

IRRADIATION EFFECT ON STRUCTURAL INTEGRITY OF BIMETALLIC WELDS

Amit sarda¹, Rahul Chibber², B.K.Dutta³

¹Astt. Professor, M P Christian College of Engineering, Bhilai, INDIA

²Astt. Professor, Thapar University, Patiala, INDIA

³Reactor Safety Division, Bhabha Atomic Research Centre, Mumbai, INDIA

E-mail of corresponding author: amitsarda3@rediffmail.com

ABSTRACT

Integrity and reliability of reactor pressure vessel (RPV) is a decisive factor for safety as well as for economical reasons, to extend plant life. As a part of the design of primary heat transport piping of pressurized heavy water reactors, which use bimetallic weld components, under high neutron flux over considerably long period of time and may become brittle, resulting in cracks which may lead to accidents, it becomes essential to assess the structural integrity of the reactors under this scenario. During the operation of the reactors, bimetallic welds become brittle under the effect of irradiation. Such an irradiation embrittlement is manifested by an increase in the ductile-to-brittle transition temperature. The fracture behaviour of bimetallic welds changes with cryogenic temperatures from ductile associated with the upper shelf, to unstable cleavage over a narrow temperature range. Under typical conditions such as cryogenics, neutron irradiation and embrittlement, a crack initiates and grows initially by ductile tearing and ultimately failure occurs by catastrophic cleavage fracture, hence only a small risk of this type of failure occurs in nuclear power plant. Information on such fracture behavior of the material at transition region is mandatory to quantify the inherent safety margin available under such undesirable events. A material will be called useful within a nuclear reactor only when it must be able to withstand not only cryogenic temperatures but high fluxes of energetic neutron for prolonged periods. A lot of studies have been carried out on the irradiation behaviors of nuclear materials to solve the practical problems associated with a nuclear reactor and to meet the desired mechanical properties to the future design of nuclear reactor. This paper aims to highlight the issue of irradiation in bimetallic welds.

INTRODUCTION

For the sake of safety policy of PWR's it is the major concern to make sure that the adequate toughness of pressure boundary materials will remain until the end of original or extended life time. Degradation of material starts as the operational activities take place, keeping this fact in mind advancement in work has been intended for providing high quality materials with low sensitivity to degradations by considering the effects of operational parameters. The attempts in this field had to be deliberated particularly on the effect of those mechanisms endorsed by the operating parameters and its alleviation as parameters such as temperature, loading history, and corrosion attack and irradiation embrittlement can produce changes in material properties and can cause crack growth.

There are several intricate processes involved in the degradation of RPV steel and other such materials. This may include the factors such as chemical composition, presence of contamination and exposure to radiation effect. Out of the several factors mentioned, radiation is the most critical cause behind the dreadful condition of materials and especially in case of bimetallic welds the decrease in the ductility is framed by radiation effect. In the present study bimetallic welds are the subject of concern, as they are employed in joining piping systems to RPV's, PWR's and steam generators. Generally due to the metallurgical discontinuity and microscopic defects BMW zones get strained. Under operational condition of the reactors, these bimetallic welds become brittle due to the irradiation effect. Such an irradiation embrittlement is manifested by an increase in the ductile to brittle transition temperature. The cooling of the vessel material can bring down the temperature of ductile to brittle transition region. Under such conditions the micro cracks in the component subjected to tensile stresses may lead to unstable cleavage fracture. Cleavage fracture and ductile tearing are two competing mechanism in the ductile-to-brittle transition regime of bimetallic welds. In this system, bimetallic welds can withstand momentous amounts of ductile tearing without considerable loss of its load bearing capacity. However, many experiments show that stable crack growth by ductile tearing eventually gives way to catastrophic cleavage fracture. The latter appears to be the critical failure mechanism limiting the load bearing capacity of the structure hence there is great scope and interest in a predictive and prognostic models for cleavage fracture.

