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# FATIGUE BEHAVIOUR OF 316 (N)/316(N) WELD JOINTS AND 316(N) WELDS

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## ABSTRACT

In fast reactors, components operating at high temperatures are often subjected to cyclic thermal stresses as a result of temperature gradients that occur on heating and cooling during start-ups and shutdowns or temperature. Further, on load periods introduce creep loads and combination of these two causes creep-fatigue interaction. Low cycle fatigue and creep fatigue are therefore important considerations in the design of high temperature systems subjected to thermal transients' variations during steady state operations.

In this paper, a comparative study of the Low Cycle Fatigue (LCF) and creep-fatigue interaction behaviors of indigenously developed 316(N) base metal, 316(N) weld metal and weld joints is presented. Total axial strain controlled fatigue tests were carried out in the temperature range of 773 – 873 K at strain amplitudes in the range of ±0.25 to 1.0%. Creep-fatigue tests were performed at 873 K introducing hold times at peak strain in the tension portions of the cycle. Further, the effects of strain rate on LCF were studied in the strain rate of 3 x $10^{-5}$ $s^{-1}$ to 3 x $10^{-2}$ $s^{-1}$ at 773 K.

Cyclic stress response behavior and fatigue life variations of the weld metal and weld joints under different testing conditions are compared with the base metal. Base metal showed an initial hardening followed by a saturated response while the weld metal and weld joints showed a softening regime in between. The initial hardening observed is attributed to dynamic strain ageing and cyclic softening observed in weld metal and weld joints to annihilation of dislocations. At high temperatures δ ferrite got transformed into brittle phases like σ phase and carbides leading to crack deflection in the weld metal. In general, the LCF and creep-fatigue lives exhibited by the base metal were higher than the of weld metal. Weld joints exhibited the lowest life. The differences in fatigue and creep-fatigue lives of the weld metals and base metal under various testing conditions have been found to be associated with the basic differences in chemical composition and transformation of δ ferrite to brittle phases. The differences in LCF and Creep-Fatigue behaviors of base and weld metal and weld joints were rationalized on the basis of deformation and fracture behavior. Further, the data generated is compared with that available from the literature and RCC-MR design curves. Life prediction has been carried out using Ostergren Frequency Modified Damage Function (FMDF) and predicted lives are found to within a factor of 2.

**Keywords:** *effect of friction, deep drawing, finite element simulation*

## 1. INTRODUCTION

In start-up and shutdown phases of many high temperature operations, structural materials 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 the 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 (LMFBR) components.

Moreover, some of the structural components are joined by welding techniques and therefore welded joints are in evitable in the design/erection of physical structures. These weldments are micro-structurally and mechanically heterogeneous, across the weld joint, which could form one of the potential sites of 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 weldments, 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 [14]. However, fracture was also observed in weld zone [3,5]. To ensure the safety of welded structures many authors have concentrated on the evaluation of fatigue damage of welded joints with inherent mechanical heterogeneity.

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 liquid sodium. The strength and ductility of 316L(N) stainless steel weldments have been reported to be lower than the properties of the base material [6]. While it is recognized that the integrity of the structure is limited by the properties of the weld joint, the design of welded components in nuclear reactors is based on the base material data with suitable scaling actors [7]. This is mainly due to the inadequate data base that is available on weld and weldments properties. Few attempts [1,5] have been made in the past to characterize the LCF behavior of weld joints and weld metals over a range of strain amplitudes, strain rates and temperatures. In this paper, comparative weld metals are presented under continuous cycling conditions. Furthermore, time-dependent effects are studied in above weld joints and weld metal. 316L(N) SS plate and 316(N) electrodes, used for weld joints, n the present tests on welds and weld joints are compared with an earlier study [8] on high temperature LCF properties of indigenously developed 3d16L(N) base material.

