The influence of Shot Penning on fatigue crack growth rate of Chemical Milling product Al-2524-T3 alloys which has been Stretched

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Abstract. This study aims to investigate the influence of shot penning on fatigue crack growth rate of chemical milling product Al 2524-T3 which have been stretched. This alloys were stretched beyond yield stress, namely 1%, 3% and 5% of each, and then performed chemical milling process of one side. The etching used in chemical milling process were NaOH+Na₂S+H₂O solutions with certain concentration. The surface was performed shot penning process with varying intensity of 0.03 A, 0.05 A and 0.07 A, respectively. These material were then tested its crack growth rate. The crack growth rate tests were performed under 20% stress level, stress ratio of 0.3 and at frequency 7-13 Hz. The average of crack propagation data against the cycle number were processed using an incremental method, in accordance with ASTM E647 standard, to obtain crack growth rate curve (da/dN vs. ∆K). The results show that the increase of shot penning intensity has no significant effect on the fatigue life, with the growth average of 4.5%. The highest increase occurred at the shot intensity of 0.03 A, 0.2 times its chemical milling, while the lowest decrease occurred at the shot intensity of 0.07A, 0.012 times its chemical milling. The crack retardation effect at the beginning of the crack plays a role in reducing the crack propagation rate.

1. Introduction
Sheet metal is widely used in the aircraft and automotive industries, especially for relatively wide components with light weights. Sheet metal is formed using several processes, to produce the desired changes, from simple to more complex shapes [1][2].

In general, sheet metal components on aircraft due to their thin and wide shape are worked with a chemical milling process, which is a non-traditional abrasive process that uses chemical solutions as a medium since working with ordinary machining processes is not supported [3].
Materials worked by using the chemical milling processes, generally solid aluminum and magnesium, will experience distortion due to the uneven distribution of residual stress due to the release of residual stress during the working process. Its can cause damage to components, due to stress instability when assembling these components [4].

The chemical milling process also tends to produce micro cracks on the surface. Micro cracks in the material will propagate if the material loaded a dynamic work load cycle until it reaches its critical crack length, causing complete damage known as fatigue failure [5].

The residual stress on the material cannot be avoided since it occurs as a result of the sheet metal manufacturing process. One of the residual stresses of the material is due to the initial cold forming process of the sheet metal. The residual stress that arises is not always beneficial in the further forming process. On the other hand, in the further forming process, another problem that arises is the appearance of micro-cracks in the material. But the reduction of residual stress in the material can be done with certain processing processes, one of which is the stretching process with a certain percentage until plastic deformation occurs on the material. The stretching process is expected to reduce the distortion that occurs as little as possible after the material subjected to a chemical milling process.

On the other hand, chemical milling process is often carried out only on one side of the surface of the material, so that the uneven distribution of residual stress creates tensile stress on one side of the process and compressive stress on the other. A treatment that can have a positive effect on such stress forms is to apply compressive stress to the surface of the material by using techniques, such as shot penning or surface rolling. The surface layer of the material, in the shot penning process, will undergo plastic deformation down to a depth, resulting in a compressive residual stress.

This study aims to determine the crack propagation of the Al 2424-T3 stretching products which undergo a chemical milling process which is then shot penning. This study was part of the continuation research conducted by Yovial et al. [6].

2. Methodology

2.1 Material
The materials used in this study are aluminum alloy types Al 2524-T3 in sheet form, with the following chemical composition: This study is

| Material         | Chemical composition (wt%) |
|------------------|-----------------------------|
|                  | Cu  | Mg | Mn | Fe | Si | Zn | Ti |
| Al 2524-T3       | 1.0 | 0.03 | 0.05 | 0.1 | 0.3 | 0.3 | 0.03 |

2.2 Procedures
Types of specimens for testing, consist of a) raw material, b) specimen from the result of stretching+chemical milling processes, with a stretching of 1%, 3% and 5%, c) specimens from the result of stretching+chemical milling+shot penning processes, with shot intensity penning 0.03 A, 0.05 A and 0.07 A.

The stretching process is the first treatment applied to the material before it is given the chemical milling and shot penning processes. The percentage of stretching refers to the percentage of the yield stress of the material (σ_{ys}). The stretching method used is pulling material using a stress that is several percent higher than the yield stress. Therefore:

\[ \sigma_{1\%} = \sigma_{ys} + 1\% \times \sigma_{ys} \] (1)
The stress at which plastic deformation began observable is taken using the offset yield strength, at a strain of 0.2 percent. Furthermore, the value of the stress is used as a benchmark for measuring the next stretching stress, as given by equation 1.

