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Evaluating the Effect of Specimen Thickness on Fatigue Crack Growth in AZ31 Alloy Using ANOVA

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분산분석법을 이용한 AZ31 합금의 피로균열성장에 미치는 시편두께 효과 평가

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ABSTRACT

This study aims to assess the effects of specimen thickness (ST) on fatigue crack growth in the early stages of crack propagation and near failure in magnesium alloys. The analysis of variance (ANOVA) method was adopted because fatigue crack propagation in magnesium alloys exhibits statistical behavior. The equality of variance test and residual diagnostics were performed on the grown cracks to confirm the validity of ANOVA by verifying the normal distribution and mutual independence of the residuals and their homoscedasticity. ANOVA confirmed that ST heavily impacts crack growth; i.e., when ST is smaller , cracks grow faster in the early crack propagation stage and break more quickly before the formation of larger cracks. We found that ST significantly affects fatigue crack growth in the early crack propagation stage and near the failure stage in magnesium alloys. The regression model was also used to predict crack formation near the failure stage.

Keywords : Analysis of variance(분산분석법), AZ31 alloy(AZ31 합금), Fatigue crack growth(피로균열성장), Specimen thickness(시편두께)

1. Introduction

Magnesium is the lightest metal used as the basis for structural alloys. Magnesium alloys are an attractive choice because they have desirable properties such as low density, high specific strength, machinability, and electromagnetic shielding properties. Indeed, decreased weight due to the use of mag nesium alloys in automobiles significantly contributes to a decrease in fuel consumption[1-4].

The fatigue performance of structural materials is crucial because many components of such materials are subjected to repeated loads. Several groups have reported on fatigue crack propagation behavior in magnesium alloys[5,6]. Ishihara et al.[5] studied the

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effect of load ratio on the crack propagation behavior and fatigue life of magnesium alloys. Zheng et al.[6] demonstrated that the specimen orientation affects the fatigue crack growth rate and crack path in extruded AZ31B magnesium alloy. Although some studies[7,8] have reported the effects of ST on fatigue crack growth in aluminum and steel, fewer studies have been conducted on magnesium alloys. Zhang et al.[9] studied the effects of ST on the mechanical properties of magnesium alloys, but not on fatigue crack growth .

Because crack growth exhibits a statistical dispersion, a statistical evaluation of the fatigue crack propagation behavior is essential to account for the range of behavior; however, the statistical investigation of fatigue crack growth in magnesium alloys has been rarely reported[10,11]. Although many studies[3,12-14] have been conducted using ANOVA, there are no reports for fatigue crack propagation characteristics of magnesium alloy using ANOVA.

The objective of this study is to use an ANOVA method to determine whether ST is an influential factor affecting the stability of crack growth in the early crack propagation stage and near the failure stage in magnesium alloys.

2. Experimental and Statistical Methods

Fatigue crack growths exhibit statistical behavior, as shown in Fig. 1. Thus, ANOVA was employed to analyze the effect of ST on fatigue crack growth in the AZ31 magnesium alloy. In this study, we tested fatigue crack propagation in AZ31 with three different ST values; compact tension specimens with three different thicknesses were tested under constant amplitude loading at a load ratio of 0.20 with a maximum fatigue load of 2.00 kN in ambient laboratory air.

The three different ST values tested were 4.75 mm, 6.60 mm, and 9.45 mm. The material tested was AZ31 magnesium alloy, and its chemical composition (wt. %) was as follows: Al, 3.29; Zn, 0.95; Si, 0.04; Mn, 0.31; Cu, 0.003; Fe, 0.01; and Mg, balance. The data gathered at the early stage of crack propagation after 5000 load cycles are presented in Table 1, while Table 2 shows crack

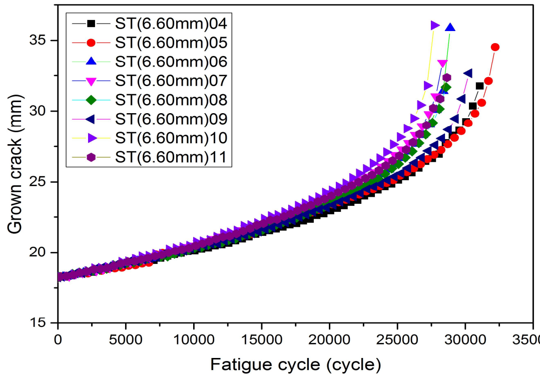


Fig. 1 Fatigue crack growth curve (Case of ST of 6.60 mm)

Table 1 Grown crack data (N=5000cycle)

