Effect of band-overload on fatigue crack growth rate of HSLA steel

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Abstract. Fatigue crack growth behavior is important parameter of structural materials. This parameters can be used to predict their life, service reliability and operational safety in different conditions. The material used in this investigation is an HSLA steel. In this investigation effect of single overload and band-overload on fatigue crack growth of same steel are studied using compact tension (CT) specimens under mode-I condition and $R=0.3$. It is observed that overload and band-overload applications resulted retardation on the fatigue crack growth rate in most of the cases. It is also noticed that maximum retardation took place on application of seven successive overload cycles. Application of ten and more overload cycles caused no crack growth retardation.

1. Introduction

Fatigue and fracture are common cause of service failure of engineering components and structures. To study about fatigue and fracture related problem is very important of any kind of machine parts, components and engineering structure that is related to various type of loading condition during their operation, so realistic fatigue crack growth and fatigue life prediction is one of the most importance part in terms of economic and safety point of view. The fluctuating load nucleates a crack, which then propagates slowly and finally the crack growth rate per cycle is accelerated and subsequently comes to the stage when the crack-length is long enough to be considered critical for a catastrophic fracture failure. The fatigue crack growth rate may be significantly affected by application of overload cycles [1]. In fatigue crack growth, load applied in the form of a single or band overloads may follow either in mode I or mixed-mode (mode I and II) [2]. It has been evidenced that a pure mode-I overload and multiple overloads leads to maximum crack growth retardation, however in mode-II overload has least effect on fatigue crack growth retardation [2,3]. Most of engineering machine parts and structures are failed by fatigue and fracture causes problem [4]. We need to understand how materials fail, how crack start and propagate how we control it and our ability to prevent such failures. Several investigators [5-9] observed that changes in magnitude of cyclic load may result in retardation or acceleration in fatigue crack growth rate. The overload induced crack tip plastic zone and crack closure level have been found to control the delay behaviour significantly [6]. Extensive published data show that the rate of fatigue crack growth rate...
under constant amplitude cyclic load fluctuation can be retarded significantly as a result of application of single or multiple tensile overload cycle having peak load greater than that of the constant amplitude loading cycles. The ductile solid generally exhibits a temporary accelerated crack growthrate during and immediately after the application of overload. Due to the application of overload the sharp edge of crack tip is get curved. This reducessevere stress concentration that would present at sharp edge of crack tip [10].The assessment of life under those complex situations is certainly tedious because of the lack of proper understanding of micro-mechanisms of retardation. Based on various mechanisms, a number of retardation models have been proposed [11-13]. However, each model has its own merits and demerits as a result; significant ambiguities and disagreements still exist in terms of the exact mechanism of retardation. Due to the number and complexity of the mechanisms involved in this problem, no universal model exists yet.

2. Materials and experimental details:

2.1. Specimen Preparation
Fatigue crack growth tests, were conducted on compact tension (CT) specimens with a narrow notch and reduced thickness, which is fabricated from 12 mm thick plate. The CT specimens were made in the L-T orientation, both sides of the specimen surfaces were given mirror-polish with the help of different grades of emery papers with the loading aligned in the longitudinal direction and notch given in the transverse direction; ASTM standard E647-13 [14] is followed for specimen design. The dimensional details of specimen are presented in Fig. 1.

2.2. Chemical composition
The material studied in current investigation is HSLA steel, collected from Rourkela steel plant, Rourkela. The chemical composition of material is provided in Table 1.

![CT specimen with reduced thickness](image)

Table 1. Chemical composition of HSLA steel

| Elements | C  | Mn  | Si  | P  | S  | Al  | V  | Nb  | Mo  | Fe   |
|----------|----|-----|-----|----|----|-----|----|-----|-----|------|
| Wt. %    | 0.2| 1.27| 0.25| 0.021| 0.014| 0.05| 0.001| 0.005| 0.001| Balance |
2.3. Microstructural investigation
Well-polished and etched metallographic specimens were studied using an optical microscope (Carl Zeiss). Typical optical micrograph of as-received material is shown in Fig. 2. The white portion of microstructure refers to ferrite and light black portion refers to pearlite. The dark black portion appears as martensitic along with carbide precipitate throughout structure in this steel. The ferrite matrix gives ductility and toughness to the investigated steel. This optical microstructure illustrates the alignment and grain structures of the rolled plate in three mutually orthogonal directions. The microstructures of all three directions were superimposed to obtain the 3-D view and shown in Fig. 2.

2.4. Fatigue crack growth rate (FCGR) test
The FCGR tests were done in a 100kN universal test machine (BiSS) using variable amplitude crack propagation (VAFCP) software. The software permitted on-line monitoring of the crack length (a), compliance, ΔK, load range and the crack growth rate per cycle (da/dN). All tests were conducted at constant load mode at stress ratio of (R) 0.3 and using 10Hz frequency at room temperature. A crack opening displacement (COD) gauge was used to measure the displacement. The gauge was mounted on knife edges on the specimen. The specimen surfaces were stickered by graph paper for manual examination of the crack extension during the test as well. Fatigue pre-cracking was done under mode-I loading (crack opening mode) at constant amplitude loading mode to an a/W ratio of 0.24. Following three different case of crack growth tests were performed in this investigation:
(i) Constant amplitude loading with constant stress ratio (R).
(ii) Constant amplitude loading with single overload in mode-I.
(iii) Constant amplitude loading with band (multiple) overload in mode-I.