## 2. EXPERIMENTAL DETAILS

The chemical composition in weight % of the Nuclear grade AISI 316L(N) SS base metal and 316(N) electrode used in the present study are given Table 1. Base metal was solution treated at 1373 K for 1 h and water-quenched. The average grain size obtained was 85μm

**Table1** Chemical composition of indigenously developed materials, in weight %

| Materials | C | Mn | Ni | Cr | Mo | N | S | P |
|---|---|---|---|---|---|---|---|---|
| 316L(N) Base metal | 0.025 | 1.75 | 12.0 | 17.0 | 2.4 | 0.09 | 0.002 | 0.023 |
| 316(N) electrode | 0.055 | 1.5 | 12.0 | 17.5 | 2.30 | 0.095 | 0.01 | 0.025 |

### a. Welding Procedure

Sections of 330 x 125 x 30 mm and 660 x 250 x 25 mm cut from the mill-annealed plates were joined along the length direction by shielded metal arc welding process using type 316(N) welding electrodes, to make weld pads for weld joint and weld metals specimens respectively as shown in figure 1. The electrodes were soaked for one hour at 473 K before the commencement of welding. During welding, the voltage, the current and an inter-pass temperature were maintained at approximately 25 V, 150 A and 423 K respectively. The weld pads were examined by X-radiography for their soundness, followed by δ ferrite measurement using a magne-gauge.

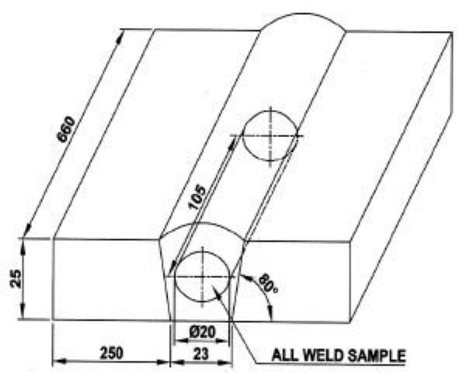


**Figure1(a)** Weld pad configuration for all weld specimen.

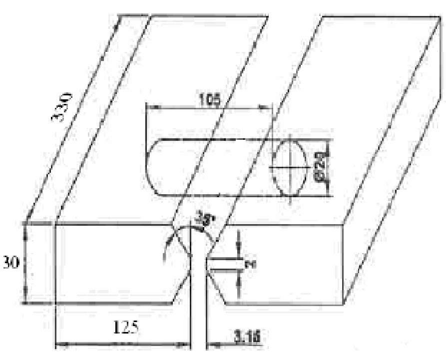


**Figure 1(b)** Weld pad configuration for weld joint specimens with double-V configuration.

### b. Low Cycle fatigue testing

Fully reversed total axial strain- controlled LCF tests were conducted using an Instran 1343 servo hydraulic machine and Electro mechanical testing system. Following tests were conducted on weld joints (WJ) and weld metal (WM).

**Table 2** LCF testing conditions

| Test parameters | Temperature, K | | |
|---|---|---|---|
| | 773 | 823 | 873 |
| $\pm$ 0.4 / 0.6 / 1.0 % at 3 * $10^{-3}$ $s^{-1}$ | WM, WJ | WM, WJ | WM, WJ |
| 3 * $10^{-3}$ to 3 * $10^{-5}$ $s^{-1}$ at $\pm$ 0.6 % | WM, WJ | WJ | WJ |
| 1 MHT / 10 MHT at $\pm$ 0.6 % | ------ | ------ | WM |

WM, weld metal ; WJ, Weld joint ; MHT, minute hold time

Fatigue crake initiation and propagation mechanisms, were characterized by optical microscopy and scanning electron microscopy.

## 3.0 RESULTS AND DISCUSSION

### 3.1 Cyclic Stress Response

Cyclic stress response represents the variation of stress response of the material during cycling, as shown in figure 2. Weld metals displayed a gradual softening regime for the major portion of the life after a brief period of hardening. Similar stress response has been reported on 316[1] and 308 weld metals [9]. 316 weld metal has been shown to contain very low dislocation density in both austenitic and ferrite phases after testing compared to that in the untested condition [1]. Valsan et al [1] have attributed softening to the annihilation of dislocations, which resulted from break down of dislocation tangles and subsequent annihilation of dislocation of opposite sign in to and fro motion cycling.

