Correlation of J_{Ic} and dJ/da versus USE

The loss in ductile resistance with increasing S content observed in CHARPY test (USE) is also exhibited by the J-Δa resistance curves. Two J-Δa resistance curves of SA 508 C13 products of very different USE are presented in figure 6. A decrease in J_{Ic} and of the slope of the tearing resistance curve is clearly associated with the reduction in USE. Compilation of new and previously published data [6] specific of the SA 508 C13 steel are reported in table 3. Figures 7 and 8 illustrate the significant correlation found respectively between J_{Ic} and USE and dJ/da and USE. From our opinion the slope dJ/da appears to be more affected by the reduction in USE than the initiation value J_{Ic}.

6.3. Extension of the Resistance curve up to high Δa values

According to the current recommanded procedure of ASTM E 24 the crack extension measurements were limited to crack extension of 1.5mm while a more extended resistance curve was needed for the crack stability analysis. Data of SHIH et al. [7] and WILLIAMS [8] obtained using 4T-CT in SA533 B steel were reanalyzed in the following way :a bilinear J resistance curve model wad adopted and the slope dJ^1/da between .2 and 1.5mm of stable crack extension was compared to the slope dJ^2/da between 1.5 and 7mm of crack extension as schematically presented in figure9. Examination of the results listed in Table 4 reveals that $dJ^2/da = \frac{1}{3} dJ^1/da$ is a conservative relationship for predicting the slope of the second part of the crack resistance line.

6.4. Establishing the design resistance curve

In spite of a J_{Ic} initiation value of 140 kJ/m^2 observed on the actual nozzle of higher sulphur content a conservative J_{Ic} = 120 kJ/m^2 was extrapolated from figure 7 for USE of 84 J (10.5 daJ/cm^2) taking into account material variability.

The dJ^1/da was taken equal to the lowest value 100 MPa deduced from local crack extensions Δa_{max}.

From paragraph 6.3 the resulting dJ^2/da was 33 MPa, leading to the design resistance curve presented in figure 10 which is cut off at a maximum crack extension of 7 mm and could be used for temperatures up to 100°C.

7. INFLUENCE OF LOADING RATE AND TEMPERATURE

For analyzing the normal conditions and some transcients, it was desirable to consider high temperatures J_{Ic} values. Special attention was given to literature [9] results mentioning that significant reductions in J_{Ic} may occur at low loading rates between 200 and 300°C. This effect was attributed by the authors to a dynamic strain aging effect.

A test temperature of 250°C and a loading rate of 0.1 $\mu m.s^{-1}$ were selected because these conditions are expected to provide the maximum effect from the results of OSTENSON [10] .

Investigations were carried out on the same nozzle material using 50 mm thick CT specimens (25% side-grooved). Results reported in figure 11 show a moderate decrease of about 11% in J_{Ic} (125 kJ/m^2). The main change consists in a significant reduction in the slope of the crack extension line. However, only considering the initiation value was sufficient for avoiding crack extension in all the analyzed situations. Unexpected behavior was encountered on two specimens which exhibited sudden rapid crack extensions, looking like a pop-in aspect on the load-displacement curve. Examinations of the surfaces always showed ductile propagation but dimples of different sizes were present. The repartition of large sulphide inclusions seems to control the path of fracture because the irregularity of fracture surfaces is strongly related to the segregated bands and the grouping of Mn S inclusions. The microscopally void formation process could be affected by a creep assited shear mechanism and/or by dynamic strain aging, these two processes can contribute to a significant reduction of ductility in the microductile regions connecting large cavities. More work will be done in this field for a better understanding of the mechanism involved.

8. CONCLUSIONS

Dynamic fracture toughness tests performed on material issued from segregated zones of heavy forgings in Mn-Ni-Mo steel show that the RT_{NDT} referencing procedure was still valid for obtaining the K_{IR} reference curve in these particular areas.

An upper bound RT_{NDT} = 0°C was conservatively obtained from the analysis of acceptance tests of the population of nozzles.

Significant correlations were found between the CHARPY V upper shelf energy and two parameters of the resistance curves : the initiation value J_{Ic} and the slope dJ/da of the propagation line. A design resistance curve was developped from the worst upper shelf energy material (84 J) of high sulphur content (0.015%). A J_{Ic} initiation value of 120 kJ/m^2 (K_{Jc} = 163 $MPa\sqrt{m}$) was conservatively established for temperatures up to 100°C.

The crack extension resistance was represented by a bilinear curve up to a maximum crack extension of 7 mm. The design curve is presented in figure 10.

A decrease in ductile crack growth resistance performance was found for low loading rates at 250°C. A conservative initiation value of 107 kJ/m^2 (K_{Jc} = 150 MPa$\sqrt{m}$) was established for analyzing low loading rate transcients occuring from 250°C up to service temperature. The more important feature was a significant reduction in the slope dJ/da of the crack extension line when compared to the 100°C behavior.