The stress intensity factor range (ΔK)[22] for CT specimen were calculated by following equation.

\[
\Delta K = \frac{\Delta P}{B\sqrt{W}} \left( \frac{2 + \alpha}{(1 - \alpha)^{1.5}} \right) \left( 0.886 + 4.6\alpha - 13.32\alpha^2 - 14.72\alpha^3 - 5.6\alpha^4 \right)
\]  

(1)

Where, \( \alpha = a/W \); expression valid for a/W>0.2

In case (I) CT specimens were tested under constant amplitude load mode maintaining a fixed load ratio, R = 0.3. In case (II) the specimens were tested under same loading conditions with single tensile overload are applied in mode I at a/W = 0.28 with overload ratio \( R_{ol} \) were applied 1.25, in 1 Hz frequency; the overload ratio is \( R_{ol} = K_{ol}/K_{max} \), where \( K_{ol} \) is overload stress intensity factor, and \( K_{max} \) is the maximum stress intensity factor for base line test. The specimens were subsequently subjected to mode-I constant amplitude load cycles after overload.
In case (III), constant amplitude loading with band (multiple) tensile overload were applied in mode-I. After band overload on the subsequent constant amplitude fatigue crack growth test were allowed for continue the test. The crack was allowed to grow up to $a/W = 0.67$, band-overload tests were followed by multiple tensile overload at $a/W = 0.28$, and overload ratio ($R_o$) were applied 1.25, in 1 Hz frequency. The number of band overload were applied during test are 3, 5, 7, 10, 100, in the same crack opening mode.

3. Results and discussion
3.1. Constant amplitude loading interposed with mode-I overload and band overload
Crack retardation behaviour of specimens under investigation are illustrated in the form of crack length ($a$) vs. number of stress cycles ($N$) in Fig.3. The figure clearly shows that the application of overload cycle retards a growing crack. It is also observed that the magnitude of retardation increases with increasing number of overload cycles.

![Fig. 3. Superimposed crack length vs. number of cycle curve](image)

This increase in magnitude of retardation is noticed up to 7 number of overload cycles. Application of overload cycles 10 and 100 has nullified the retardation effect and resulted little crack growth crack growth acceleration. To visualise the effect of overload cycle on the magnitude of retardation, number of stress cycles required to attend a fixed crack length ($a=15$ mm) following overload cycles from 1 to 100 can be viewed in Fig.4. Similar observations are also reported in literature[15].
The overload application is known to retard a growing crack. The retardation observed following overload cycles are explained on the basis of development of plastic zone in elastic enclave resulting compressive residual stresses, crack closure crack tip blunting etc. [10, 16] Compressive residual stresses and crack tip blunting[11, 12] play significant role in retarding the propagating crack. The application of an overload or a few overloads appears to introduce a plastic region embedded in elastically deformed enclosure. Repetition of the overload cycles beyond a certain number (7 in the present case) may have developed plastic regions at the crack tip larger than the critical to produce further retardation. It may be noted that the size of elastic enclave reduces with increasing plastic zone resulting reduced constrain and reduced retardation effect.

Fatigue crack growth rate as a function of applied stress intensity factor is presented on log-log scale in Fig.5. The magnified view of plots for a few overloading conditions are presented in Fig.6. This conforms that drop in crack growth rate occurs on application of 7 numbers of overload cycles. The repetition of same overload to 100 cycles caused acceleration in crack growth rate.
Fig. 5. Log-log plot of crack growth rates vs. stress of cycle curve.

Fig. 6. Log-log plot of crack growth rates vs. stress of cycle curve
The reduction in the magnitude of retardation on application of 10 and 100 overload cycle may be due to development of plastic zone large enough to upset the constrain by the reduced elastically deformed region. It may also be possible that repeated overload application had sharpened the crack resulting suitable condition for rapid crack growth [7]. However the proposed explanations need further investigation.

3.2 Photograph of fatigue fracture surface
Various regions of a fractured specimen showing fatigue crack growth, imposed to 7 cycles of overload of an HSLA steel tested at $R_o = 1.25$ are presented in Fig. 7.

4. Conclusions
In fatigue crack growth study three different loading conditions were applied: constant amplitude loading with fixed stress ratios, constant loading interspersed with single spike overload, and constant amplitude loading interspersed with multiple (band) spike overload. Effect of overload and band overload on fatigue growth life is determined. The conclusions drawn from the present work are summarized as follows:

- The application of overload and band overload reduces the crack growth rate. However, the extent of retardation is little on application of single overload cycle.
- Maximum retardation was observed on application of 7 numbers of consecutive overload cycles. This may be due to further enlargement of plastic zone and other retardation inducing factors.
- Reduced retardation effect on application of overload cycles 10 and 100 is possibly due to development of plastic zone large enough to upset the constrain due to elastic enclave.
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