Observation	Treatment (ST)		
	4.75mm	6.60mm	9.45mm
1	22.068	19.138	18.864
2	22.183	18.994	18.901
3	22.126	19.189	18.939
4	21.861	19.229	19.101
5	22.288	19.221	19.192
6	22.109	19.268	19.258
7	22.404	19.349	19.352
8	22.672	19.298	19.380

Table 2 Grown crack data (N/Nf=0.95)

Observation	Treatment (ST)		
	4.75mm	6.60mm	9.45mm
1	28.005	29.155	30.667
2	27.236	29.933	30.701
3	29.387	29.237	30.574
4	28.030	29.307	31.300
5	25.811	29.126	31.101
6	27.900	29.185	31.412
7	28.541	29.789	31.270
8	27.664	30.238	31.183

data near failure (N/Nf=0.95, where N and Nf are fatigue cycle and failure cycle, respectively).

It is necessary to analyze the fatigue crack propagation behavior to enhance the structural integrity management. Statistical analysis was performed on the fatigue behavior in the early crack propagation stage and near the failure stage. One-way ANOVA was used to assess the statistical significance of the effect of ST on fatigue crack growth in the early crack propagation stage (N = 5000 cycles) and near the failure stage (N/Nf = 0.95). One-way ANOVA was also used to analyze the effect of varying ST from 4.75 mm to 9.45 mm. The commercial statistical software Minitab was used for statistical analysis.

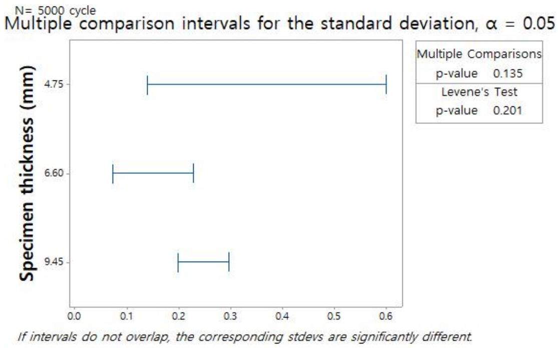
Because ANOVA assumes that the variances of the populations are equal, the homoscedasticity of the grown crack was first tested. The validity of ANOVA was confirmed by verifying the normal distribution and mutual independence of the residuals of grown cracks.

To investigate the impact of ST, ANOVA was applied to the grown crack data for three different ST values. The analysis of means (ANOM) test also verified the significance of the three different ST values. Finally, the primary effect of ST on crack growths was analyzed through the main effect plot after verifying the significance of the ST factor.

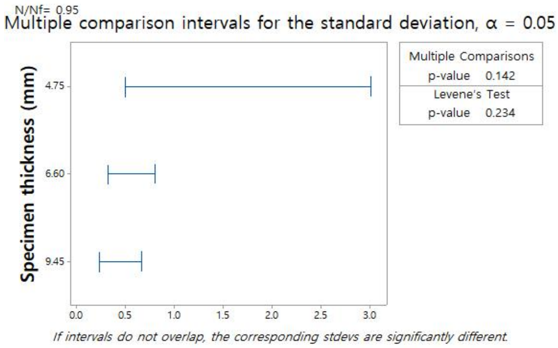
3. Results and Discussion

3.1 Test for Equal Variances

Because heteroscedasticity can invalidate ANOVA analyses, it is essential to confirm the homoscedasticity of the grown cracks. If the confidence intervals for two conditions (ST, in this study) do not overlap, those standard deviations are deemed significantly different (i.e., the populations are heteroscedastic[15]). If the p-values obtained through Levene's test and the multiple comparisons



(a) Early crack propagation stage



(b) Near failure stage

Fig. 2 Test for equal variances: Grown crack versus ST

test using Minitab fall below the significance threshold , the null hypothesis is rejected, implying that one or more standard deviations significantly differ from other standard deviations. The significance threshold (usually called α) used in this analysis was 0.05. Multiple comparison interval plots generated in Minitab were also used to identify whether the standard deviations were significantly different. As demonstrated in Fig. 2(a), the p-values obtained from Levene's test and the multiple comparisons test were 0.201 and 0.135, respectively. Because these p-values are greater than the significance threshold of 0.05, the null hypothesis can be accepted. The p-values in Fig. 2(b) are 0.234 and 0.142, which are also greater than the significance threshold. Because the null hypothesis can be accepted, there are no significant differences between the standard deviations.