The chemical milling process is carried out in stages, according to established procedures. Sheet metal soaked in a bath containing NaOH + Na₂S + H₂O solution with certain concentrations. The duration of soaked depends on the desired abrasive thickness in the material.

The specimens in this study followed the ASTM E-647 standard, as shown in Figure 1. The initial thickness of the specimens was 1.6 mm. Chemical milling process removed the center of the surface of the test area by a thickness of 0.2 mm, while the thickness of the two sides which was applied with the masking did not change. Masking is the process of applying the masking material to the surface to ensure that only desired areas were etched. The initial crack, 2ₐ₀, in the test specimen was made 10 mm long and located in the middle of the specimen by using an EDM machine. The surface of the test plane was then shot penning with varying intensity, namely 0.003 A, 0.005 and 0.007 A.

![Figure 1. ASTM E-647 specimen](image)

### 2.3 The seven-point incremental polynomial method

The fatigue crack propagation test carried out by a servo pulsar machine that operates at a frequency of 7-15 Hz. The crack length was measured using a traveling optical microscope from each side of the specimen surface, namely the left side of the crack on the first surface and the right side of the crack on the second surface. The optical traveling microscope has a magnification of 20x and the scale for each strip is 0.1 mm. Testing using a stress level of Sₓ ± 20%, was carried out at a stress ratio of R = 0.3.

The maximum load given, \(P_{\text{max}}\), calculated by the equation:

\[
P_{\text{max}} = \frac{S_x \sigma_y t w}{1000} \text{kN}
\]

where:
- \(\sigma_y\) = yield stress of raw material (kg/mm²),
- \(t\) = thickness (mm),
- \(w\) = width (mm)

Meanwhile, the minimum load obtained from:

\[
P_{\text{min}} = R \cdot P_{\text{max}} \text{kN}
\]

The crack propagation data obtained were in the form of crack length (\(a_i\)) and cycle (\(N_i\)). The average crack length at a given cycle were

\[
a = \frac{(a_{0i} + a_{0max} + 2a_f)}{2}
\]

The scattered data processed by the 7-point incremental polynomial method[7], which provides the equation for a collection of local points in the form of:
\[ a_1 = b_0 + b_1 \left( \frac{N_i - C_1}{C_1} \right) + b_2 \left( \frac{N_i - C_1}{C_2} \right)^2 \]  
for
\[ -1 \leq \left( \frac{N_i - C_1}{C_2} \right) \leq 1 \]

Constants \( b_0, b_1 \) and \( b_2 \) are the regression parameters obtained from the least square method in the range of \( a_{1-n} \leq a \leq a_{1+n} \), while the parameter \( C_1 \) and \( C_2 \) were calculated by the equation:

\[ C_1 = \frac{1}{2} (N_{i-m} + N_{i+m}) \]  
(7)

\[ C_2 = \frac{1}{2} (N_{i+m} - N_{i-m}) \]  
(8)

The crack propagation rate at the \( N_i \) cycle value and the crack length \( a_i \) obtained from the equation:

\[ \frac{da}{dN} = \frac{b_1}{C_2} + 2b_2 \left( \frac{N_i - C_1}{C_2} \right) \]  
(9)

The stress intensity factor (\( \Delta K \)) at the number of \( N \) cycles calculated from [8]:

\[ \Delta K = \frac{\Delta P}{B} \sqrt{\frac{\pi \alpha}{2w}} \sec \left( \frac{\pi \alpha}{2} \right) \]  
(10)

Where
\[ \alpha = \frac{2a}{w} \text{ (mm)} \quad B = \text{thickness (mm)} \quad \Delta P = P_{\text{max}} - P_{\text{min}} \text{(kg)} \quad W = \text{width (mm)} \]

3. Result and Discussion

Some of the crack propagation results test are shown in Table 2, with the number of fracture cycles of the specimen reached 108 cycles.

| No | \( a_{\text{left}} \) (mm) | \( a_{\text{right}} \) (mm) | \( N \) (cycles) | \( a_{av} \) (mm) | \( \frac{da}{dN} \) (m/cycles) | \( \Delta K \) (MPa.m\({}^{1/2}\)) |
|----|----------------|----------------|--------------|-------------|------------------|------------------|
| 1  | 5.1            | 4.95           | 0            | 5.025       |                  |                  |
| 2  | 5.1            | 5.1            | 5090         | 5.1         |                  |                  |
| 3  | 5.2            | 5.2            | 5610         | 5.2         |                  |                  |
| 4  | 5.2            | 5.3            | 6150         | 5.25        | 1.27E-07         | 11,8278327       |
| 5  | 5.3            | 5.4            | 6820         | 5.35        | 1.39E-07         | 11,9469025       |
| 6  | 5.3            | 5.5            | 7370         | 5.4         | 1.33E-07         | 12,03533074      |
| 7  | 5.4            | 5.6            | 7830         | 5.5         | 1.32E-07         | 12,11396239      |
| 102| 23.2           | 23             | 37256        | 23.1        | 6.81E-06         | 31,04118591      |
| 103| 23.8           | 23.5           | 37353        | 23.65       | 9.03E-06         | 32,09115657      |
| 104| 24.4           | 24             | 37413        | 24.2        | 1.20E-05         | 32,92689248      |
| 105| 25             | 24.5           | 37455        | 24.75       | 1.70E-05         | 33,7825963       |
| 106| 25.3           | 25             | 37476        | 25.15       |                  |                  |
| 107| 26             | 25.5           | 37512        | 25.75       |                  |                  |
| 108| 27             | 26             | 37528        | 26.5        |                  |                  |
3.1 Stretching effects

