An Evaluation of Cast Stainless Steel (CF8M) Fracture Toughness Caused by Thermal Aging at 430℃

Jae Do Kwon*, Jae Hyun Ihn, Joong Cheul Park, Sung Jong Choi
Department of Mechanical Engineering, Yeungnam University, Gyeongsan, Gyeongbuk 712-749, Korea
Yun Won Park
Korea Institute of Nuclear Safety, Guseong-dong, Yuseong-gu, Daejeon 305-338, Korea

Cast stainless steel may experience embrittlement when it is exposed approximately to 300℃ for a long period. In the present investigation, the three classes of the thermally-aged CF8M specimen were prepared using an artificially-accelerated aging method. After the specimens were held for 300, 1800 and 3600hrs. at 430℃, respectively, the specimens were quenched in water which is at room temperature. Load versus load line displacement curves and $J-R$ curves were obtained using the unloading compliance method. J_{IC} values were obtained using the ASTM E 813-87 and ASTM E 813-81 methods. In addition to these methods, J_{IC} values were obtained using the SZW (stretch zone width) method described in JSME S 001-1981. The results of the unloading compliance method are $J_Q=543.9\text{kJ/m}^2$ for virgin materials. The values of J_{IC} for the degraded materials at 300, 1800 and 3600hrs. are obtained 369.25kJ/m^2, 311.02kJ/m^2, 276.7kJ/m^2, respectively. The results obtained by the SZW method are compared with those obtained by the unloading compliance method. Both results are quite similar. Through the elastic-plastic fracture toughness test, it is found that the value of J_{IC} is decreased with an increase of the aging time.

Key Words : CF8M, Virgin Material, Degraded Material, Elastic-Plastic Fracture Toughness Test, Unloading Compliance Method, Stretch Zone Width Method

1. Introduction

Thermal embrittlements have been observed in reactor coolant pump bodies (REP), reactor coolant pipes and fittings, surge lines and the spray heads of pressurizers, etc. all of which belong to the primary pressure boundary within a nuclear power plant. Some of these materials are made of duplex austenite-ferrite cast stainless steel (CF8M).

When CF8M is exposed for long a period to temperatures below 500℃, the materials are degraded by thermal-aging-induced embrittlement. The aging embrittlement is usually identified as a 475℃ degradation (Ustinovshokov, 1996 ; Nichol, 1980 ; Vrinat, 1986 ; Williams, 1958 ; Solomon and Lionel, 1978). The range of temperatures varies from a minimum of 300℃ to a maximum of 500℃ (Trautwein and Gysel, 1982). However, a more severe embrittlement is observed at 475℃ when it exceeds the linear range (Trautwein and Gysel, 1982). Therefore, thermal-aging embrittlement is maximum at 475℃. Material degradation can be observed in the operating temperature range of the pressurized water reactor, i.e. 290~330℃ (Trautwein and Gysel, 1982 ; Chopra and Chung, 1988). Thermal-aging embrittlement is caused by a phase known as precipitation of α' Cr-rich bcc structure (Vrinat,

* Corresponding Author,
E-mail : jdkwon@yu.ac.kr
TEL : +82-53-810-2462; **FAX** : +82-53-813-3703
Department of Mechanical Engineering, Yeungnam University, Gyeongsan, Gyeongbuk 712-749, Korea.
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1986; Williams, 1958; Solomon and Lionel, 1978). The precipitation of α' phase is a primary cause of the degradation and this precipitation is formed by spinodal decomposition (Solomon and Lionel, 1978; Trautwein and Gysel, 1982). The spinodal decomposition is a material with two different compositions and properties even though the phases have identical crystal lattice structures. Therefore, spinodal decomposition can be considered as a different phase with identical crystal structures and it is formed by a miscibility gap of an alloy. For example, the miscibility gap consists of a Fe-rich phase and a Cr-rich phase, α'. This α' phase causes material degradation at 475℃. Consequently, the existence of the α' phase in the ferritic phase results in the reduction of fracture toughness (Chopra and Chung, 1988; Chopra and Sather, 1990; Chopra, 1993). Many investigators (Trautwein and Gysel, 1982; Chopra and Chung, 1988; Chopra and Sather, 1990; Chopra, 1993; Bamford et al., 1983; Kwon et al., 2000) performed experiments associated with mechanical property variations caused by thermal-aging embrittlement, using cast stainless steel, aged by the artificially accelerated-aging technique.