Most of the existing experimental data on cleavage fracture have a propensity to be highly scattered. Basically two reasons have been tendered for the large variations in measured cleavage fracture toughness at a given temperature within the transition region. First is the use of statistical sampling of a critical cleavage crack nucleus for the control of cleavage fracture toughness in the transition region. Second, the absolute dependency of cleavage fracture on crack geometry as intensity of stress triaxiality ahead of the crack tip is a strong function of the geometry of the crack and the amount of crack growth. Therefore the population of eligible particles for cleavage fracture depends utterly on crack geometry and this population changes with alterations in stress triaxiality.

These attributes of brittle fracture can be duly modeled by Bermin's Local approach. This model is based on Weibull's statistics for distribution of fracture strength of a material and facilitates to estimate the probability of brittle fracture. Further, the ductile fracture can be modeled using Gurson-Tvergaard-Needleman's (GTN) continuum damage mechanics approach that determines the accurate stress distribution ahead of the crack tip. Hence, for the ductile to brittle transition regime, both models need to be used and are explained in the present paper.

BIMETALLIC WELDS (BMW'S)

For a long time now, bimetallic welds (BMWs) have been a necessity within the pressurized water reactor (PWR) designs which uses enriched (about 3.2% U 235) uranium dioxide as a fuel in zirconium alloy cans. The fuel, which is arranged in arrays of fuel "pins" and interspersed with the movable control rods, is held in a steel vessel through which water at high pressure (at 16 MPa, to suppress boiling) is pumped to reactor vessel via cold lag pipeline to act as both a coolant and a moderator. After taking heat from core of reactor, the high-pressure water is passed to a steam generator, via hot lag pipeline which raises steam in the usual way. Both hot lag and cold lag pipe lines are joined by reactor vessel nozzle by a bimetallic weld joint. So it is required to use bimetallic welds, to get the benefit of different properties of two or more different metals and to overcome the problems such as size and other functional requirements like in case of nuclear reactor vessels. These bimetallic welds are used in manufacturing of equipment to satisfy different functional requirements of components. So that the bimetallic weld (BMWs) play a critical and indispensable role in the primary heat transport piping system in the pressurized water reactor. [1]

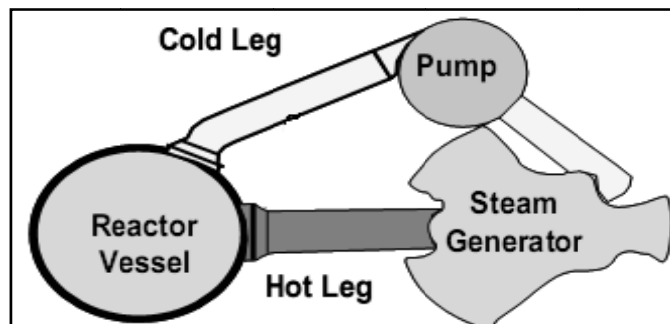


Fig 1: Arrangement of Reactor Pressure Vessel and Piping System

FABRICATION OF BMW'S

Bimetallic weld joint is a combination of 5 different zones (i.e. Base Metal 1, HAZ of Base Metal 1, weld, Base Metal 2, and HAZ of Base Metal 2). In bimetallic welds, base materials comprise of ferritic low-alloy steel SA508 and austenitic stainless steel of AISI 304 type as shown in (Figure 2) are used widely in steam generators of the nuclear power plant. The weld was manufactured by applying a buttering technique, where the first layer was of over-alloyed Ni-enriched E309L (24% Cr and 12% Ni), while the rest of the layer and the final weld were deposited with matching E308L (18% Cr and 8% Ni).

The use of Ni-enriched buttering layer (BU) is a common approach for reactor pressure vessels applications to reduce toughness degradation as a consequence of carbon precipitation faced with matching austenitic filler materials. After this post weld heat treatment of buttering layer is performed. The temperature of treatment depends upon layer thickness. The weld configuration is presented in figure 3 [2].