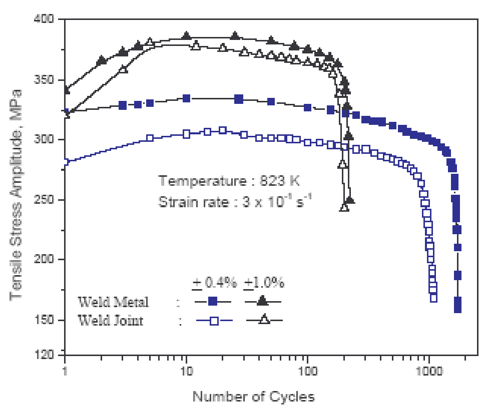


**Figure 2** Cyclic stress response of weld metal and weld joint at 823 K

Weld joints exhibited initial hardening followed by a continuous and graded softening regime, except at low strain amplitudes, Figure 2. Initial hardening is similar to the 316L (N) base metal [8], 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 low strain amplitude i.e., ± 4%, quasi-plateau saturation has been observed suggesting the predominance of deformation in the base metal or micr structurally altered region (HAZ). Similar stress response has been observed at 773 & 873 K also.

The initial cyclic hardening can be attributed to the individual or combined effects of a) mutual interaction among dislocation, b) formation of fine precipitates (for ex.: $Cr_2N$ complexes, Carbides) on dislocations during testing, and c) interaction between dislocations and solute atoms. Contribution from precipitates can be ruled out due to shorter duration of LCF tests as $3*10^{-3}s^{-1}$. However, it has been reported [10] that, at shorter ageing times also, substitutional-interstitial complex of a few atomic layers thick can also lead to rapid initial strain hardening due to the increased resistance to dislocations motion in the ordered domains in the matrix. It has been observed [8] that 316L (N) stainless steel showed dynamic strain ageing (DSA) in the temperature range 573-873 K. Though serrations are not observed in the present tests, possibility of DSA cannot be ruled out since high degree of hardening (defined as ratio peak stress to first cycle stress) is observed at 823 K in weld joints and at 773 K in weld metals.

Decrease in strain rte from $3x10^{-5}$ to $3x10^{-5}$ $s^{-1}$ has resulted in an anomalous stress response. i.e., increase in stress response with decrease in strain rate, as shown in figure 3a for weld metal at 773 K. In addition to this, increase in number of cycle to attain peak cyclic stress, serrations in plastic portions of stress-strain hysteresis loops, increase in degree of hardening (ratio of peak stress/first cycle stress) are also observed indicting the occurrence of dynamic strain ageing. Srinivasan et al [11-12] and Seong-Gu Hong [13] have reported similar manifestations signifying the occurrence of DSA. It has been suggested that DSA essentially refers to the attractive interaction between diffusing solute species and mobile dislocations during the deformation. This ageing of mobile dislocations results either during viscous type dislocation motion or during the period of their temporary stay at local obstacles in the glide plane. Srinivasan et al [11-12] found an increase in the value of friction stress with increasing temperature or decreasing strai rate in the domain where DSA is active and Weiss et al [14] have reported an increase in dislocation density in the DSA regime. The matrix thus hardens during DSA, causing an increase in the flow stress needed to impose the same total strain during successive cycles. The increase

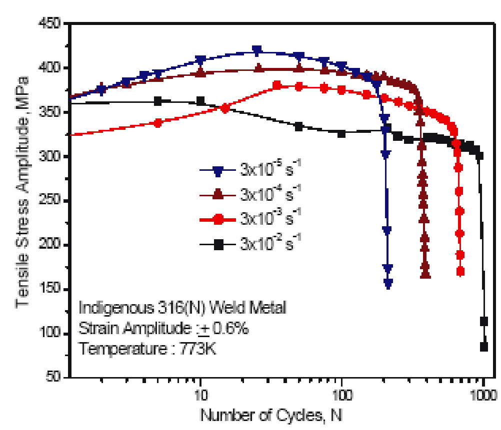


**Figure 3a** Strain rate effect on cyclic stress response of weld metal

in cyclic stress response with decreasing strain rate due to DSA during LCF has been reported by several investigator [15-16]. It has been reported that in austenitic stainless steels, DSA occurs due to the interaction of mobile dislocations with chromium atoms [17].

