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# Instrumented indentation measurements of residual stresses around a crack tip under single tensile overloads

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ABSTRACT

In this study, the residual-stress fields around crack tip of M(T) specimens under three single tensile overload ratios ($R_{ol}$) during fatigue crack growth of aluminum alloy 2524-T3 were investigated using the instrumented indentation tests (IIT). The results showed that both the magnitude and region of the compressive residual stress around the crack tip increase with the increase of $R_{ol}$. Finite element method was also used to simulate the residual stress distributions near the crack tip at the same loading conditions as experiments, which confirmed that the estimation of the crack-tip residual stress using Suresh et al.'s model based on IIT was feasible. The profiles of the crack tip under constant-amplitude loading and three overload ratios were examined using optical microscopy. It was found that the geometry of crack tip changes significantly from the sharp crack to the blunt crack with increasing $R_{ol}$ after applying a tensile overload. The probable mechanisms resulting in the change of the crack-growth behavior due to tensile overloads were also discussed. It was suggested that the combined effects of the residual stress, crack tip profile and the crack tip hardening may be responsible for the observed overload retardation effect of the present M(T) specimens during fatigue crack growth.


## 1. Introduction

Many fatigue-critical parts of structures, vehicles and machines in services are generally subjected to random or variable-amplitude loadings, rather than constant-amplitude loadings. Load variations in magnitude or order lead to a significant impact on fatigue crack growth. Therefore, adequate evaluation of these load interaction effects is of great value for the development and improvement of a fatigue life prediction model.

Tensile overload, as the simplest case in variable-amplitude loadings, has been widely studied [1]. Tensile overload has a delayed effect on the fatigue crack propagation. There are many factors influencing the tensile overload effect, in which overload ratio $R_{ol}=S_{ol}/S_{max}$ plays a decisive role, where $S_{max}$ and $S_{ol}$ represent the maximum stress in constant-amplitude loading and the overload stress, respectively. A number of studies [2,3] have shown that, when $R_{ol}$ reaches a certain value (usually about 1.5), delayed effects begin to appear; with increasing $R_{ol}$, the retardation effect becomes more obvious; when $R_{ol}$ is close to 3, crack is completely arrested and crack propagation stops, resulting thereby in the great extension of crack propagation life. Although interpretation for this phenomenon is still at issue, it is generally believed that the compressive residual stress is the main reason for the overload effect [4,5]. Therefore, accurate measurement of residual stress field around the crack tip becomes very important.

Steuwer et al. [6] investigated the overload effects under different $R_{ol}$ of aluminum alloy using synchrotron X-ray diffraction and tomography. Their study did not, however, give a decisive conclusion on the issue of the importance of residual stress in the overload effects. Croft et al. [7–9] examined the strain distribution around the crack tip before and after the overloads with high-energy X-ray diffraction. Their work also did not directly address the controversy over the origin of the overload effect. Lee et al. [10] using the neutron diffraction method directly measured the residual stress distribution in front of the crack tip of the nickel-based superalloy on compact tension (CT) specimens under variable-amplitude loadings. They observed an expanded compressive strain from the "blunting region" to the crack tip, and confirmed the importance of residual stress to crack face interactions. Colombo et al. [11] and Christopher et al. [12,13], through systematic experiments on fatigue crack photoelasticity on polycarbonate materials, indicated that the crack faces behind the crack tip interacts with each other which is the key role leading to crack growth retardation.

Despite diffraction method such as high-energy X-ray and neutron diffraction is a powerful technique in the direct measurement of the crack-tip residual stress field and has obtained great progress, there is still a long way to fully understand the crack-tip

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behavior. Crack tip is the convergence of various defects and damage, and also the focus of the microstructure inhomogeneity and inconsistency of stress and strain. Due to the presence of localized high stress gradients around the crack tip, it is difficult to measure local residual stress fields near the crack tip. In addition, the above diffraction techniques are unable to study the micro-mechanical properties and microstructure evolution around the crack tip. Recent research work [14–20] showed that instrumented indentation load–depth (*P–h*) curves can be used to determine average mechanical properties in small volumes and additionally these *P–h* curves can be used to evaluate residual stresses. Both theoretical and experimental investigations [14,15] also confirmed that residual stresses have significant effect on the *P–h* curve determined by indentation testing. Various indentation parameters including hardness, the maximum indentation depth, contact area, pile-up, and unloading contact stiffness, have been utilized to estimate the magnitude of residual stresses [16–20]. So far, several models for the determination of the residual stresses have also been proposed, among which the model proposed by Suresh and Giannakopoulos [16] is most representative and has been verified by a lot of materials, especially the aluminum alloy, and thus has been widely used.

In this study the estimations of the residual-stress distribution around crack tip of M(T) specimens under three different single tensile overload ratios during fatigue crack growth of aluminum alloy 2524-T3 were carried out by using Suresh et al.'s model and based on the instrumented indentation technique (IIT). In order to verify the effectiveness of the proposed residual stress evaluation model, finite element method was used to simulate the same loading conditions as experiments. The morphologies of the respective crack tips for the different overloading cases were also examined using optical microscopy. The present investigation would be helpful not only for the explanation of the possible mechanisms responsible for tensile overload retardation effect, but also for the development of more accurate residual-stress-based prediction models of fatigue crack growth.