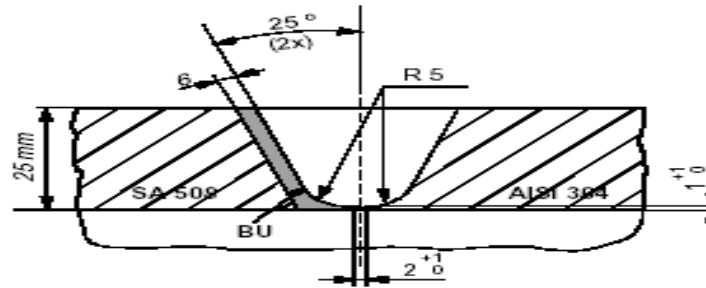


Fig 2: Weld assembly [2]

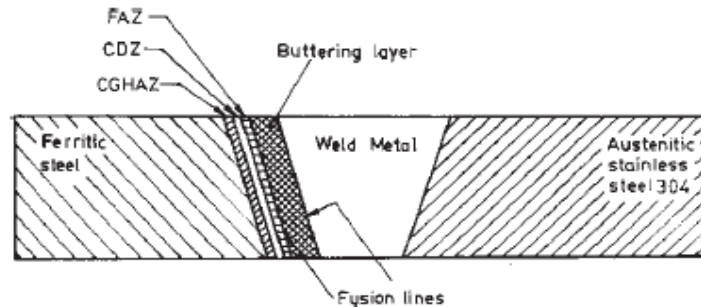


Fig 3: Bimetallic austenite-ferrite weld configuration with a buttering layer and different zones [2]

HOW BMW'S REACHES TO CRYOGENIC TEMPERATURE

As a part of the design of primary heat transport piping of pressurized heavy water reactors, which use bimetallic weld parts under high neutron flux over considerably long period of time and may become brittle, resulting in cracks which may lead to accidents. Hence, it is essential to assess the structural integrity of the vessel under this scenario. During the operation of the reactors, bimetallic welds become brittle under the effect of irradiation. Such an irradiation embrittlement is manifested by an increase in the ductile-to-brittle transition temperature. Brittle behaviour is characterized by an abruptly cracking without preceding plastic deformation, whereas ductile material shows plastic deformation before failure. The brittleness and ductility are also functions of the temperature. Some materials show a distinct change of the ductility within a certain temperature range, the so-called ductile to brittle (DBT) transition zone. The reactor core re-flooding in the event of loss of coolant lowers the temperature of the core. The analysis scenario considers the occurrence of loss of coolant accidents (LOCA) and subsequently the reactor core gets flooded through emergency core cooling system. This kind of analysis finds more relevance at higher fluency levels, i.e. when the vessel becomes more aged. As a result, the temperature of the material decreases and falls in the ductile-to-brittle domain.

The cooling of the vessel material can bring down the temperature of ductile to brittle transition region. Under such conditions the micro cracks in the component subjected to tensile stresses may lead to unstable cleavage fracture.

IRRADIATION EFFECTS

It is well known that bombardment of metals by energetic neutrons induces considerable changes in their physical and mechanical properties. An increase in yield stress associated with a reduction in ductility was observed in RPV steels used for cladding of RPV. There is considerable difference between the irradiated & unirradiated microstructure of the steel. The variation is depicted in figure 4.[3]

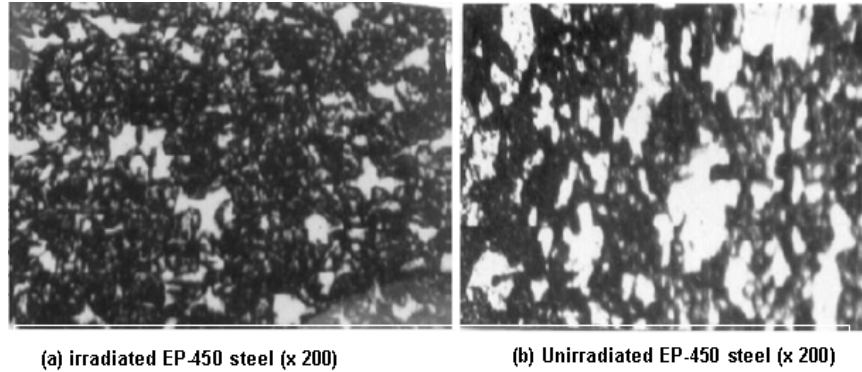


Fig 4: Microstructure of steel grains [3]

In the above figure the dark areas are sorbite grains & light areas are ferrite grains. The sorbite grains are very distinct, i.e., the grain boundaries are very clearly defined and always continue in nature. After irradiation, the boundaries are less distinct, becoming smaller, with their grain boundaries broken and unfinished.