As shown in Figs. 2(a) and 2(b), all confidence intervals overlapped . Therefore, we can confirm that there are no significant differences between the standard deviations. Thus, the variances in crack propagation in the early crack propagation stage and near the failure stage are equal for each ST value. This result also implies that the experiment was performed properly[16].

3.2 ANOVA Residual Diagnostics

To validate the use of the ANOVA method, the following assumptions[15] are required: (1) the populations being sampled are normally distributed, (2) the populations being sampled are homoscedastic, and (3) the observations are independent.

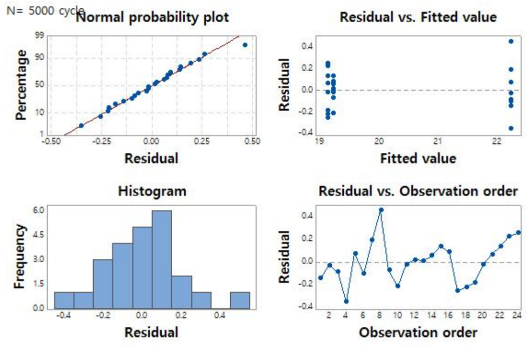
The residual diagnostic graphs shown in Fig. 3 were created using one-way ANOVA to analyze the grown crack data. Fig. 3(a) shows the results of the ANOVA residual test for the grown crack in the early crack propagation stage. The normal probability plot demonstrates that the residuals approximately fall along a straight line, implying that the residuals are normally distributed. As evident in the plot of residuals versus the fitted values, the variation in the residuals appears to be comparable irrespective of the magnitude of the response; thus, the residuals are likely homoscedastic with respect to the fitted values.

It is known that if a run chart does not have any patterns, the residuals are mutually independent[15]; accordingly, the residuals are independent of one another because there are no patterns on the run chart in Fig. 3(a). The residuals of the grown crack also appear to be homoscedastic with respect to the run order[15]. Additionally, the residuals of the grown crack near the failure stage are approximately normally distributed, as shown in Fig. 3(b). Because the variations in the residuals are found to be comparable and do not have any characteristics in the plot of residuals versus fitted values , the residuals are random and likely homoscedastic with respect to the fitted values. As evident in Fig. 3(b), the run chart has no particular pattern; therefore, the residuals of the grown crack are mutually independent.

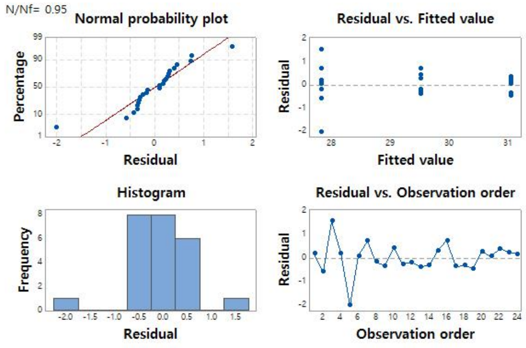
The residual test results shown in Fig. 3 demonstrate that the residuals of the grown crack are normally distributed and homoscedastic with respect to the fitted values and run order. Therefore, the normality and independence of the residuals of the grown crack were verified, and, accordingly, the validity of ANOVA was confirmed.

3.3 One-way ANOVA

The validity of ANOVA was confirmed by



(a) Early crack propagation stage



(b) Near failure stage

Fig. 3 ANOVA residual diagnostics for grown crack

Table 3 One-way ANOVA: Grown crack versus ST (N=5000cycle)

Source	DF	Adj SS	Adj MS	F value	P value
Treatment(ST)	2	49.540	24.770	656.48	0.000
Error	21	0.792	0.037		
Total	23	50.332			

* where, DF, Adj SS, and Adj MS denote the Degree of Freedom, Adjective Sum of Squares, and Adjective Mean Square, respectively.

Table 4 One-way ANOVA: Grown crack versus ST (N/Nf=0.95)

Source	DF	Adj SS	Adj MS	F value	P value
Treatment(ST)	2	41.097	20.548	45.45	0.000
Error	21	9.494	0.452		
Total	23	50.591			

verifying the normal distribution and mutual independence of the residuals, as described above. As demonstrated in Fig. 2, it was confirmed that the variances of the grown crack are equal for the three ST values in the early crack propagation stage and near the failure stage.