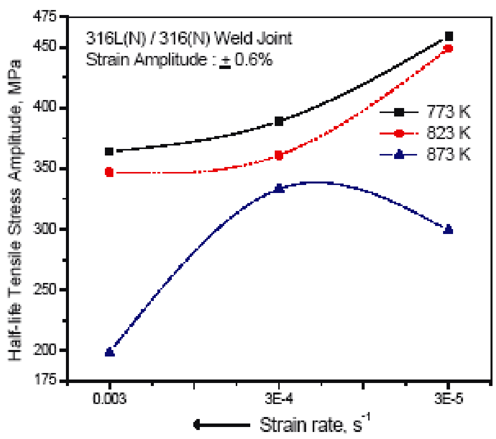


**Figure 3b** Strain rate effect on half tensile stress amplitude values of weld joint

Weld joints have also shown similar stress response, but at 873 K cyclic stress response deceased with decrease in strain rate from $3x10^{-4}$ to $3x10^{-5}$ $s^{-1}$, figure 3b. Several authors [12, 18] reported differences in the dislocation substructure in the strain rate and temperature domain depicting DSA and non DSA regimes. In general, cell structures were observed for test conditions above and below DSA regime and planar slip bands in the DSA regime. Tendency for cell formation and sub grains associated with thermal recovery was observed at low strain rates less than 3 x $10^{-3}$ $s^{-1}$ at 873 K in 316L (N) SS [11-12]. The decrease in cyclic stress 873 K can therefore be attributed to thermal recovery that causes a change in dislocation substructure from discovered cell wall into ordered sub grain boundaries

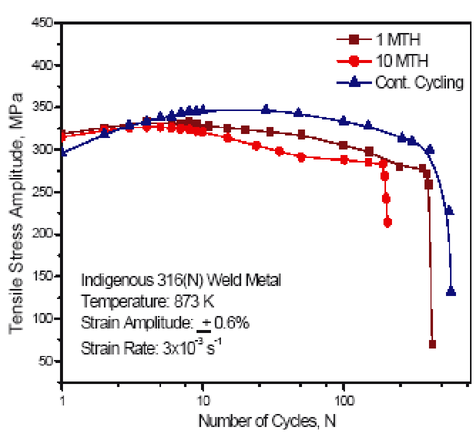


**Figure 4** Effect of time on cyclic stress response at 873 K ± 0.6 %, in weld metal

In case of hold time tests on weld metal, saturation is observed and is increased with increase in hold time, figure 4. As the testing time in hold time test is fairly large, the contribution from precipitates, such as carbides/carbnitrides, to cyclic hardening cannot be ruled out. Detailed investigations by TEM to delineate the hardening mechanism in hold-time tests are in progress. However such hardening contribution, at the expense of the decrease in strength, resulting from the depletion of elements responsible for solid solution strengthening also has to be taken into account

### 3.2. Fatigue Life and Fracture

Fatigue life has been found to decrease with increase in temperature figure 5a, hold time figure 5b and decrease in strain rate figure b and figure 5 c and has been attributed to the individual/combined effects of cyclic plasticity, creep, oxidation and DSA [15, 19]. At all testing conditions, weld joints showed lower fatigue lives when compared with the weld metals.