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TABLE 1 : Chemical composition of the two SA 508 Cl 3 components.

Products	C	S	P	Si	Mn	Ni	Cr	Mo	Cu
Nozzle	.14	.015	.012	.17	1.38	.71	.21	.50	.08
Tube plate	.175	.016	.009	.023	1.38	.74	.24	.51	.07

TABLE 2 : Mechanical properties of the two SA 508 Cl 3 components.

Products	Yield Strength at R.T. (MPa)	Tensile Strengh at R.T. (MPa)	Elongation at R.T.(%)5d	Reduction of area at R.T.(%)	KV at 0°C(J)
Nozzle (SA508C13)	462	587	20.2	51	45
Tube plate (SA508C13)	508	634	21.8	67.4	51.2

TABLE 3 : Compilation of USE, J_{Ic} and dJ^1/da for different products in SA 508 Cl 3 steel.

Product	Orientation	Temperature (°C)	Flow (MPa)	USE (J)	J_{IC} (kJ/m2)	dJ^1/da (MPa)
Tube plate	TL	100	409	130	172	233
Tube plate	LT	100	391	147	-	360
Tube plate	TS	100	527	153	176/200	207/187
Nozzle shell	S	100	563	106	140	119
Nozzle shell	LT	100	559	172	205	360
Nozzle shell	LT and TL	100	422	196	284	484
Nozzle shell	TL	85	506	169	202	398
Nozzle shell	TL	70	512	182	217	337
Nozzle	LT and TL	100	454	166	192	398
Nozzle	TS	100	535	95	140	100

TABLE 4 : Analysis of initial (dJ^1/da) and high crack extensions (dJ^2/da) tearing slopes (mean values).

Material	J1c (kJ/m2)	$\frac{dJ^1}{da}$ (MPa)	$\frac{dJ^2}{da}$ (MPa)	Reference
A533B(121°C)	180	450	146	8
A533G(177°C)	86	95	36	8
A533B(93°C)	-	336	134	7

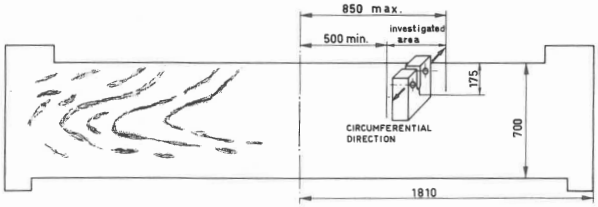

Figure 1 : Schematic of the A Segregates and specimen locations in the tube plate.

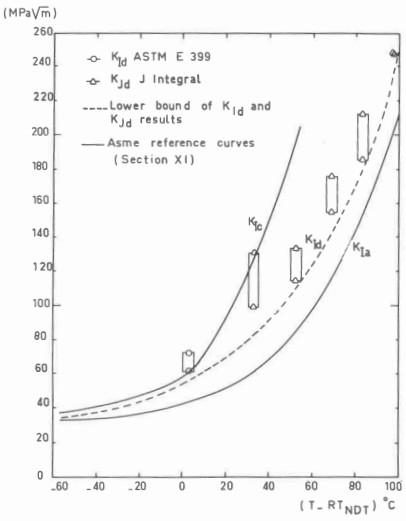

Figure 2 : Dynamic fracture toughness tests in segregated zones of tube plate.

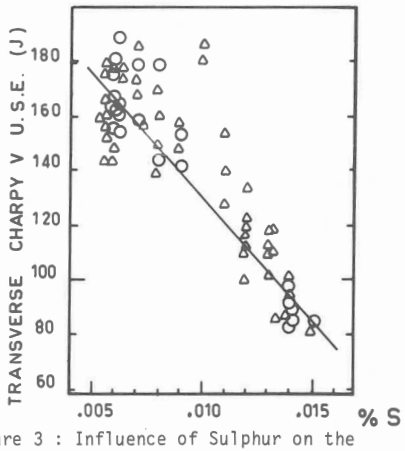

Figure 3 : Influence of Sulphur on the transverse USE of nozzles.

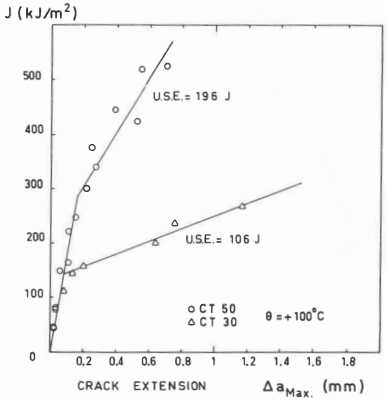

Figure 4 : Effect of USE level on J-Δ a resistance curves.