The reduction of toughness of the CF8M could cause a catastrophic failure within the structure and a leakage of coolants. These two failures can cause a cessation of a nuclear power plant's functional operation. Therefore, estimation of the CF8M fracture toughness requires some evaluation and guidelines to determine the structural integrity of the CF8M.

In the present paper, J-R curve and J_{IC} values of aged specimens prepared at various aging times under the fixed temperature 430℃, are found, including those of the virgin specimen. The experimental methods associated with the J-R curve and J_{IC} are followed by descriptions given in the ASTM. However, the estimation of the J_{IC} value of the virgin specimen using a CT(1T: 25mm) specimen is realized to be difficult when the ASTM method is employed. The reason will be explained later. An effort is made to estimate J_{IC} values of the virgin specimen using the stretch zone width method as described in JSME S001-1901.

In the present work, the effect of thermal embrittlement at 430℃ were investigated by means of fracture toughness test in CF8M. The main purpose of the study was to determine how the fracture toughness (J_{IC}) are affected by aging at 430℃. Values of J_{IC} were obtained using two different methods, i. e. unloading compliance and stretch zone width method.

2. Material Properties and the Experimental Method

The material used in the present experiment is ASTM A351 grade CF8M cast stainless steel which is used in the primary coolant system of some PWR nuclear power plants. The chemical composition and mechanical properties of the material are given in Tables 1 and 2, respectively.

Table 1 Chemical composition of CF8M

Composition, wt. %								
C	Mn	P	S	Si	Ni	Cr	Mo	Ferrite content (%)
0.074	1.21	0.0318	0.0126	1.14	9.59	18.67	2.73	9.6

Table 2 Mechanical properties of CF8M

	Yield strength σ_y(MPa)	Tensile strength σ_u(Mpa)	$\sigma_{fs}=(\sigma_y+\sigma_u)/2$	Elongation (%)	Reduction of area (%)	Elastic modulus (GPa)	Poisson's ratio
virgin	284	525	404.5	68.6	46.5	193.178	0.28
300hrs	291	620	455.5	67.9	43.4		
1800hrs	299	624	461.5	59.8	34.1		
3600hrs	303	580	441.5	41.6	30.3		

It is well known that the ideal specimens needed to investigate the effect of degradation of mechanical properties are those removed from real equipment exposed to actual operational environments.

However, in the present circumstance, it is difficult to obtain actual degraded materials exposed to actual working environmental conditions. Such degraded materials would include materials exposed to high temperatures, pressures and aging times. All specimens used in the investigation were prepared in the laboratory using designed methods to accelerate the degradation of the materials.

Specimens employed in the present investigation were selected specimens which show significant impact energy reduction. In the previous experiment (Kwon et al., 2000; 2001), the specimens which show significant impact energy reduction were found in the specimens aged for 300, 1800 and 3600 hrs. at 430℃, respectively. Based on these results, the specimens, used in the experiments are aged for 300, 1800 and 3600 hrs. at 430℃ and quenched in water at room temperature.

The specimens employed in the experiments are compact tension specimens (CT) using the ASTM E813-87 (ASTM, 1989; Seok, 2000). The thickness of the CT specimen is 25mm and the detail shape and dimensions of the specimen are shown in Fig. 1. The fatigue pre-crack characteristic induced in the notch tip was prepared so that

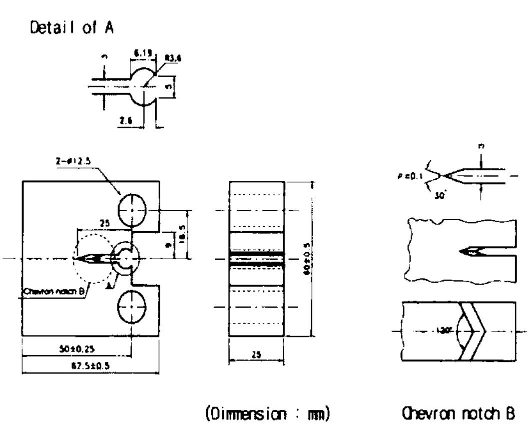


Fig. 1 Geometry of the CT specimen

requirements ASTM E1152-87, E813-87 are satisfied.