## 2. Material, experiment and finite element simulation details

### 2.1. Material

The material used in the present study is aluminum alloy 2524-T3 with the chemical compositions shown in Table 1. Table 2 lists the room-temperature mechanical properties of this alloy for both the longitudinal (L) and transverse (T) orientations. The dimensions of the middle-tension (MT) specimens are 400 mm × 100 mm × 2.35 mm with initial crack length $2a_0$=20 mm. The specimens have been subjected to heat treatment prior to the experiments to remove residual stresses from the manufacturing processes. To obtain smooth surfaces, the specimens were ground using emery papers of various grinds from 600 to 2000 grit, and then electropolished for 15 s at room temperature in a solution containing 10 vol% of perchloric acid and 90 vol% ethanol at a potential of 25 V and then etched for 15 s in Keller Reagent. Fig. 1 presents the microstructure of the alloy in three dimensions. The average grain sizes are 320 μm (in LT), 180 μm (in LS) and 56 μm (in TS), respectively, where LT, LS and TS respect to the rolling plane, long transverse plane and short transverse plane.

**Table 1**
Chemical composition of AA 2524-T3 (wt%).

| *Si* | *Fe* | *Cu* | *Mn* | *Mg* | *Cr* | *Zn* | *Ti* | *Al* |
|---|---|---|---|---|---|---|---|---|
| 0.04 | 0.08 | 4.3 | 0.578 | 1.4 | 0.05 | 0.008 | 0.10 | Balance |

**Table 2**
Tensile properties of AA2524-T3 at room temperature.

| Orientation | *E (GPa)* | $\sigma_y$ *(MPa)* | $\sigma_b$ *(MPa)* | $\delta_5$ (%) |
|---|---|---|---|---|
| *L* | 71 | 338 | 470 | 18.8 |
| *T* | 71 | 337 | 469 | 20.1 |

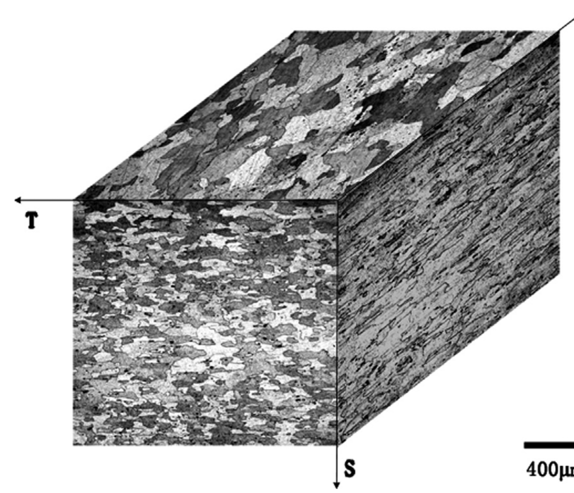


**Fig. 1.** Optical micrographs of grain structures of AA2524-T3.

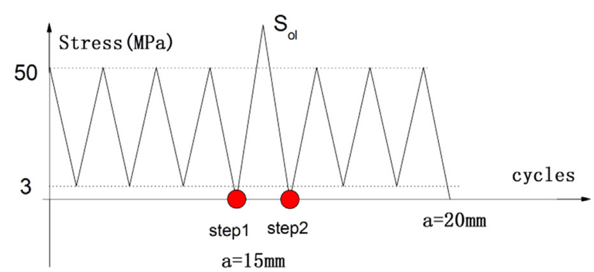


**Fig. 2.** Indentation measurement points.

### 2.2. Fatigue crack growth tests

Fatigue crack propagation tests were conducted using M(T) specimens in accordance with ASTM E647-00 with a MTS servohydraulic testing system. A sinusoidal waveform with a maximum stress $S_{max}$=50 MPa at a stress ratio of $R$=0.06 and a loading frequency of 10 Hz was used. All specimens were cycled under the constant amplitude loading until the half crack length ($a$) reached 15 mm and then subjected to a single tensile overload with different overload ratios, $R_{ol}$=1.375; 1.685; 2.6, respectively. The instrumented indentation measurements were carried out around the crack tip before and after the tensile overloads for each specimen, as illustrated in Fig. 2, where step 1 and step 2 represent, respectively, the case before and after overlord. After overloading, all specimens were cycled continuously until the half crack length ($a$) reached 20 mm. During fatigue crack growth testing, the crack length was measured using both optical microscopy and crack-opening-displacement gauge using the compliance method.

### 2.3. IIT measurements

Instrumented indentation measurements were carried out around the crack tip of M(T) specimens, as shown in Fig. 3, where the upper region (a) and lower region (b) represent, respectively, the measurement positions of the crack tip before and after overload. The indentation tests were made by setting a fixed