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# Experimental study on crack propagation of stainless steel 304 material under amplitude overloads

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**Abstract.** Fatigue mechanisms caused by dynamic loadings starts with cracks that occurred in a material. Under conditions such as transient conditions, an earthquake or instantaneous external loads, some parts of nuclear reactor that initially receive operating loads can be overloaded. The purpose of this research is to investigate the change of crack propagation in stainless steel 304 material related with amplitude overloads. The crack propagation test used the axial dynamic testing with the maximum stress ($\sigma_{max}$) of 145 MPa, stress ratio R= 0.1 and over loading ratio (OVR) of 1.5, 1.75, 2. The results showed that the amplitude overloads caused the crack to propagate slowly as the crack tip formed a branch. The higher crack growth rate also showed the higher stress intensity factors in the crack tip.

## 1. Introduction

Nowadays, extensive research studies have been carried out contributing to the understanding of the mechanisms of fatigue damage along with stages of fatigue in the structures of metallic materials. For many fatigue-critical parts of structures, fatigue crack propagation under service conditions generally involves variable amplitude rather than constant amplitude loading conditions. If these structures contain fatigue cracks and the crack propagation rate depends on the loading sequence, it is difficult to persistently understanding the fatigue life. The reason for this is that many factors affect the initiation and the growth of fatigue cracks. Much works has been done on the subject related with the following aspects such as (i) geometrical effects like stress concentrations, (ii) microstructural effects: grain size and shape, second phase particles, precipitation and texture, (iii) surface effects: surface roughness, surface damage or surface treatment, (iv) environmental effects: corrosion and temperature, and (v) overload effects [1].

Fatigue crack growth could be retarded after applying a tensile overload while a constant tensile load is being repeated. However, the crack growth rate can be accelerated after applying an overload at a critical level while a tension-compression load is being repeated [2]. Figure 1 shows graphs of overload cycle (top graph) and crack length (bottom graph) related with number of cycles [3]. On the beginning of the graph, the loads are constant, however on a certain cycle the loads given are exceeding the normal value causing the crack closure, such as plasticity, crack tip blunting, branching or deflection. This crack closure will also start the crack retardation. As seen in the Figure 1 (bottom graph) this overload effect has two different crack lengths on the same cycles. The crack with constant load is not retarded and the crack with overload is retarded. Crack retardation after overload caused by crack closure such as plasticity, crack tip blunting, branching or deflection on crack tip. Crack closure first introduced onto the fatigue crack growth analysis by Wolf [4]. After that, many of researches have been done concerning the crack closure using experimental investigation, numerical analysis and theoretical studies [5-14].

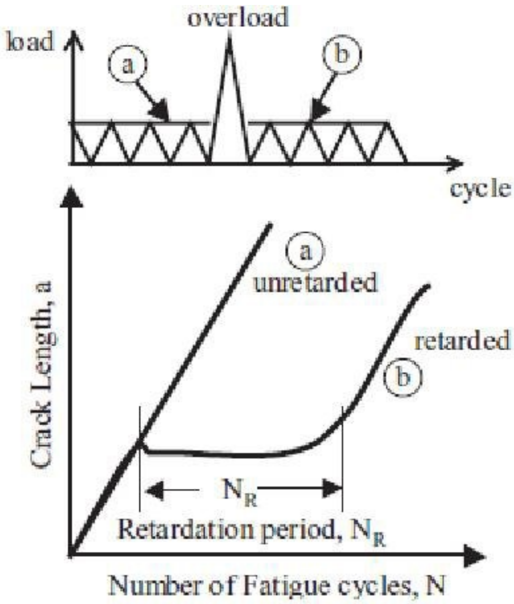



**Figure 1.** Illustration of the overload effect [3].

Paris and Erdogan proposed a fracture mechanics in 1860s using a method of fatigue life prediction related with the fatigue crack rate to the applied of stress intensity factor range [15]. Many modifications Paris law after that which one of the most important is the inclusion of the crack closure concept. A general fatigue crack growth model was showed as (1) by Wolf [4]. The fatigue crack growth rate is determined by the effective stress intensity factor range,