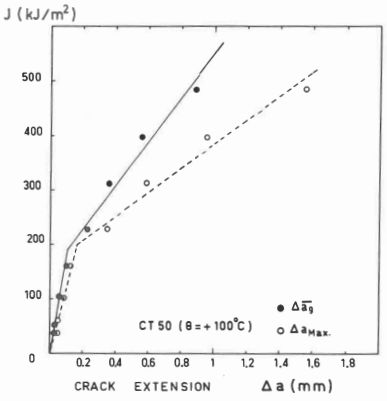

Figure 5 : J-Δ a resistance curve of the tube plate in segregated zones.

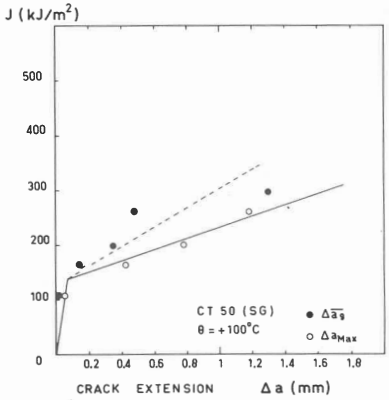

Figure 6 : J-Δ a resistance curve of the highest S nozzle (USE=95J).

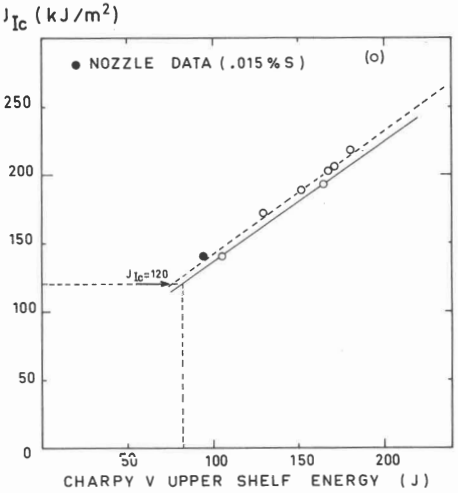

Figure 7 : Correlation between J_{Ic} and USE.

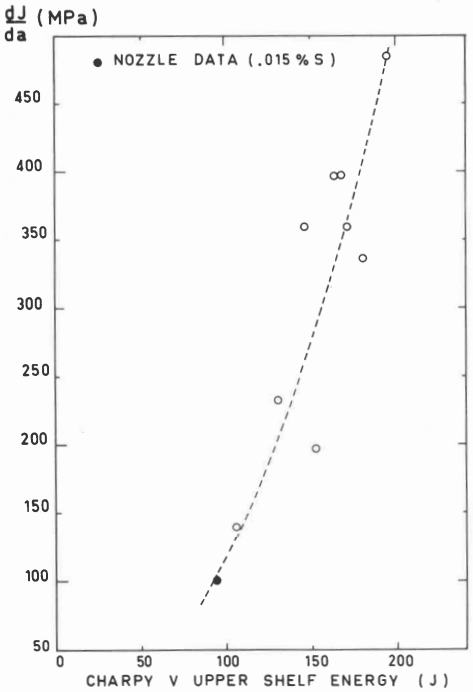

Figure 8 : Correlation between dJ'/da and USE.

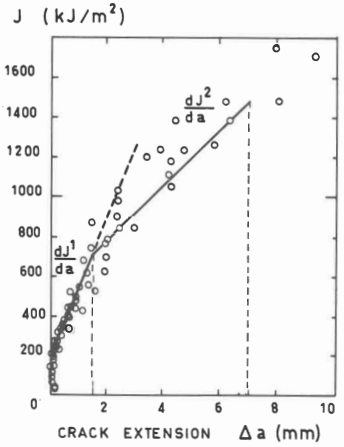

Figure 9 : Schematic of the bilinear J-Δ a resistance curve model.

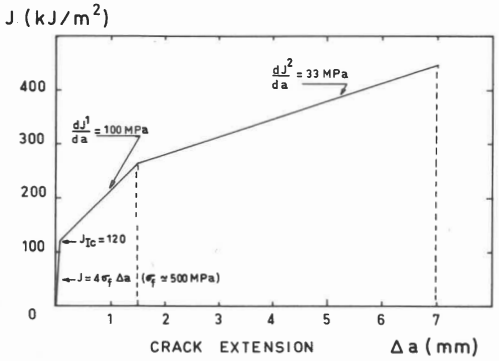

Figure 10: Design resistance curve for nozzles (S ⩽ .015% ; θ⩽+100°C).

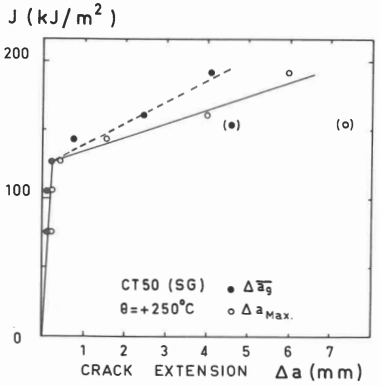

Figure 11: Low loading rate resistance curve at 250 °C for nozzles.