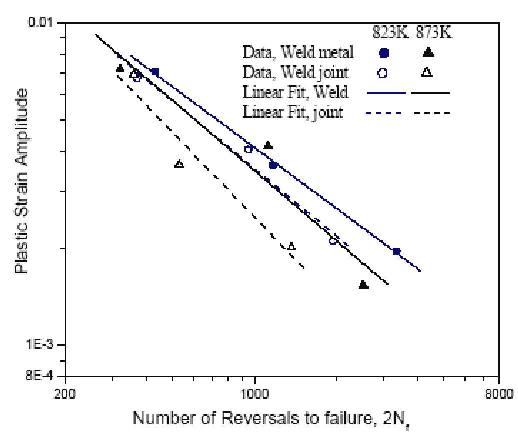


**Figure 5a** Effect of temperature on fatigue life and weld joints and weld metals

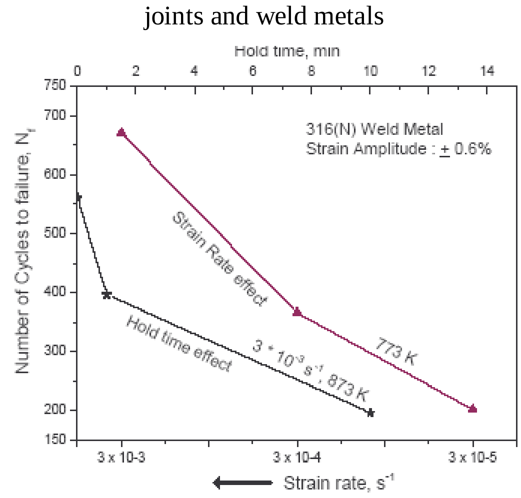


**Figure 5b** Effect of strain rate on fatigue life and weld joints and weld metals

 

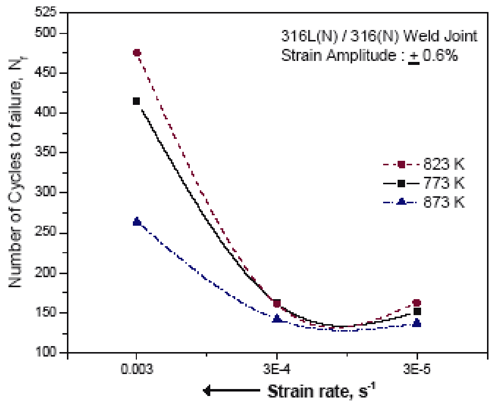


**Figure 5c** Effect of hold time on fatigue life and weld joints and weld metals

At strain rate of $3*10^{-3}s^{-1}$, crack initiation in weld joint is found to take place in coarse-grained HAZ as shown in figure 6a. In this figure the large grain size of faceted grain corresponds to that in HAZ, because grain size of base metal was found too be about 85μm. Valsan et al [1] have reported inter granular crack initiation in HAZ due to slip band grain boundary interaction. Though the observed crack initiation both weld metal and weld joint was trans-granular, there exists significant crack propagation differences which exerts considerable influence on their fatigue life.

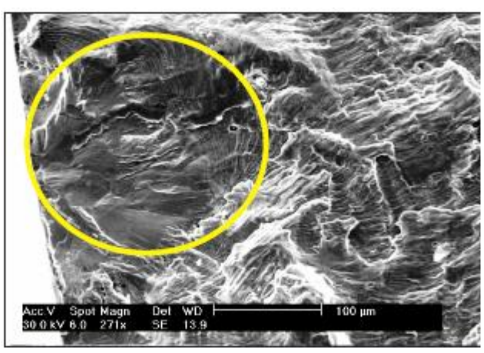


**Figure 6a** Trans-granular crack initiation at 773 K ± 0.4% in weld joints. Encircled region indicates the faceted region