Table 2, were than plotted in a vs. N, and combined with the test results of several specimens with different processes. This graph, as in Figure 2.1, showsthat the higher the stretching percentage, the lower the number of testing cycles.

In the form of da/dN vs. ΔK curve, a clear difference is shown between the stretching percentages of 3% and 5%. Figure 2.2 shows the da/dN vs. ΔK curve appears to be shifted more to the left at the percentage of 5%. The curve shift indicates a decrease in fatigue life. In other words, the more to the left of the da/dN vs. ΔK curve, the lower the fatigue life of the material.

This phenomenon indicates that the ductility of the material decreases with the higher the stretching percentage. Ductility is related to the toughness of the material, namely the ability of the material to absorb energy in the plastic area. Therefore, the higher the stretching percentage, the less tough the material will be. The decrease in toughness is also caused by the reduction in residual stress due to the chemical milling process given earlier, so that the residual stress cannot accommodate the given dynamic tensile stress. The chemical milling process causes a reduction in residual stress on the material, especially on the surface, due to the erosion. This reduction causes an imbalance of residual stress distribution which is compensated by the material in the form of distortion. After the material is stretched, the residual stress it has is reduced, so the material no longer experiences distortion [9].

It can be concluded from the estimated life cycle, the increase in the stretching percentage from 1% to 3% reduces the fatigue life by 0.0776 times, and more decreased by 0.107 times at the 5% stretching percentage. This phenomenon also shows that the increase of stretching percentage of aluminium alloy Al 2524-T3 does not appear to be effective in increasing the fatigue life of the material.

3.2 Shot Penning effects

Figure 3.1 shows an a vs. N graph of the process with different shot intensities. It also shows that the higher the intensity of shot penning, the lower the number of testing cycles. The same phenomenon is also found in other materials with different processes (different in stretching percentage), which are not shown in this paper. However, for a low shot intensity, the increase in the test cycle that occurs is quite significant, and then decreases as the shot intensity increases. This phenomenon indicates that the chemical milling product which is given a shot penning process with low intensity significantly increases the number of test cycles.

In the form of da/dN vs. ΔK curve, as shown in figure 3.2, 3.3 and 3.4 respectively, a clear difference is shown between the shot intensities of 0.03 A, 0.05 A and 0.07 A. Figure 3.2 shows the da/dN vs. ΔK curve appears to be shifted more to the right at the shot intensities of 0.03 A. The curve...
shift indicates an increase in fatigue life. In other words, the more to the right of the \( \frac{da}{dN} \) vs. \( \Delta K \) curve, the higher the fatigue life of the material.

The shot penning intensity is related to the impact or the number of impacts per surface area. The direct result of this is the occurrence of deformations at a certain depth. The greater the intensity of the shot, the greater the impact energy received by the material, so that the more plastic deformation surface area will be. The deformation that occurs will cause the dislocation density to increase, which in turn results in a buildup of dislocations in the slip plane. The buildup causes a high dislocation density, so that the movement of the dislocations will inhibit each other; in other words, a stuck dislocation causes the material to become hard and strong.

In other words, shot penning should increase the resistance to the development of crack tip plasticity, or have an impact on the arrest of fatigue cracks [10].

It can be concluded from the estimated life cycle, an increase in shot intensity of 0.03 A increased fatigue life by 0.2 times, although it still increased at a shot intensity of 0.05 A, but it had decreased to 0.016 times. However, the life cycle reduced by 0.032 times at the shot intensity of 0.07 A.

4. Conclusion
Sheets of aluminium Al 2524-T3 alloy were prepared by a different process that involved stretching, chemical milling and shot penning. The results shown that effect of stretching percentage reduces the
fatigue life of material. The higher the stretching percentage, the lower the fatigue life. On the other hand, shot intensity increased the fatigue life of material to certain intensity.

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