The neutron irradiation leads to changes of several material properties. These changes can be used as indicators for the state of the degradation, i.e., the decrease of fracture toughness. Neutron embrittlement represents a difficult problem especially in case for PWRs, where the bimetallic welds are attaching the piping system to the various nozzles of the reactor pressure vessel (RPV) and steam generators (SG).

MICROSCOPIC CAUSES OF RPV EMBRITTLEMENT

The microscopic causes of embrittlement lie in the forming of obstacles to dislocation motion, called “hardening centers”, as well as to change the composition and structure of the microscopic interfacial regions along which crystal plane sliding occurs. Both these phenomena are caused by several types of radiation-matter interactions, most of which are, in PWRs, induced by fast neutrons. Also γ -rays, in less frequent circumstances, may give a substantial contribution. From this consideration it follows that fast neutron irradiation is not the only cause of vessel wall embrittlement, even though its contribution is very often the dominant one.

NEUTRON IRRADIATION

Neutron irradiation is exposure to penetrating radiation. Irradiation occurs when all or part of the body is exposed to radiation from neutron source. The reactor pressure vessels of commercial power plants are subject to embrittlement mainly due to exposure of high-energy neutrons from the core. Thermal neutrons and γ -rays are also additional sources of damage. For a given exposure, copper, phosphorus and nickel are recognized as the major deleterious element of concern for irradiation degradation of material properties. However, an accurate prediction of the radiation damage cannot account only for the consequences of the occurrence of a postulated collision event, but also for the probability that this event can actually occur. Since boron is often present in RPV steels as impurity, neutron irradiation can yield helium production. Then, the bubbles so formed tend to coalesce at the grain boundaries, initiating the so-called grain-boundary cracking, which causes structure embrittlement.

NEUTRON EMBRITTLEMENT MECHANISMS

The understanding of irradiation embrittlement of the pressure vessels of nuclear reactors is a key issue for plant lifetime assessment and much effort has been done in the last decades to tackle this complex issue. For the understanding of mechanisms of embrittlement, and the role of elements like Ni, Cu and P, the use of model alloys has proven to be a key methodology in connection with the utilization of material testing reactors or suitable channels of commercial ones.

The embrittlement of steels exposed to radiation fields (neutron and γ -radiation mainly) is directly and indirectly caused by displacements of atoms from their original positions due to collisions by energetic particles. After the collision, a so-called displacement cascade is formed containing several vacancies in the middle, surrounded by a cloud of interstitial atoms. Most of the defects recombine and relatively minute defects survive to become freely migrating point defects, which, together with collapsed cascades, take part in the radiation induced

damage processes. The radiation damage of RPV materials is proportional to the number of neutrons hitting the material with high magnitude energy to induce atom displacement(s).

The embrittlement mechanisms taking place during neutron irradiation of reactor pressure vessel (RPV) steels and welds have been analyzed in several papers [2-4]. The three basic mechanisms contributing to neutron embrittlement for both steels and welds are: direct matrix damage, irradiation induced precipitation and elements segregation. In spite of this fact the models for analysis of radiation embrittlement are mainly based on statistical correlation of large sets of data.

A critical-temperature-shift-based methodology is used for assessment of irradiation embrittlement of pressure vessel steels. Conventionally, the Charpy temperature shift methodology is utilized. Moreover, the attempts are made to use the Master curve technique to solve this problem. Recently, the local approach to fracture (LAF) has been developed, which can be used as a powerful tool for solving this problem. In the present case, the behaviour of fracture mechanism can be understood by using GTN model [5-6] for ductile fracture & Beremin's models [7-9] for cleavage fracture.