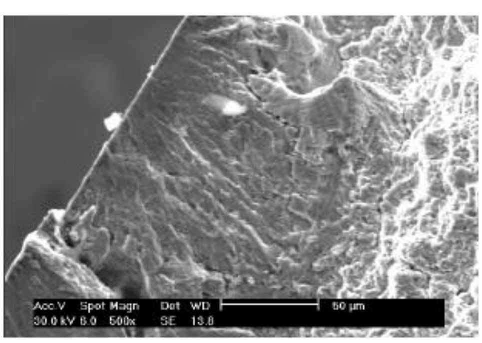


**Figure 6b** crack initiation at 773 K ± 0.6% in weld metal

In general fatigue life of weld metal is determined by the level of weld defects and the transformation of delta-ferrite to sigma phase [20]. In austenitic stainless steel welds, the delta ferrite introduced to reduce their tendency to hot cracking and micro fissuring gets transformed to hard and brittle sigma phase when these materials are exposed to elevated temperatures, 773 to 1173 K, for extended periods of time [21]. In the present study the transformation increased with increasing temperature Table 3. 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, figure 7. This has been also observed by other authors in 316 weld metal [1].

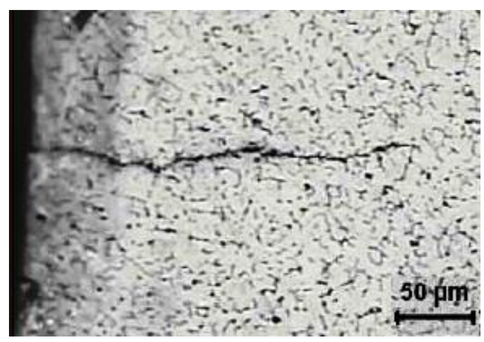


**Figure 7** Crack deflection in weld metal 873 K

**Table 3** % δ-ferrite in tested welded samples at ± 0.4%

| Temp. K | δ-ferrite, % (FN) |
|---|---|
| 300 | 5.0 (initial %) |
| 773 | 5.0 |
| 823 | 4.19 |
| 873 | 3.68 |

Since the transformation is a time and temperature dependent process the test at the lowest strain range and highest temperature shows the maximum amount of transformation. 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 trans granular crack propagation in HAZ is less because of its coarse grain size. It has been well established [11'22] that a larger grain size leads to a faster crack propagation rate under LCF deformation.

With decrease in strain rate from $3*10^{-3}$ to $3*10^{-5}$ $s^{-1}$, a crack initiation is found to be inter granular or oxidation assisted trans-granular and crack propagation is mixed mode (trans-granular + inter-granular), figure 8. It is apparent from figure 8 that

