5-6 Estimating Fracture Resistance of Reactor Pressure Vessel Steels –Estimating Toughness against Combination of Cleavage and Intergranular Fracture–

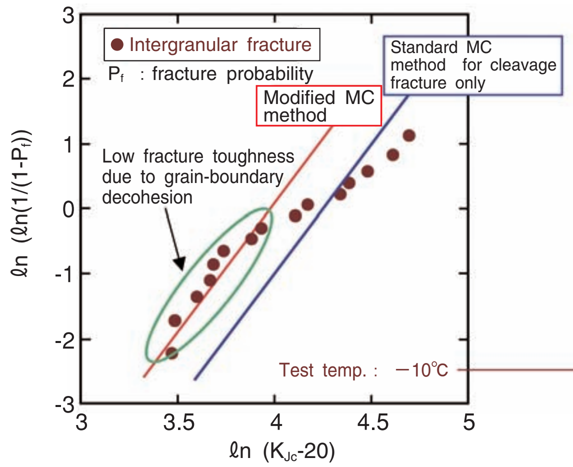

Fig.5-12 A Weibull plot of fracture toughness of intergranularly brittle material
The distribution of fracture toughness (K_{Jc}) values indicating grain boundary decohesion does not follow the linear regression defined in the standard method for cleavage fracture. A modified method is needed to estimate lower K_{Jc} values.

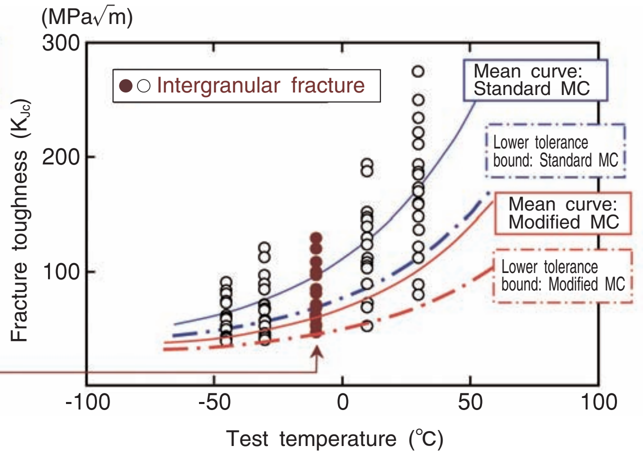

Fig.5-13 Temperature dependence of K_{Jc} values for the intergranularly brittle material together with the Master Curve
The K_{Jc} values are beyond the lower tolerance bound. The modified method enabled us to estimate lower K_{Jc} values due to intergranular fracture.

The reactor pressure vessel (RPV) is one of the most important safety-related structural components, because it has no redundancy and its failure is not considered in the design of the reactor. There is concern is that because the portion of the RPV surrounding the core region called "beltline" is exposed to neutron irradiation, the RPV material will be degraded (irradiation embrittlement). The effect is manifested by an increase in yield strength, a decrease in ductility, and degradation of toughness which are monitored by surveillance tests during plant operation. In the technical evaluation of every nuclear power plant whose operating period reaches 30 years, the irradiation embrittlement upon 60-years operation at high neutron fluence is estimated to ensure the structural integrity of RPV. One of possible types of embrittlement by such high neutron fluence is intergranular embrittlement caused by grain-boundary phosphorus (P) segregation. The P segregation is promoted by neutron irradiation and the presence of P weakens the cohesive strength of grain-boundaries, leading to embrittlement through intergranular fracture. How to estimate fracture toughness for the materials exhibiting intergranular fracture is one of the issues.

For fracture toughness evaluation of RPV steels, extensive efforts have been made to achieve direct determination of fracture toughness (K_{Jc}) in the ductile-to-brittle transition temperature region, using the so-called the "Master Curve" (MC) method. This estimates the fracture toughness versus temperature curve from a test at one temperature. Since fracture initiation is assumed to be cleavage in the MC method, it is questionable whether the method is applicable to materials subject to intergranular fracture.

The K_{Jc} values of the material exhibiting a mixed mode fracture of intergranular and cleavage due to intergranular embrittlement exhibit a large scatter. A Weibull plot of K_{Jc} values is shown in Fig.5-12, together with the data fitting denoted as a blue line by the standard MC method. The figure clearly indicates that the distribution of K_{Jc} values does not follow the linear regression defined in the standard method. It seems that the distribution of K_{Jc} values is from an inhomogeneous material creating two distributions of fracture toughness. This feature becomes more pronounced with increase in P concentration at the grain-boundaries. Since fracture toughness depends on the type of brittle fracture which initiates at the crack front, the obtained K_{Jc} values may follow the dual fracture toughness distributions of cleavage and intergranular fracture. We applied a modified MC analysis to the estimation of intergranular fracture by censoring the upper K_{Jc} data in Fig.5-12. The test temperature dependence of K_{Jc} is shown in Fig.5-13. The solid and dashed blue lines represent the mean curve and lower bound for fracture, respectively. The dependence of material subject to intergranular fracture as well exhibits low K_{Jc} values below the lower tolerance bound of brittle fracture. The modified method enables a more conservative fracture toughness estimate, as shown by the solid and dashed red lines in Fig.5-13.

Reference

Nishiyama, Y., Onizawa, K. et al., Phosphorus Segregation and Intergranular Embrittlement in Thermally Aged and Neutron Irradiated Reactor Pressure Vessel Steels, Journal of ASTM International, vol.4, issue 8, 2007, p.12, Paper ID JAI100690.