The test condition thats employed has a stress ratio, $R=0.05$ which satisfies the requirement, $R \leq 0.1$. The experiments are preformed using a hydraulic-servo fatigue test machine with a maximum capacity of 10 tons. Depths of the side grooves are induced 10% of the total thickness, 25mm from each surface so that the total depth of the grooves is 20% in thickness. This satisfies the requirement of the ASTM E813-87. Side grooves of 60° are made using a notch cutter so that the grooves coincide with the pre-crack. The radius of curvature of the side groove tip is 0.4mm. Therefore, if the total thickness of the CT specimen is 25mm, then the thickness of the net section of the side grooves (B_N) is 20mm. It is known that two methods are available in the determination of fracture toughness, namely, the single specimen and multi-specimen methods. The J-R curve and J_{IC} values in the present investigation are obtained using two methods, i.e. the unloading compliance method (Clarke et al., 1976; ASTM, 1995) which is a single specimen method and the stretch zone width method (JSME, 1981; Kobayosh, et al., 1977) which is a multi-specimen method.

2.1 The determination of the J-R curve and J_{IC} using the unloading compliance method

The relationship between the load and the COD is obtained by using the method described in the ASTM which is associated with the determination of fracture toughness. The ductile crack length, Δa at each unloading and reloading process can be determined by following ASTM descriptions. J-R Curve and J_{IC} values are obtained using the results of the P-COD relationship and the Δa values based on the ASTM E 813-87 method.

The experiments to determine the fracture toughness are performed twice for the virgin as well as for each aged specimen. The results showing a lower P versus COD relationship are shown in Fig. 2. Applied J values are found using Eq. (1) and the crack length a is found from Eq.

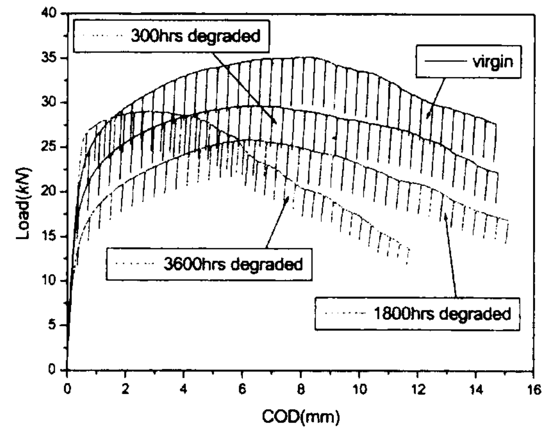


Fig. 2 Load-load line displacement curves

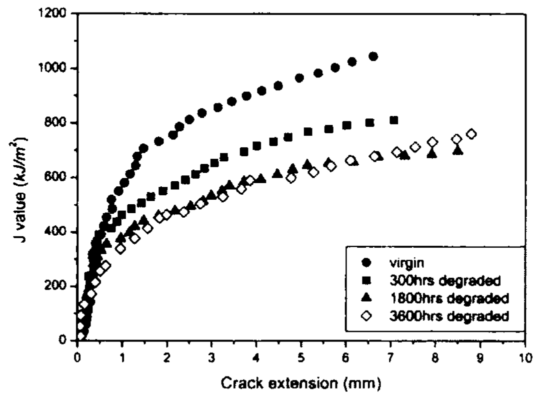


Fig. 3 J-R curves for virgin and degraded specimens

(2) which is described in the ASTM 813-87. Compliances are found at each unloading-reloading process juncture using the data P and $\Delta\delta$ (COD) difference taken at 10% and 90% of the unloading range. The J value is found by the J value in an elastic range J_{el} superposing on J value in a plastic range (J_{pl}) and it is given by as,

$$J = J_{el} + J_{pl} \quad (1)$$

where $J_{el} = K^2(1-\nu)/E$, $J_{pl} = \eta A_{pl}/B_N b_i$, $\eta = 2 + 0.522 b_i/W$, b_i : the specimen ligament, E : modulus of elasticity (193.178 GPa), B_N : net thickness of the specimen (20mm), K : stress intensity factor, A_{pl} : plastic area under the load versus load-line displacement and W : the specimen length (50mm).

