THE EFFECT OF CHEMICAL MILLING ON THE CHARACTERISTIC OF FATIGUE CRACK GROWTH RATE IN AL 2024-T3

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ABSTRACT

The effect of the chemically milled surface of aluminum alloy Al 2024-T3 on the characteristic of fatigue crack growth rate has been investigated. The effect of a single overload has also been studied. The test was carried out under sinusoidal loads with firstly constant amplitude at the stress ratio (R) of 0.3 and 0.6. Secondly, similar to the first test, however, it was followed by a single tension overload with the overload ratio (OLR) of 1.5 and 2.0. Application of the overload was conducted manually at a static load after the crack propagated approximately 4.0 mm length.

The experimental result shows that the chemically milled surface specimen has slightly higher the fatigue crack growth rate for higher stress ratio. However, the effect of chemical milling becomes more significant for lower stress ratio. The existence of a single overload can delay crack growth, and the increase of the overload ratio can significantly decrease the crack growth rate.

***Key words:** Crack growth, fatigue, aluminum alloy, overload*

INTRODUCTION

Chemical milling process has been used in aerospace companies, specifically to remove unnecessary material from a thin plate. The surface of the chemically milling product usually changes in surface texture. Therefore, the chemically milled aluminum possibly has less fatigue resistance.

A tension overload in ductile material theoretically can generate a plastic zone around the crack tip. Therefore, the crack growth can be delayed as long as the crack tip is still covered by the plastic zone. This phenomenon can be understood due to the fact that the size in the plastic zone region has enlarged permanently, and this plastic region occurs locally. As a result, when the overload is removed the plastic zone still exists at the crack tip. This zone is covered by an elastic field. Consequently, the plastic zone around the crack tip is compressed by the elastic fields. This compression is a residual stress, which can close the crack for a certain distance. In a dynamic load condition with constant amplitude, crack growth rate, da/dN, has tendency to decrease at higher stress ratio (Tsukuda et al., 1995 and 1996).

The effect of an overload on structures has intensively been studied in some materials and load conditions. It is agreed that the overload can delay crack growth rate, therefore the number of cycle increases as well as the lifetime of the structures (Changqing et al., 1996; Shuter et al., 1996; Ng'ang'a et al., 1996; and Damri et al., 1991)

THEORETICAL BACKGROUND

In general, fatigue crack growth rates have specific characteristic and can be observed on the fracture surface. The initial crack is surrounded by plane fields and the crack growth occurs very slow. This field is specified by lines, those can be seen microscopically. When the field is observed in an optic microscope, this slow crack growth is noted by fatigue striations.

There are some models to show the fatigue crack growth phenomena. One of them is shown in figure 1. Under a tension load, slip will occur as shown in figure 1a. On the other hand, when the load is in compression, the slip will occur in opposite direction as shown in figure 1b. Therefore, intrusion and extrusion can be formed. The intrusion will become a crack, when the cycle load happens in certain time.

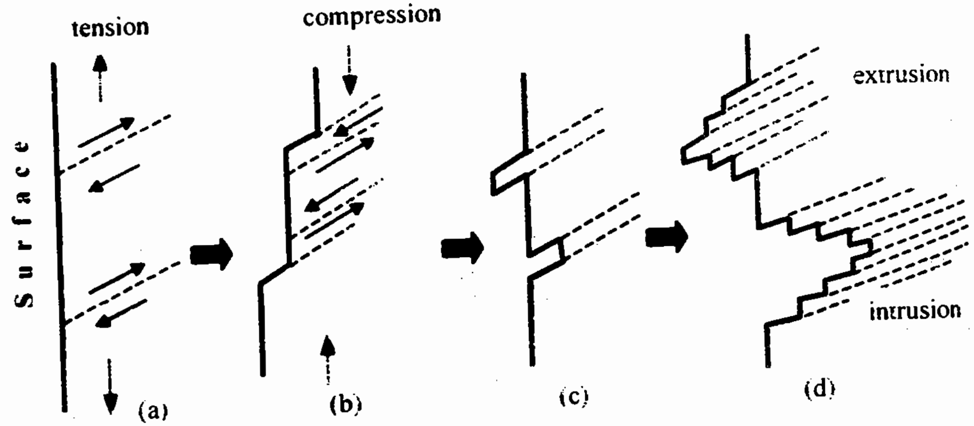

Figure 1. Fatigue crack initiation due to plastic deformation

In an elastic condition, a plastic zone at the crack tip is relatively small compared to the crack length, therefore stress intensity factor can become the indicator of stress distribution at the crack tip. The level of crack growth rate in one cycle depends on the stress at the crack tip. From the experimental work shows that the crack growth rate is dependent of the crack length and amplitude of stress, that can be written as follows:

$$\frac{da}{dN} = f(\Delta S) = f\{(S_{maks} - S_{min})\sqrt{\pi a}\} = f(2S_a\sqrt{\pi a}) \qquad (1)$$