DUCTILE TO BRITTLE TRANSITION

The ductile to brittle transition is characterized by a sudden and dramatic drop in the energy absorbed by a metal subjected to impact loading. This transition is practically unknown in FCC metals but is well known in bcc metals. As temperature decreases, a metal's ability to absorb energy of impact decreases. Thus its ductility decreases. At some temperature the ductility may suddenly decrease to almost zero. This transition is often more abrupt than the transition determined by the energy absorbed. This temperature is called the nil-ductility transition temperature (NDT).

According to USNRC Regulatory Guide 1.99 Rev. 2, the shift in DBTT as a function of the neutron fluence is given by: $\Delta DBTT = [CF] \times f (0.28 - 0.1 \log f)$, Where CF is a function of the weight percentages of copper and nickel in the material. Here, f is the fluence in the unit of 10^{19} n/cm^2 .

MICROMECHANICAL MODELLING

Bimetallic welds are used extensively in the construction of nuclear reactor pressure vessels (RPV). Though these welds have a high strength, they are susceptible to a change in fracture mode from ductile to brittle. This change in fracture behaviour may be due to reductions in temperature, radiation exposure, increased strain rate/stress triaxiality (i.e. constraint) or a combination of these factors. In order to design these welds to exist at cryogenic temperatures, so it is important to understand the micro mechanisms of fracture.

The concept of micromechanical modelling as a method for better understanding of fracture mechanism and the characterization of materials is embedded in continuum mechanics. It combines theoretical, experimental and numerical methods enable a less conservative assessment in structural integrity on a micro scale level. It describes the phenomenological, smoothed behaviour of volume elements containing inhomogeneous microstructure by means of uniform stresses and strains. The final goal is to develop predictive approaches which can be used in FE codes for structural analysis. Several excellent reviews and books have already been written on the micro mechanism of failure in metals.

BEREMIN MODEL FOR CLEAVAGE FRACTURE

It is now a well-accepted fact that the fracture of ferritic steels in the temperature range in which the fracture propagates by cleavage is originated in microcracks (mostly in precipitates), ahead of the macrocracks; the macrocracks could be either pre cracks in a test specimen or surface cracks in structures. For cleavage fracture, a local failure criterion has been proposed such that cleavage occurs when the opening stress exceeds a critical cleavage stress over a characteristic distance ahead of the crack tip. It is unclear, however, whether this criterion can be applied to cleavage fracture preceded by ductile crack growth. Also, the prediction of lower bound toughness (the minimum value of the scatter band in a transition curve) is of particular importance to those industries where safety issues are involved. The mechanism of cleavage fracture is "growth controlled" cleavage microcracks are progressively nucleated under the influence of plastic strain and are detained at microstructural barriers. Fracture occurs when the longest crack reaches the Griffith stress given by:

$$\sigma_c = \sqrt{\frac{2E\gamma_s}{\alpha a}} \quad (1)$$

where E is the Young's modulus, γ_s the "effective" surface energy, α a numerical constant function of the crack shape, and a the size of the longest microcrack. However this theory is too simple since it does not account for the different steps encountered during microcrack initiation and microcrack propagation.

Rather surprisingly, although the scatter in cleavage stress measurements is well known since a long time, it was only in the 1980's that models have been proposed to account for this scatter. Nowadays the most widely used models are those derived from the work by Beremin. Assuming that the material contains a population of micro defects (inclusions, martensite-austenite (M.A.) constituents in welds, grain-sized microcracks, etc.) distributed according to a simple (power or exponential) law, $p(a)$, the weakest link theory writes that the probability to failure $P(\sigma)$ of a representative volume element, V_u , is given by:

$$P(\sigma) = \int_{a_c(\sigma)}^{\infty} p(a) da \quad (2)$$

where $a_c = 2E\gamma_s/\alpha\sigma_c^2$ is simply given by Eq. 1. Knowing the distribution $p(a)$ it is therefore possible to calculate $P(\sigma)$.