$$\frac{da}{dN} = C\left(\Delta K_{eff}\right)^{m} \quad (1)$$

$$\Delta K_{eff} = K_{max} - K_{op} \quad (2)$$

where dA/dN is the crack growth rate, ΔKeff is the effective stress intensity factor, Kmax is the stress intensity factor of peak load and Kop is the crack closure level. C and m are the calibration parameters. The objective of this research is to investigate the change of crack propagation for stainless steel 304 material related with amplitude overloads. Stainless steel 304 material is commonly used for many parts of nuclear reactor in power plants.

## 2. Experimental Procedure

Experiments used stainless steel 304 (SS 304) materials as testing specimens, because of its usage as nuclear reactor's components. Results from chemical composition test using Dyna-tech spectrometer are shown in Table 1. The mechanical properties SS 304 material are tensile strength = 621 MPa, yield strength = 290 MPa and elongation (%) = 55 [16].

The specimen's first form is a strip plate. Then, for crack propagation test, the specimen M (T) is formed following the ASTM E647 standard as seen in Figure 2 [17]. The EDM machine is used to form a notch on the specimen. The 2a value on the crack propagation test is the length of crack initiation.

**Table 1.** Chemistry composition of SS304 material.

| Element | C | Mn | P | S | Si | Cr | Ni | Fe |
|---|---|---|---|---|---|---|---|---|
| % | 0.0283 | 1.62 | 0.038 | 0.0126 | 0.36 | 18.8 | 7.58 | balance |

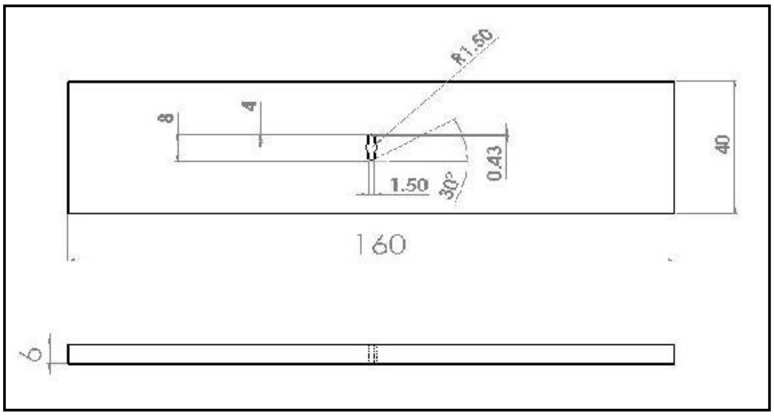



**Figure 2.** Specimen of SS304 material for experiment (in mm).

Crack propagation test was done using 250 kN axial dynamic test machine. Figure 3 shows the fixture for specimen on the dynamic test machine. The tests were done gradually, due to observing and measuring the crack's length were done manually. Also, for each specimen, the test was done until 50.00 cycles and the propagation was observed using optical microscope with 10x magnification. On this test, load ratio used is 0.1 and the assumed value of maximum stress (σmax) as normal load is 145 MPa, which came from the half of the SS 304's yield strength. There are three overload ratios (OVR) which are 1.5; 1.75; and 2.

$$OVR = \frac{\sigma_{OVL}}{\sigma_{max}} \quad (3)$$

**Figure 3.** Fixture of dynamic test machine for specimen

## 3. Experimental Results

Crack propagation tests used specimens of SS304 material with three different overload ratios OVR 1.5; 1.75 and 2 are shown in Figure 4. On Figure 4, there is a similarity on all of the specimens. Before the overload cycle, the crack growth is increasing, however, after the overload cycle, the crack growth on specimens are starting for retardation.