The detailed configurations of the specimen are given in Fig. 1 and the E values of the virgin and aged specimens are found to be identical ν : Poisson's ratio (0. 28) and these values are taken from the handbook (1992).

The crack length a is found from Eq. (2), as described in the ASTM

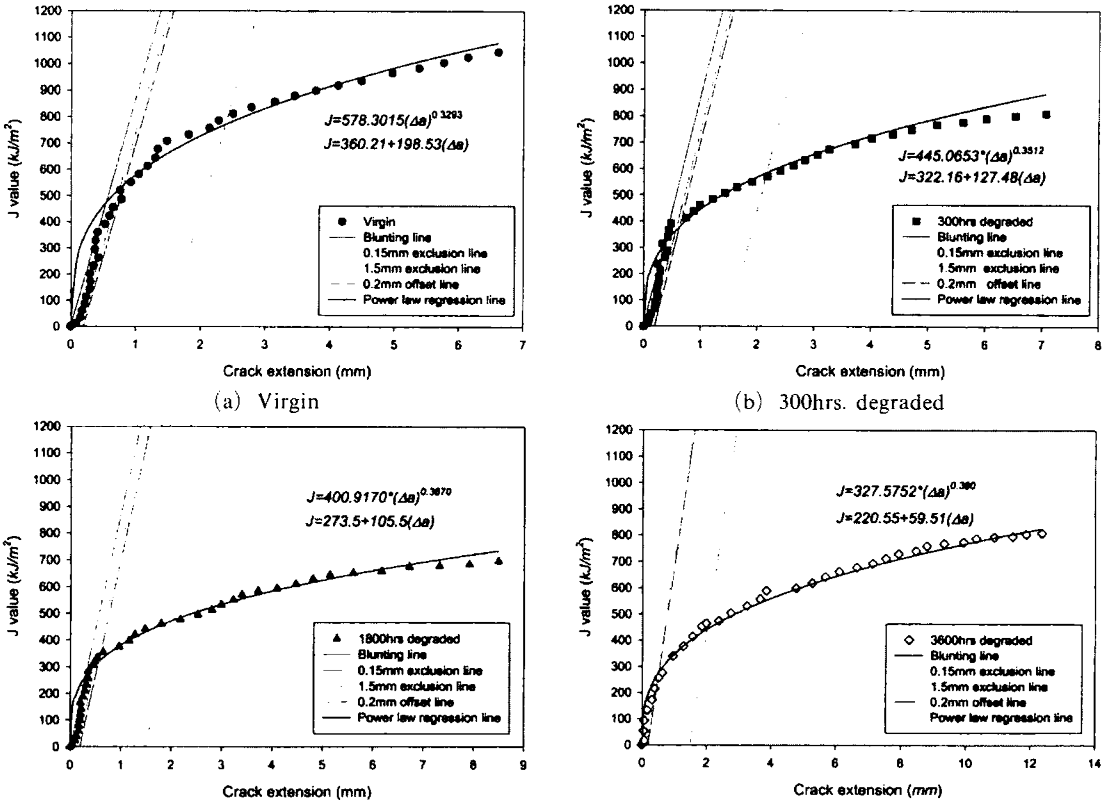
$$a/W = 1.00196 - 4.06319 U_L + 11.242 U_L^2 - 106.043 U_L^3 + 464.335 U_L^4 - 650.677 U_L^5 \quad (2)$$