Where S_{maks} and S_{min} are maximum and minimum stresses, respectively, and S_a is stress amplitude. The ratio between S_{min} and S_{maks} is called stress ratio defined by R. In constant amplitude, the range of stress intensity factor (ΔK) can be determined by the following equation:

$$\Delta K = K_{maks} - K_{min} = (S_{maks} - S_{min})\beta\sqrt{\pi a} \qquad (2)$$

If S_{min} is compression stress, and then K_{min} equal to zero. According to Paris, the relation between crack growth rate (da/dN) and ΔK can be expressed as follows (Broek, 1987):

$$\frac{da}{dN} = C(\Delta K)^n \qquad (3)$$

C and *n* is a constant value depending on the materials and load conditions.

The existence of single overload in ductile materials can generate plastic zone at the crack tip. When the overload disappears, there will be residual stress at the crack tip due to enlargement of plastic size. This residual stress tends to close the crack for a certain distance from the crack tip such as shown in figure 2.

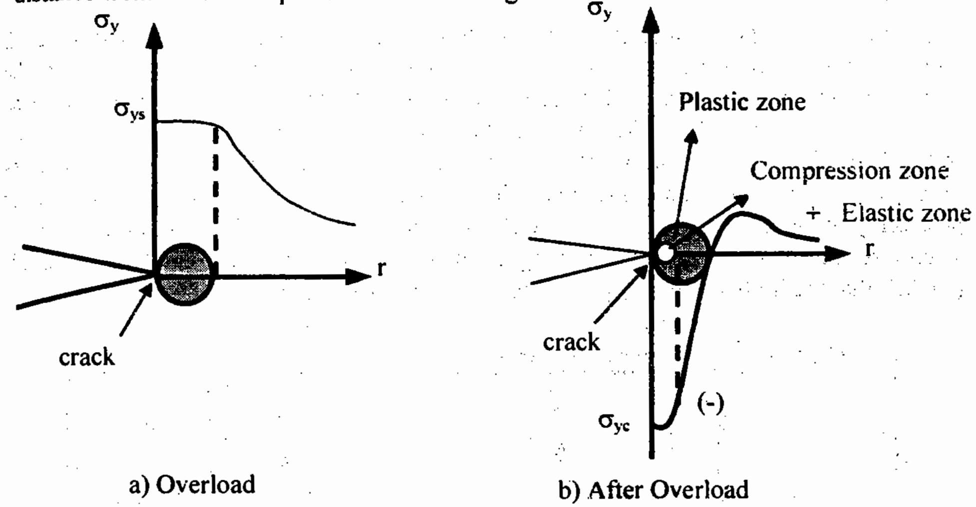

Figure 2. Overload and after overload condition

METHODOLOGY

The material used in this research was aluminum alloy AL 2024-T3 with the chemical composition as follows: AL-4.5%Cu, 1.5%Mg, 0.5%Mn and the yield stress is 45 ksi. The material was cut to obtain the dimension required in this research, i.e. *80mm x 250mm*, and the center crack was milled by EDM approximately *12mm* length. A set of specimens was then chemically milled using etchant of NaOH and Na_2S (Sulistyanti et al., 1996). The surface roughness of the base and chemically milled materials is 0.32μm and 0.76μm, respectively, which was measured using Surfcom type120A.

The test was conducted in room condition using a Servohydraulic Testing Machine, that was operated under load control and the frequency was adjusted between 10 to 20 Hz depending on the performance of the machine which corresponds to the crack length to be observed. At the starting test, the frequency was set up at higher level and gradually decreased as the crack begins to propagate. This test was performed at constant amplitude with stress ratio (R) of 0.3 and 0.6. The crack growth was monitored using two traveling microscopes each for the left and right side of the crack. From the test can be obtained the crack growth data correspond to the number of cycles. These data were subsequently treated according to the incremental polynomial method recommended by ASTM E 647 (ASTM, 1991).

The test was developed by applying a single overload. The overload was applied manually with overload ratio (OLR) of 1.5 and 2.0 after the crack growth reached approximately 4 mm from the initial crack.