For crack propagation test, the purpose of deciding da/dN value is to see how big the propagation rate value related with stress intensity factor. Analyzing the value of da/dN could give an insight on how the crack growth after overload is given. Strain intensity factor used in fracture mechanics to predict the strain intensity near the crack tip that is caused by residual stresses. Results from tests of crack propagation rate are shown on Figure 5. For specimen with OVR = 1.5 showed that the crack propagation rate is different but it has similarity on how the crack propagation test is retarding after overload cycle. Other experiments with OVR = 1.75 and 2 also showed retardation after overload cycles as in Figure 5.

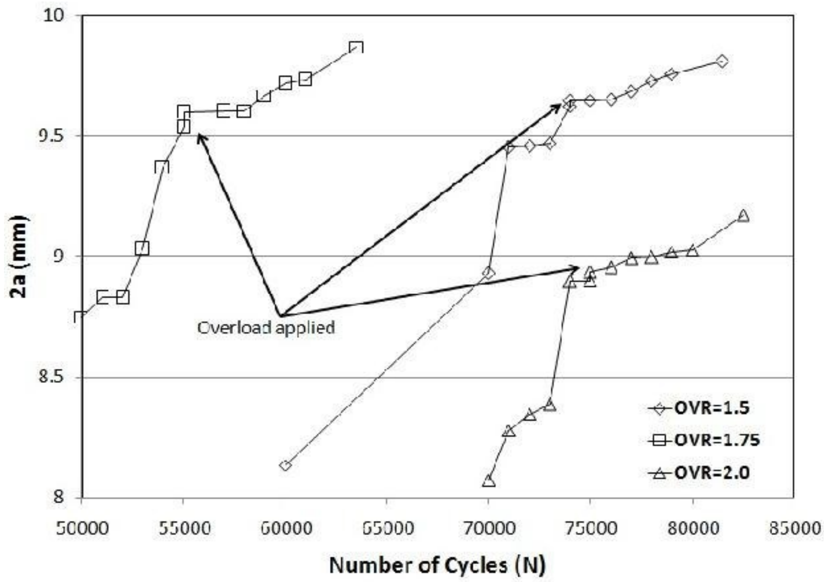



**Figure 4.** Graph of crack length 2a vs number of cycles N for OVR 1.5; 1.75 and 2 with OVL position.

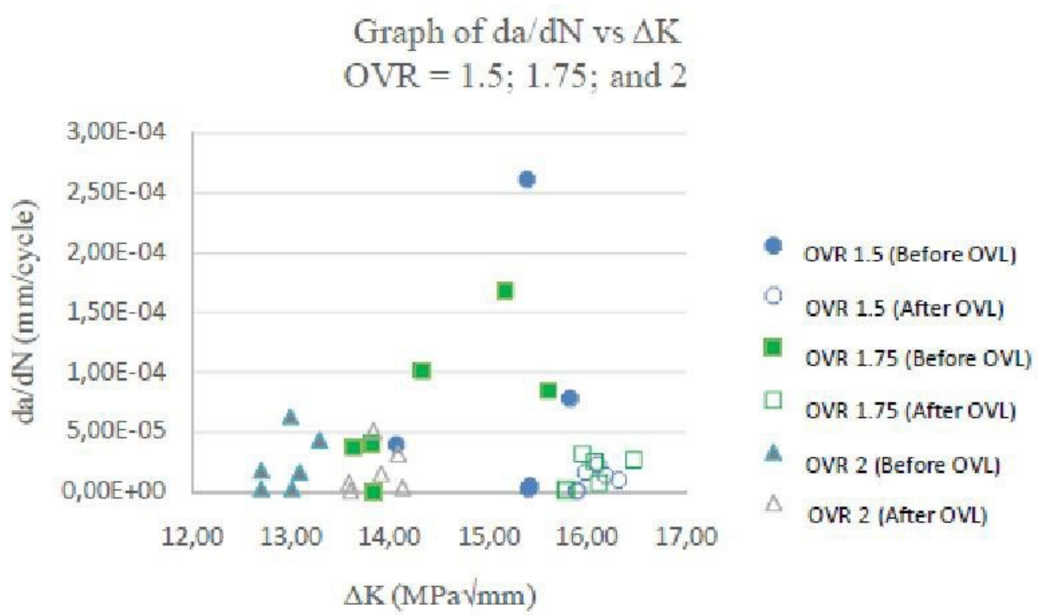
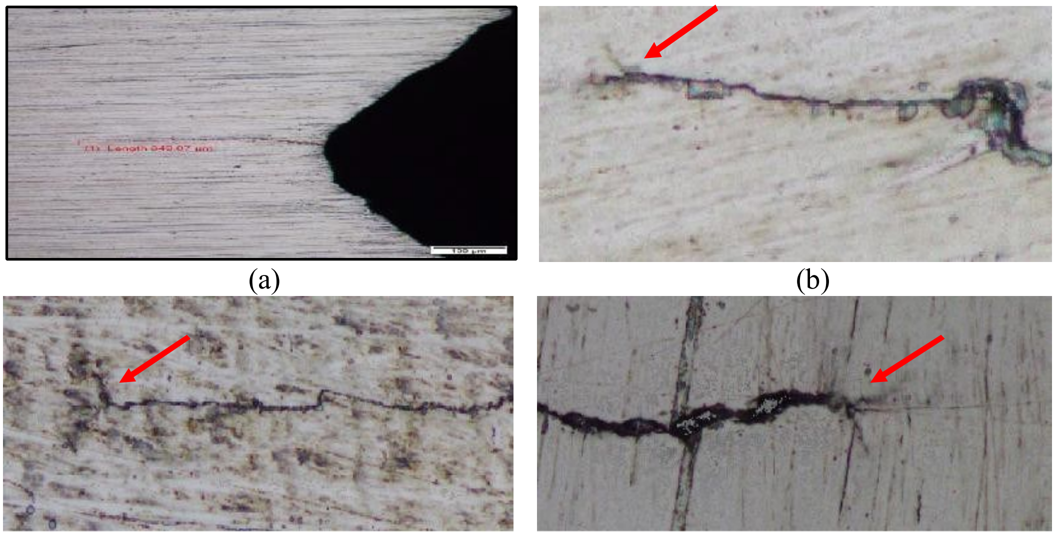



**Figure 5.** Comparison of crack propagation rate (da/dN) with stress intensity factor for overload ratio OVR 1.5, 1.75 and 2 before and after OVL.

Branched crack tip is one of the factors that causing crack growth retardation. The observation of crack from the notch point to the crack tip is seen in Figure 6 a. On crack propagation test, after the overload cycles, the observed crack tip is become branched. As seen in Figure 6 b, c and d the crack propagations for OVR 1.5, 1.75 and 2 are shown with the crack tip after overload (see the arrow on the picture). The crack tip after overload will cause crack growth retardation. The driving forces on that crack tip are distributed that causing crack growth retardation.



(a) (b)

(c) (d)

**Figure 6.** (a) Sample of specimen test, (b) Crack tip after overload with OVR = 1.5, (c) Crack tip after overload with OVR 1.75, (d) Crack tip after overload with OVR 2.

## 4. Conclusions

From this study concerning the influence of overload with differential overload ratio as 1.5, 1.75 and 2 using crack propagation test of σmax = 145 MPa in stainless steel 304 (SS304) material, the following conclusions can be drawn.

Graphs of 2a vs. N and da/dN vs. ΔK shows the results of crack propagation test for all specimens with the results that overload caused crack propagation retarding. On crack observation using optical microscope, after overload, the crack tip will become branched. Bigger value of crack propagation rate also makes strain intensity value on crack tip become higher.

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