where $U_L = 1/[(B_E E C_i)^{1/2} + 1]$, $B_E = B - (B - B_N)^2/B$, C_i : the specimen elastic compliance ($\Delta\delta/\Delta P$) and B : the specimen breath (25mm) After the specimen is fractured, the ductile fractured surface in the direction of the width is divided into 8 equally-spaced partitions. The final crack lengths are measured in seven different sections excluding the crack lengths in the two free surfaces and the lengths are considered to be average in value. The final calculated crack length, a in Eq. (2) is adjusted so that the crack length, a in Eq. (2) is equal to the measured value. Every crack length, a in Eq. (2) is re-adjusted, based on the ratio of the final crack length, a in Eq. (2) to the measured final crack length so that a in eq. (2) is equal to the measured values. The adjustments are required because of the pre-crack curvature induced in the specimens prior to the experiment. The relationship between the J value and the crack extension (Δa) for the virgin and degraded specimens is shown in Fig. 3. The J values are decreased with an increase of the aging time and the relationships between J and Δa for 1800hrs. and 3600hrs. aged specimens at 430℃ show very close curve shapes. The shapes of the J-R curve for various aging times are similar to the impact energy reduction caused by the degradation (Kwon et al., 2000). In the previous study (Kwon et al., 2000), we carried out the impact test with virgin and various aged specimens of same condition. Impact energy was decreased with aging time such as tendency of Fig. 3.

ASTM E813-87 explains the method in which to obtain the JIC from the J-R curve as represented in the form of the power law,

$$J = C_1(\Delta a)^{C_2} \quad (3)$$

where material constants C_1 and C_2 are obtained



(a) Virgin (b) 300hrs. degraded

(c) 1800hrs. degraded (d) 3600hrs. degraded

Fig. 4 Determination of J_{IC} by the ASTM E 813-87 method

by a curve fitting of the J-R curve. The J-R curve of the virgin specimen, the aged specimen at 300hrs., 1800hrs. and 3600hrs. are shown in Fig. 4 including the C_1 and C_2 values found by the curve fitting. Also, the J_{IC}, obtained using the ASTM E813-87 method, is included in Fig. 4. The J_{IC} value is found by the value of the intersection of the J-R curve which is obtained by the curve fitting that is shown in Eq. (3) with the 0.2mm offset line parallel to the blunting line. The blunting line is found from $J=(2\sigma_{fs})\Delta a$, where σ_{fs} is the flow stress, as shown in Table 2. The value at the intersection of the J-R curve is denoted as J_Q. The condition where the J_Q value becomes the J_{IC} value is used to satisfy the requirement, $B_N \geq 25J_Q/\sigma_{fs}$.

From the results of the J_Q values as noted in Fig. 4, it is found that the value of $25J_Q/\sigma_{fs}$ of the virgin specimen is 33.62 and this value is $B_N=$ 20mm$<$33.62mm. Therefore, the requirement of the J_Q becoming J_{IC} is not satisfactory for the virgin specimen while the requirements for the other three classes of aged specimens at 300hrs., 1800hrs. and 3600hrs. are satisfied. The tunneling and the curvature formation at the crack tip, caused by the ductile fracture, is not able to measure precise crack growth in the experiment concerning the virgin specimen. This difficulty may arise from the fact that the J_Q value of the virgin specimen violates the requirement of $B_N \geq 25J_Q/\sigma_{fs}$. However, the other three classes of aged specimens show fewer tunneling and curvature effects compared with the virgin specimens.

The J_Q value of the virgin specimen is found as J_Q=485.7kJ/m^2. The J_{IC} values of the three classes of aged specimens at 300hrs., 1800hrs. and 3600hrs. and at 430℃ are shown in Fig. 4 where J_{IC}=369.25kJ/m^2, J_{IC}=311.025kJ/m^2 and J_{IC}= 276.7kJ/m^2, respectively.

In addition to the ASTM E813-87 method, J_{IC}

values are found using ASTM E813-81 as a reference. These values are compared to those found in ASTM E813-87 and the stretch zone width method which will be explained in Sec. 3.2.1. The method described in ASTM E813-81 is used to determine the J_{IC} value from the intersection of the blunting line with the linear curve fitting of the J-R curve in the range of the 0.15mm and 1.5mm offset lines which are parallel to the blunting line. The J expression in the linear curve fitting ASTM E813-81 is expressed as,

$$J = B + M(\Delta a) \tag{4}$$

where B and M values are found from the linear curve fitting.

The values of B and M for the virgin specimen and the three classes of aged specimens are shown in Fig. 4.