RESULTS AND DISCUSSION

a. Fatigue crack growth rate under a constant amplitude load

The test results for fatigue crack growth under constant load are shown in figure 3 and 4. Figure 3 shows the relation between crack length and number of cycles. It can be seen that the chemically milled material (CM) has shorter life compared to the base material (NCM). The effect of chemical milling is more significant for the stress ratio (R) of 0.6. This phenomenon can be explained through the stress amplitude. The lower stress ratio means that it has higher stress amplitude. The higher stress amplitude has stronger possibility to close the crack. The crack closure can make the crack tip becomes sharper. Therefore, the crack is easier to propagate. It may also be seen for the base materials (NCM), that the higher stress ratio produces significantly higher number of cycles.

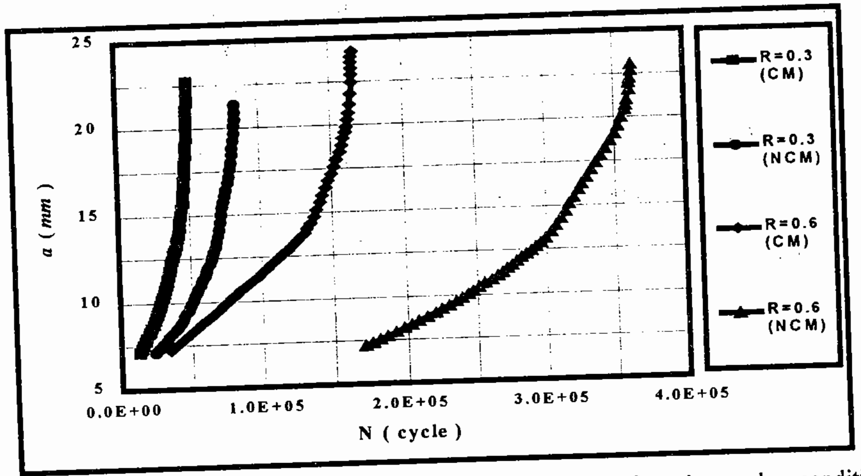

Figure 3. Correlation between crack length, *a*, and number of cycles under condition of ... for stress ratio, R of 0.3 and 0.6

Figure 4 shows the correlation between crack growth rate, d*a*/dN and range of stress intensity factor, ΔK. It can be seen that the lower stress ratio of the characteristic of fatigue crack growth rate tend to move to the left. This is caused by the increase of the range of stress intensity factor, ΔK. On the other hand, the crack growth rate, d*a*/dN, tend to decrease. For the same stress ratio, the chemically milled specimen gives slightly higher crack growrth rate.

From figure 4, it can be obtained a characteristic equation of crack growth rate, d*a*/dN, for each condition based on Paris' equation (Eq. 3), which can be written as follows:

Chemical milling material:

$$\frac{da}{dN} = 2.10^{-9}(\Delta K)^{3.61} \qquad (R=0.6)$$

$$\frac{da}{dN} = 7.10^{-10}(\Delta K)^{3.16} \qquad (R=0.3)$$

Base material:

$$\frac{da}{dN} = 1.10^{-9}(\Delta K)^{3.36} \qquad (R=0.6)$$

$$\frac{da}{dN} = 2.10^{-9}(\Delta K)^{2.35} \qquad (R=0.3)$$

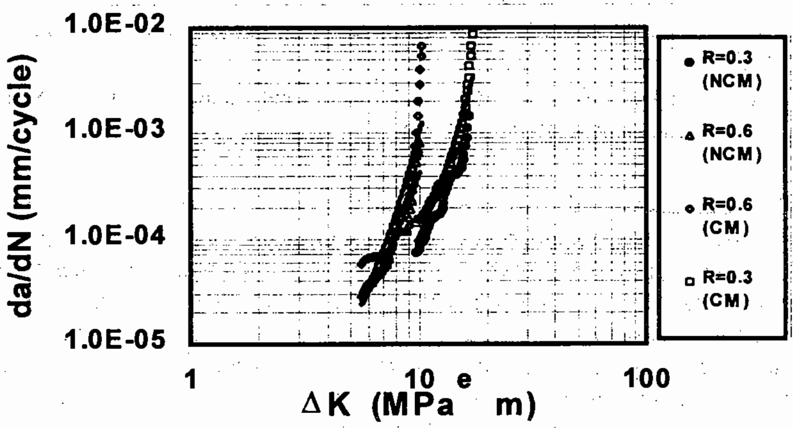

Figure 4. Relation between crack growth rate, d*a*/dN, and range of stress intensity factor, ΔK, under condition of stress ratio, R, of 0.3 and 0.6.

b. Fatigue crack growth rate under constant load with single overload

The test results for fatigue crack growth rate under constant load following by single overload can be seen in figures 5 to 7 (for R=0.6). Figure 5 shows that by applying single overload, the increase of crack length is significantly delayed. From the figure, it can also be seen that the increase of overload ratio can prolong the fatigue life. However, the base materials can dramatically extent the fatigue life compared to the chemically milled material. This condition is obviously caused by the surface roughness, and also possibly due to of hydrogen embrittlement.