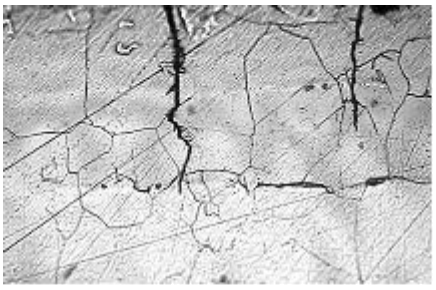

**Figure 8a**

**Figure 8b**

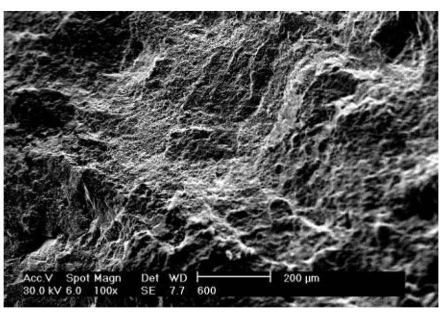


**Figure 8c**

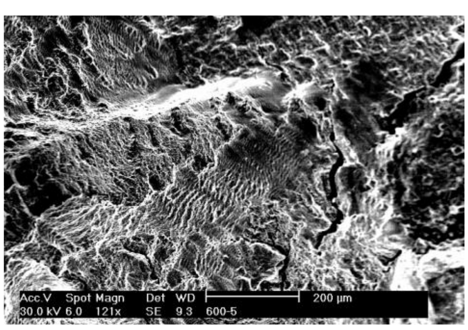


**Figure 8d**

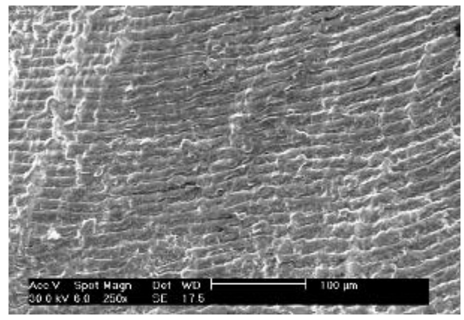


**Figure 8e**

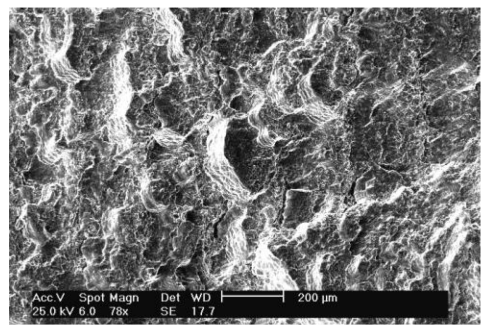


**Figure 8f**

**Figure 8** Oxidation assisted crack initiation (a) Weld Joint 823 K, $3*10^{-3}s^{-1}$ (b) Weld Joint 773 K, $3*10^{-4}s^{-1}$. Oxidation assisted II stage crack propagation, (c) Weld Joint 873 K, $3*10^{-3}s^{-1}$ (d) Weld Joint 873 K, $3*10^{-5}s^{-1}$ (e) Weld Joint 823 K, $3*10^{-3}s^{-1}$ (f) Weld Joint 773 K, $3*10^{-5}s^{-1}$.

Oxidation seems to have strong interaction with the cyclic plasticity, particularly at the low strain rates (figure 8d and 8f) where trans-granular fatigue striations interspersed with inter-granular cracks are seen. Driver et al [23] have observed that, in 316L SS fatigue life in vacuum is about 2 to 3 times that in air, 3 to 5 times at high temperature high strain amplitude and about 20 times at high temperature low strain amplitudes. Further, DSA has been considered to cause a faster reduction in cyclic life over its temperature range of operation as a consequence of smaller number of cycles to crack initiation and rapid propagation particularly at low strain amplitudes [16, 18, and 24]. Brittle inter-granular cracks could result, if the local stresses associated with the dislocation pile ups in the planer slip bands exceed earlier in type 304 SS [16} and Nimonic PE 16 [15] super alloy in the peak DSA regime. Therefore, combined effects of oxidation and DSA could have caused decrease in fatigue life with increase in temperature and decrease in strain rate.

Fatigue life decreased with increase in hold time and has been mainly attributed to the creep cavitations and oxidation, which causes inter-granular crack initiation and propagation and oxidation assisted trans-granular crack propagation [25]. In tensile hold time tests, rapid stress relaxation occurs in the first few seconds followed by a slow rate of stress relaxation during the hold period. It has been suggested that during relaxation tensile inelastic strain accumulates and relaxation strain rates are typically of the order of $10^{-4}$ to $10^{-8}s^{-1}$ that cause grain boundary damage in the form of cavitations [26].

Figure 9 shows the RCC-MR best fit curve for base metal deducted from the RCC-MR design curve for base by a factor of 2 on strain and 20 on cycles. Best fit curves for weld metal is then deduced using a reduction factor of 1.25 on base metal strain [7]. The data generated on weld metal and weld joints at 3* $10^{-3}s^{-1}$ are superimposed on best fit curve for weld and it can be seen that data lies within the conservative limits close to or above the lower bound line for weld.

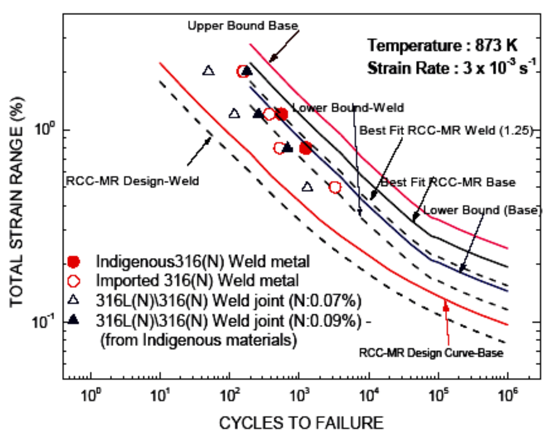


**Figure 9** Comparison of Strain-life data with imported materials in an earlier study [1] and RCC-MR design curves at 873 K, $3*10^{-3}s^{-1}$