2.2 The determination using the stretch zone width (SZW) method

2.2.1 The measurement of the SZW

The J_Q value, as determined using the unloading compliance and ASTM E813-87 methods for the virgin specimens, does not satisfy the requirement that the J_Q value can be J_{IC}, namely $B_N \geq 25 J_Q/\sigma_{fs}$.

Therefore, attempts are made to obtain the J_{IC} value of the virgin and degraded specimens, aged for 300hrs. and 1800 hrs. using the SZW method. The J_{IC} value of the virgins and degraded specimens are obtained using six different specimens. The multi-specimen method is used.

The results of the J_{IC} values obtained using the SZW method are compared with those obtained using the unloading compliance method as mentioned previously.

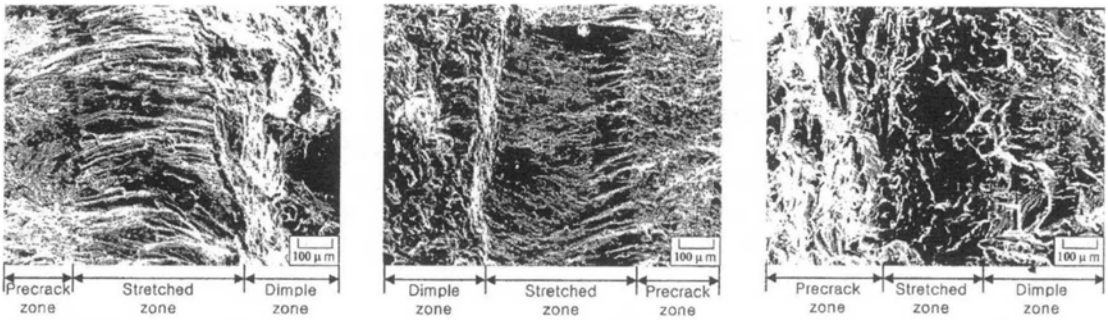
The stretched zone width shown in the fractured surface is measured after the specimen applied to an arbitrary load is immersed into liquid nitrogen and is fractured. The experiment is repeated six different times at different load levels for the virgin and aged specimens at 300hrs. and 1800hrs. and at 430℃, respectively. The stretched zones for each class of specimen are measured by dividing them into eight equally-spaced partitions of the stretched zone region beginning at the pre-crack tip boundary and ending in the dimple zone boundary. The measurements are performed at 3/8, 4/8 and 5/8 of the stretched zone and an arithmetic mean value (JSME, 1981) is considered as the stretched zone width. The typical fractographs are shown in Figs. 5, 6 and 7 and these pictures are taken at 100 times magnification (100×) using the SEM. The SZW of virgin, 300 hrs. and 1800 hrs. aged specimens are decreased in that order and it was 530μm, 312μm and 290μm, respectively. J_{IC} values of each specimen are estimated using the formula given in Eq. (5) (Kohayash, et al., 1977) . Table 3 shows the SZW and J values.

$$J = \frac{A}{Bb_0} f(a_0/W) \tag{5}$$

where $f(a_0/W) = 2(1+\alpha)/(1+\alpha^2)$, $\alpha = [(2a_0/b_0)^2 + 2(2a_0/b_0) + 2]^{1/2} - (2a_0/b_0 + 1)$ A : area under the curve of load-COD, B : thickness of specimen (if a groove is made, then $B = B_N$, B_N : net thickness (20mm)), b_0 : ligament ($W - a_0$), a_0 : fatigue pre-crack length and W : width of specimen.

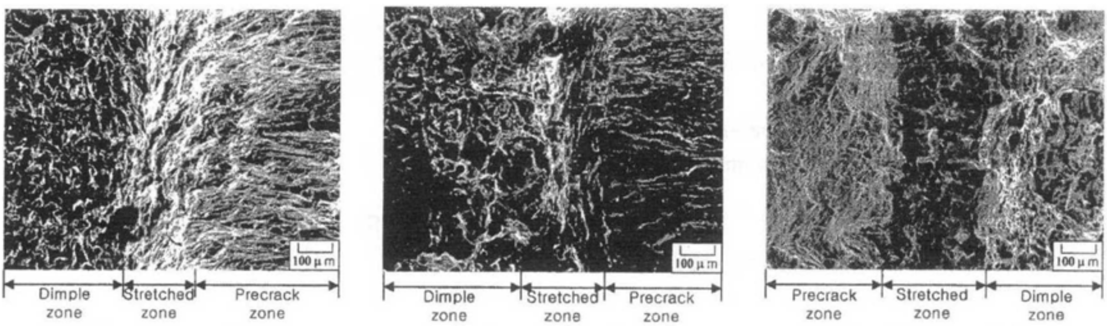
Table 3 SZW and J values of virgin and each degraded materials