In a volume, V, which is uniformly loaded and which contains V/V_u statistically independent elements, the probability to failure based on the weakest link theory can thus be written as:

$$P_R = 1 - \exp\left[-\frac{V}{V_u} P(\sigma)\right] \quad (3)$$

However when the critical step for cleavage fracture is the propagation of microcracks initiated from particles (inclusions, M.A constituents, carbides) which can be metallographically observed, the distribution $p(a)$ can be determined experimentally. Two types of laws have been proposed from these observations: the power law and the exponential law. The power law is simple since it leads to the well know Weibull expression. When $p(a)$ is expressed as:

$$p(a) = \gamma a^{-\beta} \quad (4)$$

it can easily be shown that P_R can be written as:

$$P_R = 1 - \exp\left[-\frac{V}{V_u} \left(\frac{\sigma}{\sigma_u}\right)^m\right] \quad (5)$$

The 'm' is the Weibull exponent or Weibull modulus or shape parameter which describes the scatter of the distribution, where the Weibull shape factor is given by:

$$m = 2\beta - 2 \quad (6)$$

while $\sigma_u = (m/2\gamma)^{1/m} (2E\gamma_s/\alpha)^{1/2}$, Eq. (5) is a simplified expression since no threshold is introduced.

In three dimensions and in the presence of smooth stress gradients, this equation can be expressed as:

$$P_R = 1 - \exp\left[-\frac{\int_{PZ} \sigma_I^m dV}{\sigma_u^m V_u}\right] \quad (7)$$

where the volume integral is extended over the plastic zone (PZ). The Weibull stress, σ_w , is defined as follows by a summation of the maximum principle stresses σ_I . Introducing to so-called Weibull stress written as:

$$\sigma_w = \sqrt[m]{\int_{PZ} \frac{\sigma_I^m}{V_u} dV} \quad (8)$$

Eq. (7) can simply be expressed as:

$$P_R = 1 - \exp\left[-\left(\frac{\sigma_w}{\sigma_u}\right)^m\right] \quad (9)$$

Where σ_u is the scaling parameter to describe the point of distribution function on the stress axis at $\ln\left(\frac{1}{1-P_f}\right)=0$. This gives $P_f=0.632$, i.e. failure probability value of 63.2%. Since plastic deformations are a prerequisite for cleavage fracture, the summation is taken over the plastically deformed part of the volume only.

The values of 'm' and σ_u are generally determined using Maximum Likelihood Method. In this approach, the values of the two parameters are adjusted such that there is 'most likely' representation of experimental data by Weibull function.

MODELLING DURING DUCTILE FRACTURE

Ductile fracture of metallic materials involves cavity nucleation and void growth to coalescence. Many studies have been devoted to the micro mechanisms accompanying void nucleation from second-phase. Much progress has been made to model cavity growth since the pioneering studies by different researchers. Significant progress has also been made in modelling the onset of void coalescence by internal necking in ductile materials. All these models dealing with the three stages of ductile fracture are very promising, since theoretically, they are able to predict the strain to failure as a function of stress triaxiality when the initial microstructural parameters of the material (volume fraction of inclusions, shape of the voids and void spacing) are known. However the comparisons between experimental and theoretical results are still limited since the new models required for providing detailed quantitative information on the microstructural. The Gurson model is the first micromechanical model for ductile fracture which introduces a strong coupling effect between deformation and damage. This model is representative of the void growth stage only. It is derived from an analysis similar to that of Rice and Tracey for an isolated void. The Gurson yield surface is given by the following equation:

$$\phi = \left(\frac{\sum_{eq}}{\sigma_o}\right)^2 + 2f \cosh\left(\frac{1}{2}\left(\frac{\sum_h}{\sigma_o}\right)\right) - (1+f^2) = 0 \quad (10)$$

This yield surface is identical to the von mises yield surface when the volume fraction of cavities, f is equal to zero. It is also very similar to the von mises yield surface for low hydrostatic stresses. The main difference is that, owing to the presence of a void, plastic deformation takes place under large hydrostatic stresses whatever the value of the effective stress, σ_e while a von mises material is incompressible and does not yield plastically under pure hydrostatic stresses. As soon as voids have started to nucleate, the accumulation of plastic deformation causes the enlargement of the voids and an increase of the void volume fraction which, by stating volume conservation, writes:

$$\dot{f}_{growth} = (1-f) \dot{\epsilon}_{ij}^p \quad (11)$$

where $\dot{\epsilon}_{ij}^p$ are the ij components of the overall plastic strain rate tensor. The full evolution law for the void volume fraction is written as:

$$\dot{f} = \dot{f}_{growth} + \dot{f}_{nucl} \quad (12)$$

The material damage and ductile fracture initiation considers alloy as a porous medium where the influence of nucleated voids on the stress/strain state and plastic flow cannot be avoided so that the original Gurson model (Eq. 10) has been modified by Tvergaard and Needleman and is written as the GTN potential:

$$\phi = \left(\frac{\sum_{eq}}{\sigma_o}\right)^2 + 2q_1 f^* \cosh\left(\frac{3}{2}q_2 \left(\frac{\sum_h}{\sigma_o}\right)\right) - (1+q_3 f^{*2}) = 0 \quad (13)$$

Here, \sum_{eq} and \sum_h denote the macroscopic equivalent stress and the hydrostatic macroscopic stress, respectively. σ_o is the equivalent tensile yield stress. The constitutive model is implemented in a F.E. code to

simulate the initiation and growth of the crack. A micromechanical damage model, such as the GTN model (and its extensions) is used in such a way that it should adequately reproduce the behavior of a material cell. Near a crack tip strong stress and strain gradients develop at the scale of the void cell size. These gradients are roughly averaged by only using a single FE. This approach requires thus the introduction of a length scale in the model which is related to the mean spacing between cavities.

DISCUSSION & CONCLUSION

With the help of above two mechanisms one can perform characterization of the mechanical behavior and micro structural examination of the bimetallic weld at cryogenic temperatures as well as experiments can be easily carried out for determination of fracture characteristic of the real components at cryogenic temperature through micromechanical modelling approach.

While operating under cryogenic conditions the bimetallic welds are very sensitive to the failures due to effects of irradiation & embrittlement behaviour. Such operations generally cause for two failure modes i.e. ductile & cleavage and to understand these failure mode it is require to use probabilistic models such as GTN & Beremin's, which are explained in the study work. With the help of this study it may become quite fantastic job to apply the experiments on bimetallic joints used in reactor pressure vessels and access the integrity & safety of vessels to enhance the life cycle of nuclear reactor.

REFERENCE

- [1] Faidy C., "BIMET: Structural integrity of Bi-Metallic Components- Program overview", SMIRT 15. Paper G02-6, Seoul, KOREA August 1999. Nevasmaa
- [2] Chhibber, R; Arora, N; Gupta, S; Dutta, B. K., "Use of Bimetallic welds in Nuclear reactors: Associated problems and Structural integrity assessment issues", Journal of Mechanical Engineering Science, Volume 220, Number 8, pp.1121-1133, 2006.
- [3] O. P. Maksimkin, F. A. Garner "Phase Transformations Observed In EP-450 Ferritic/Martensitic Steel Irradiated at 30 Oc to 40.3 Dpa in the Bn-350 Fast Reactor" Institute of Nuclear Physics, National Nuclear Centre, Alma Ata, Kazakhstan and Pacific Northwest National Laboratory
- [4] Odette G.R. and Lucas G.E., (2001), "Embrittlement of Nuclear Reactor Pressure Vessels", journal JOM, 53(7) 92001), pp. 18-22.
- [5] A. L. Gurson (1977) Continuum theory of ductile rupture by void nucleation and growth: Part I—yield criteria and flow rules for porous ductile media. J. Engng Mater. Tech. 99, 2–15.
- [6] Needleman A, Tvergaard V. An analysis of ductile rupture modes at a crack tip. J Mech and Phys of Solids 1987; 35:151-83.
- [7] F.M. Beremin, A local criterion for cleavage fracture of a nuclear pressure vessel steel, Metall. Trans. A. vol. 14A (1983) 2277-2287.
- [8] F. Mudry (1987) A local approach to cleavage fracture. Nuclear Engng Design 105, 65–76.
- [9] B. K. Dutta, et al. (2007) "Temperature Dependency of Beremin's Parameters for 20MnMoNi55 Material", BARC Mumbai.