**3. 3. Life prediction by Ostergren's Frequency Modified Damage Function (FMDF)**

Life prediction models either explicitly (separately) include fatigue, creep and oxidation contribution to fatigue life or simply imply time dependence through modification of strain rate or cycle time. Some of them are based on monotonic tensile properties, damage summation methods, frequency modified strain range, strain range partitioning methods and methods based on hysteresis energy. In Ostergren's life prediction methods [27], product of tensile stress and inelastic strain range is considered as the basic measure of the LCF damage at elevated temperature, which most of the past life prediction methods consider inelastic strain range as the damage parameter. These net prediction methods consider inelastic strain range as the damage parameter. This net tensile hysteresis energy is used in propagating the fatigue crack and hence affects the fatigue life. If $\Delta W_T$ is the measure of damage in LCF, then the damage equation is given as:

$$\sigma_T \, . \, \Delta\varepsilon_p \, . \, N_f^{\beta} = C \qquad \text{(for Time independent damage)}$$

$$\sigma_T \, . \, \Delta\varepsilon_p \, . \, N_f^{\beta} . \, \nu^{\beta(k-1)} = C \qquad \text{(for Time dependent damage)}$$

$$\nu = 1/\tau = 1/\,(\tau_o \pm \tau_T \pm \tau_C)$$

$N_f$ = number of cycles to failure, $\sigma_T$ = maximum tensile stress, $\Delta\varepsilon_p$ = inelastic strain range, k, β and C are material constants; ν = frequency, $\tau_o$ = time per cycle of continuous cycleing and $\tau_T$ ($\tau_C$) = tensile (or compression) hold duration Figure 10 shows the predicted fatigue lives for some experimental results.

Figure 10 shows the predicted fatigue lives for some experimental results. The predictred fatigue lives are in good agreement with the observed fatigue lives. The predicted lives are within acceptable factor 2 for welds and weld joints

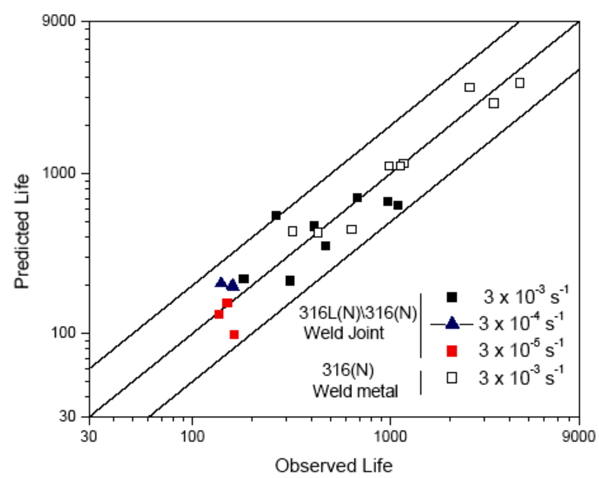


**Figure 10**. predicated lives , by Ostergren 's Damage function, Versus Observed lives.

## 4.0 CONCLUSIONS

(i) 316 (N) weld metals have shown a higher cyclic streee response and fatigue life than 316L(N)/316(N) weld joints.
(ii) The difference in fatigue lives of weld metal and weld joint is essentially due to the crack propagation differences, i.e., crack deflection in weld metal and rapid crack propagation in HAZ of weld joint.
(iii) The reduction in fatigue life at high temperatures and low strain rates is attributed inter-granular crack initiation and propagation due to synergistic interactions between cyclic plasticity, oxidation and DSA.
(iv) LCF lives predicted, by Ostergren's Damage Function method, are found to be in good agreement

 

with the observed lives. The predicted lives lie within a acceptable factor of 2 for weld joints and weld metal.

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