		SZW (μm)	J-value (kJ/m^2)
virgin	No. 1	503.27	784.21
	No. 2	530.01	896.41
	No. 3	353.17	314.54
	No. 4	437.20	412.80
	No. 5	266.33	199.76
300 hrs degraded	No. 1	288.34	625.42
	No. 2	312.09	698.51
	No. 3	216.67	307.03
	No. 4	185.97	188.96
	No. 5	201.45	203.45
1800 hrs degraded	No. 1	283.07	562.50
	No. 2	292.37	593.75
	No. 3	224.14	289.07
	No. 4	205.34	234.60
	No. 5	188.56	190.46



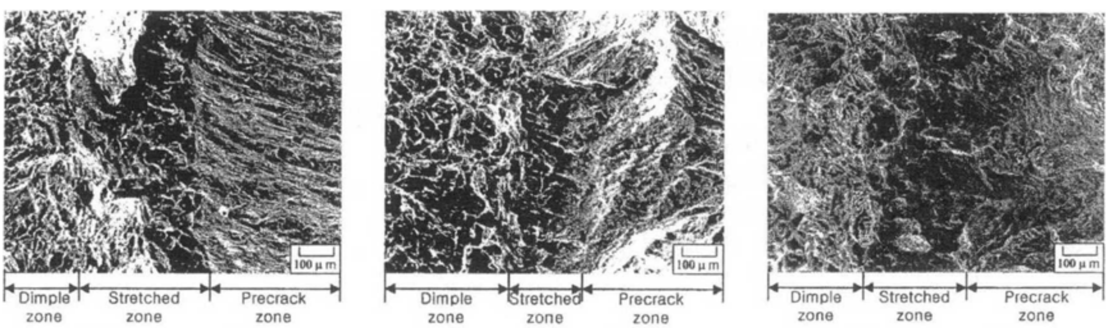
(a) Specimen # 1 (b) Specimen # 3 (c) Specimen # 5

Fig. 5 Fractograph of the virgin specimens in the stretched zone



(a) Specimen # 1 (b) Specimen # 3 (c) Specimen # 5

Fig. 6 Fractograph of the 300hrs. degraded specimens in the stretched zone



(a) Specimen # 1 (b) Specimen # 3 (c) Specimen # 5

Fig. 7 Fractograph of the 1800hrs. degraded specimens in the stretched zone

The J values of the virgin, 300hrs. and 1800hrs. aged specimens are decreased in that order. The toughness of the virgin specimens is at a higher value than the toughness of the degraded specimens. The larger stretch zone width of the virgin specimen is caused by large glide plane decohesion until the fracture is terminated. The stretch zone width of the degraded specimens is smaller than that of the virgin specimens. (Brothers et al., 1971)

2.2.2 The determination of J_{IC} using the SZW method

The relationships between the J and the SZW methods for virgin and aged specimens at 300hrs. and 1800hrs. are shown in Fig. 8. All J_Q values obtained using the SZW method satisfy the requirement that the J_Q value can be J_{IC} value.

