High Temperature Low Cycle Fatigue of 316L(N) Stainless Steel base, Welds and Weld Joints

EXECUTIVE SUMMARY

Cyclic stress evolution and fracture behavior of 316(N) weld metal and 316L(N)/316(N) weld joints are studied in strain controlled Low Cycle Fatigue. The fatigue life of the weld metal is found to be better than the weld joints. Microstructural heterogeneity across the weld joint has resulted in poor fatigue life with most of the failures being initiated in heat affected zone. Some failures have been observed in weld metal zone of weld joint at high strain amplitudes. Differences in flow stress of weld metal and base metal contribute to most of the plastic strain in weld joint. As a first approximation to this strain incompatibility, plastic strain contribution from the weld metal and base metal zones of the weld joint are calculated by the rule of mixtures under equi-stress conditions and it is observed that base metal zone contributes to most of the plastic strain in weld joint.

OUTLINE

In start-up and shutdown operations, structural components operating at elevated temperatures are often subjected to reversed plasticity due to cyclic thermal stresses. Cyclic thermal stresses arise when free expansion and contraction of the component is totally/partially constrained either by external or by internal constraints. In addition to this, steady state operation at elevated temperature introduces creep resulting in creep-fatigue interaction. In view of this, design against fatigue and creep-fatigue interaction is a major consideration for Liquid Metal cooled Fast Breeder Reactor (LMFBRs) structural components.

The weldments are micro-structurally and mechanically heterogeneous, which could form one of the potential sites for the fatigue failure. In addition, this heterogeneity introduces the differences in fatigue damage evolution mechanisms, fatigue crack initiation life and crack propagation rates in three zones of the weldment, i.e., base metal, Heat Affected Zone (HAZ) and Weld metal. Therefore, weldments are the critical sections to be considered carefully in the design of LMBFR components. Most of the failures have been found to originate from HAZ in the weld joint. Occasionally, fracture was also observed in weld zone. 316L(N) austenitic stainless steel is the material chosen for the primary components in LMFBRs due to its excellent high temperature mechanical properties and compatibility with the heat transfer medium i.e., liquid sodium. LCF behavior of 316L(N) \ 316(N) weld joints and 316(N) weld metal are presented in the range 773 K - 873 K. 316L(N) SS plate and 316(N) electrode, used for weld joints, in the present study are indigenously developed materials.

Cyclic stress response represents the variation of stress response of the material during cycling and it can include regimes of hardening, softening and saturation. The relative proportion of each of these regimes depends on the initial microstructure and also the microstructural changes that take place during cycling. Weld metals displayed a gradual softening regime for the major portion of the life after a brief period of hardening. Weld joints exhibited initial hardening followed by a continuous and gradual softening regime. Initial hardening is similar to that observed in 316L(N) base metal though the degree of hardening is less. This seems to be justifiable since major part of the gauge length is made up of base metal.
At all the testing conditions, weld joints showed lower fatigue lives compared with weld metal. This can be ascribed to the microstructural influence on the fatigue crack initiation and crack propagation. Crack initiation and propagation was found to be transgranular at all testing conditions, in both weld metal and weld joints.

Crack initiation in weld joint occurred in coarse-grained HAZ as shown in Fig. 2. In this figure cleavage faceted fracture corresponds to that of large grain size in HAZ. Though the observed crack initiation in both weld metal and weld joint was transgranular, there exists significant differences in crack propagation that display profound influence on their fatigue life. In austenitic stainless steel welds, the delta ferrite intentionally introduced to reduce their tendency to hot cracking and micro-fissuring gets transformed to a hard and brittle sigma phase when these materials are exposed to elevated temperatures, 773 to 1173 K, for extended periods of time. The fine duplex austenite-ferrite microstructure of weld metal, with its many transformed phase boundaries during testing, offers greater resistance to the extension of fatigue cracks by causing deflection of the crack path. This has been also observed in 316 weld metal. Crack deflection leads to reduced stress intensity at the crack tip and an associated reduction in the crack propagation rate. While in the weld joints, the resistance to transgranular crack propagation in HAZ is less due to its coarse-grain size, i.e. the smaller the grain boundary area the less is the number of crack-arrest events that causes the crack front to be held back and necessitates the crack initiation phase to occur in the adjacent grain.

Fig. 2: Transgranular initiation and propagation in the coarse grained HAZ of weld joint

To determine the strain incompatibility between weld metal zone and base metal zone in weld joint, an attempt has been made (as a first approximation) to calculate strain contributions from weld metal and base metal zones, by the rule of mixtures. It states that under equi-stress conditions, stress borne by each of the phases in a composite laminate is the same, but the strains they experience are different. Base metal zone takes up most of the imposed plastic strain in the weld joint. Thus accumulated plastic strain in weld metal is small in magnitude which can cause spring-back effect on adjacent base metal. With increasing stress amplitude on weld joint, strain incompatibility and associated spring back effect on adjacent base metal increases and could cause cracking in HAZ.

This work characterizes the deformation and damage mechanisms of indigenously developed 316L(N) SS base, weld and weld joints during Low Cycle Fatigue deformation. The mechanisms of crack initiation and propagation in weld joints and welds have been identified.