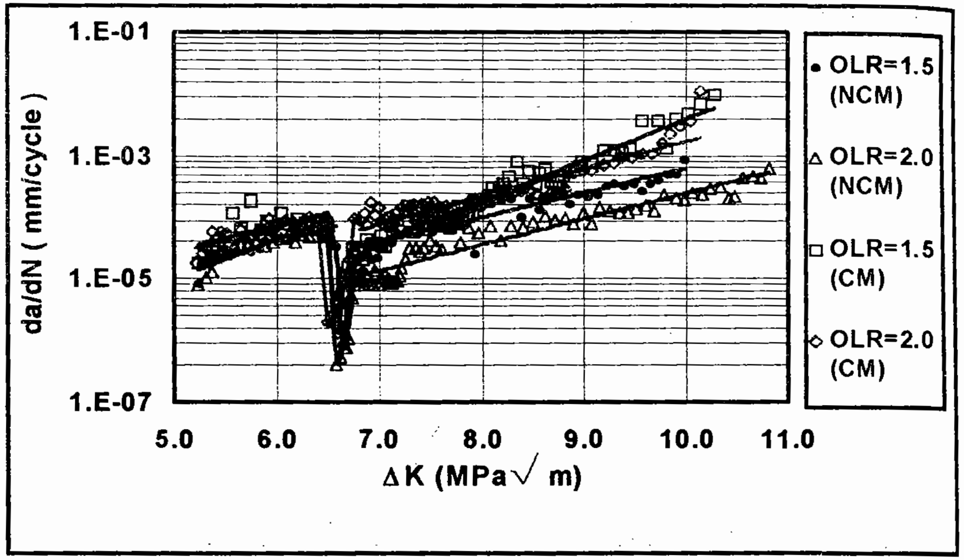

Figure 5. Correlation between crack length, a-a_{OL}, and number of cycles, N-N_{OL}, from the overload point for R=0.6

The crack growth data were subsequently used to produce the crack growth rate, d*a*/dN corresponding to the range of stress intensity factor, ΔK. Figure 6 shows the relation between d*a*/dN and ΔK for the base and chemically milled material. In general, it can be seen that the overload can resist the crack growth, the acceleration even becomes a negative trend. However, the characteristic of the crack growth is back to the normal trend after reaching certain number of cycles. The increase of surface roughness gives significantly higher value of the crack growth rate for the same level of overload ratio. However, the increased of the overload ratio can extent significantly the number of cycles.

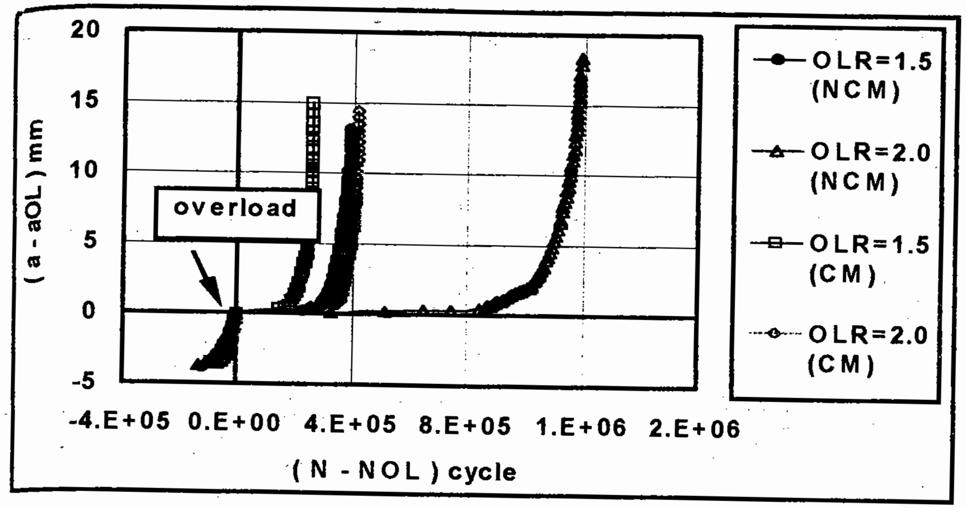

Figure 6. Correlation between crack growth rate, d*a*/dN and range of stress intensity factor, ΔK for R=0.6

The graphs shown in figure 6 have been analyzed to determine the condition before and after applying the overload. The result is shown in table 1.