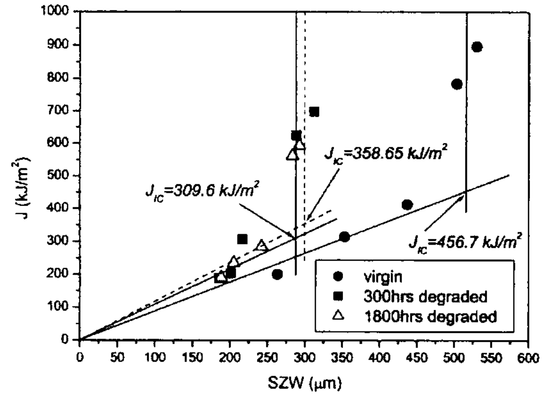


Fig. 8 Determination of the J_{IC} for virgin and degeaded specimens by the SZW method

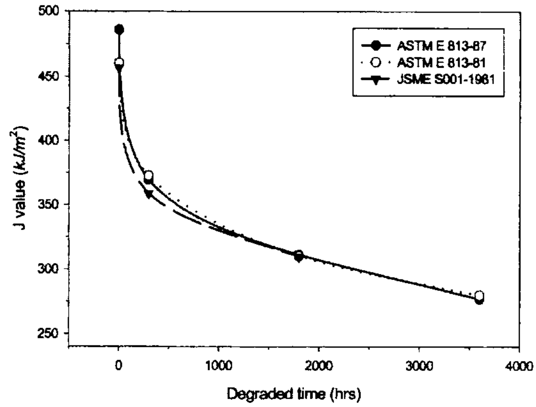


Fig. 9 Relationship between the ASTM E 813-87, the ASTM E 813-81, and the JSME S 001-1981 SZW method for the J_{IC}

Therefore, all J_Q can be considered as a J_{IC} value. The values of J_{IC} are decreased with an increase of degradation, as seen in Fig. 8. However, J_{IC} values obtained using the SZW method show somewhat smaller values than those obtained using the unloading compliance method. The J_Q value of the virgin material, obtained using the unloading compliance method, does not satisfy the requirement that J_Q can be J_{IC} while that value obtained using the SZW method does satisfy the requirement. This discrepancy occurs based on the method used to measure the crack growth in the unloading compliance method. The crack growth measurements in the unloading compliance method are performed by measuring seven points including the curvature effect of the pre-crack scenario. The SZW measurements exclude the curvature effect of the pre-crack by measuring three points in the middle point of the fracture surface. This can minimize the effect of the pre-crack curvature of the SZW measurement.

The comparison of J_Q and J_{IC} values obtained by the ASTM E813-87, the ASTM E813-81, and the JSME S001-1981 methods are shown in Fig. 9 for virgin and degraded specimens. The values of J_{IC} are decreased with an increase of the aging time. The J_{IC} values obtained by the ASTM E 813-81 show the largest values and these values are slightly decreased depending on the method used to evaluate the J_{IC} values. The J_{IC} values show the lowest values obtained by the JSME S001-1981. However, the J_{IC} values obtained by the three different methods agree reasonably well, as displayed in Fig. 9. When the J_Q and J_{IC} values obtained by the ASTM E 813-87 are compared with those of the JSME S001-1981 (SZW), the two results show reasonable agreement.

Therefore, the JSME S001-1981 can be used as in the case where the J_Q value violates the requirement that J_Q can be J_{IC}. If this requirement achieves satisfaction, both the ASTM E813-87 and JSME S001-1981 methods result in identical conclusions in the determination of the J_{IC}.

3. Summary and Conclusions

The elastic plastic fracture toughness was determined experimentally using the unloading compliance method, the ASTM E813-87 method, and the JSME S001-1981 method.

The specimens used in the investigation are virgin and aged specimens at 300hrs., 1800hrs. and 3600hrs. at 430℃ of ASTM A351 grade CF8M. These specimens are aged by an artificially-accelerated aging method in the laboratory. Via experiments to determine J_{IC} values, the following conclusions are found :

(1) The J_{IC} values decreased significantly with an increase of aging time. The J_{IC} value appears to reach an asymptotic value of after the aging for 3600hrs.

(2) The J_Q value of the virgin specimen that was obtained using the ASTM E813-87 method

does not satisfy the requirement of that the J_Q value which can be the J_{IC} value while the J_Q value of all specimens obtained by the SZW method (JSME S001-1981) satisfies the requirement, $B_N \geq 25 J_Q / \sigma_{fs}$.

(3) When the J_{IC} values obtained by the ASTM E813-87 method are compared with that found by the SZW method, it is concluded that the two results agree reasonably well even though the results obtained using the SZW method show somewhat smaller values than those obtained using the ASTM E813-87 method.

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