Table 1. Comparison the range value of stress intensity factor and crack growth rate before and after applying overload

OLR	ΔK (MPa√*m*)		d*a*/dN (*mm*/cycle) applying overload		description
	initial	final	before	after	
1.5	5.236	9.994	3.232×10^{-5}	8.680×10^{-7}	Base material
2.0	5.231	11.047	1.006×10^{-4}	3.864×10^{-7}	
1.5	5.236	9.895	8.379×10^{-5}	2.428×10^{-6}	*Chemical milling*
2.0	5.221	10.151	7.254×10^{-5}	1.979×10^{-6}	

The relation between crack growth rate, d*a*/dN, and crack length, a-a_{OL}, is shown in figure 7. From the graphs, it can be seen that the effect overload is more significant for higher value of overload ratio. This result has a good agreement with a similar research carried out by other investigators [1,3,4].

Table 2 shows that after applying overload, the crack starts to grow about 0.2mm length with the crack growth rate of 8.680×10^{-7} *mm*/cycle for OLR=1.5. The crack growth rate is slightly higher compared to OLR=2.0, where the crack starts to grow about 0.125mm length with the crack growth rate of 3.864×10^{-7} *mm*/cycle.

Table 2. Comparison crack growth rate after applying overload between OLR=1.5 and OLR=2.0

OLR	*a (mm)* Start growing	d*a*/dN (*mm*/cycle) Applying overload before	after	Description
1.5	0.200	$3.232x10^{-5}$	$8.680x10^{-7}$	Base Material
2.0	0.125	$1.006x10^{-4}$	$3.864x10^{-7}$	
1.5	0.350	$8.379x10^{-5}$	$2.428x10^{-6}$	*Chemical milling*
2.0	0.500	$7.254x10^{-5}$	$1.979x10^{-6}$	

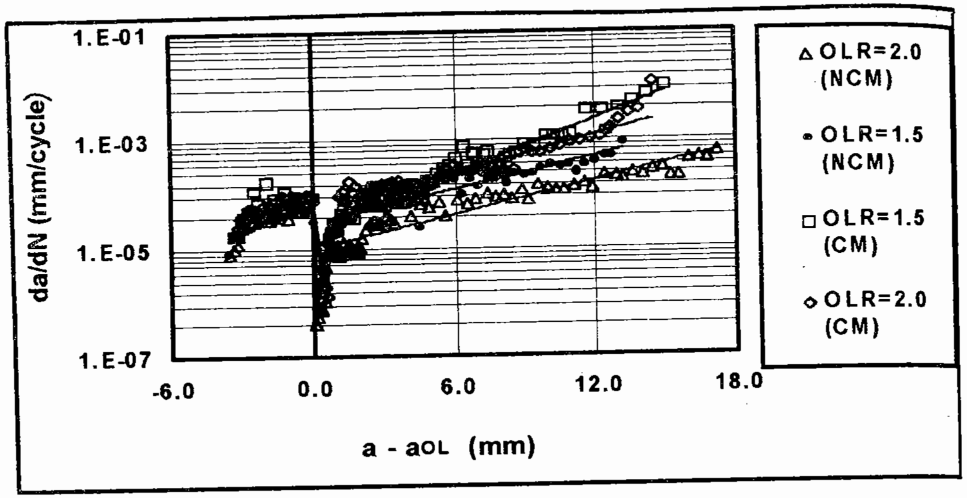

Figure 7. Correlation between crack growth rate, d*a*/dN, and crack length, a-a_{OL}, for R=0.6

Table 3 shows that the effect of overload can delay failure of material, where for the base material, it fails on 628486 cycles for OLR=1.5, and significantly increase to be 1425331 cycles for OLR=2.0. These phenomena also happen in the chemically milled aluminum.

Table 3. Crack length and number of cycles to reach failure

OLR	*a (mm)*	N (cycle)	Description
1.5	23.200	628486	Base Material
2.0	28.275	1425331	
1.5	24.750	329880	Chemical milling
2.0	23.950	487398	

CONCLUSION

From the experimental results and discussion, it can be concluded as follows:

1. The chemically milled surface specimen has slightly higher the fatigue crack growth rate for higher stress ratio. However, the effect of chemical milling becomes more significant for a lower stress ratio
2. The existence of a single overload can delay crack growth, and the increase of the overload ratio can significantly decrease the crack growth rate.
3. Due to a single overload, the acceleration of the crack growth rate becomes a negative trend. However, it returns to the normal characteristic after the crack extents beyond the plastic zone.

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