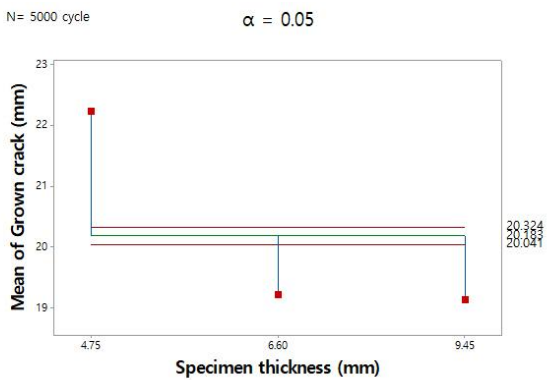
The residual diagnostics presented in Fig. 3 verified that the residuals are normally distributed, homoscedastic, and mutually independent. Because the assumptions required to validate the use of ANOVA were satisfied, two ANOVAs were performed on the grown crack in the early crack propagation stage and near the failure stage, respectively, using Minitab. The results of the two ANOVAs are summarized in Tables 3 and 4.

The first ANOVA, shown in Table 3, demonstrates that ST has a significant effect on crack growth in the early crack propagation stage because the p-value is less than the significance threshold of 0.05. The results of the second ANOVA, shown in Table 4, also shows that the ST considerably affects crack growth near the failure stage because the p-value is less than the significant level . Thus, ST significantly affects crack growth in magnesium alloys.

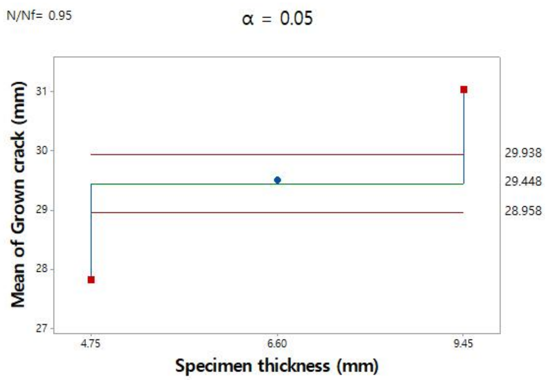
3.4 One-way ANOM Test

The ANOM test provides a graphical method for testing the null hypothesis (Ho : μ1 = μ2 = ⋯ = μ k, where μ denotes the mean of population k) versus the alternative hypothesis (Ha : “Ho is false”)[17].

The graphical results of a one-way ANOM for the grown cracks following a normal distribution are shown in Fig. 4.



(a) Early crack propagation stage



(b) Near failure stage

Fig. 4 One-way ANOM test for grown crack following normal distribution

The red lines in Fig. 4 represent the upper decision limit (UDL) and lower decision limit (LDL). The green line indicates the total mean of the grown crack . The condition (ST, in this study) means are plotted against the corresponding factor level and connected to the center line through vertical line segments. If a point falls outside the decision limits, the null hypothesis is rejected[16,17].

In the early crack propagation stage, the UDL and LDL are 20.324 and 20.041, respectively, as evident in Fig. 4(a); however, those near the failure stage are 29.938 and 28.958, respectively. Because at least one mean falls outside the decision limits, as demonstrated in Fig. 4, we conclude that the means of the three treatments are not equal and reject Ho. The means of treatments significantly differ from the total mean. Therefore, the ST value has a significant effect on crack propagation in the early crack propagation stage and near the failure stage.

3.5 Overall Effect of Specimen Thickness

Figs. 5(a) and 5(b) show the overall effects of ST on crack growth in the early crack propagation stage and near the failure stage, respectively. The dotted horizontal line in Fig. 5 indicates the total mean of the grown crack and the data points represent the mean of the grown crack at a given ST value.

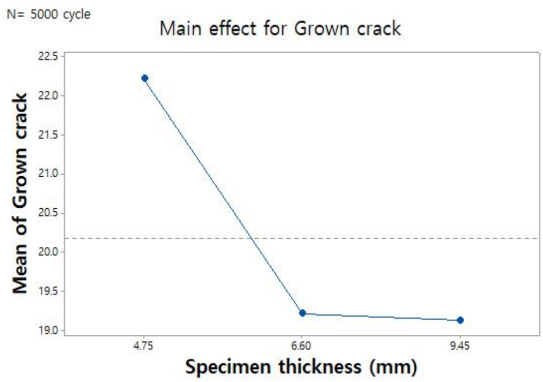
As evident in Fig. 5(a), the grown crack in the 4.75 mm specimen is the largest of the three specimens, and the crack growth rate at this ST value is the fastest. If the crack grows rapidly, the structure becomes unstable; therefore, the ST value should be increased to slow crack growth.

The larger the ST, the slower the crack growth rate in the early crack propagation stage. Indeed, even small increases in ST significantly decrease the crack growth rate. Thus, changes in thickness were found to have a significant impact on crack growth in the early crack propagation stage.

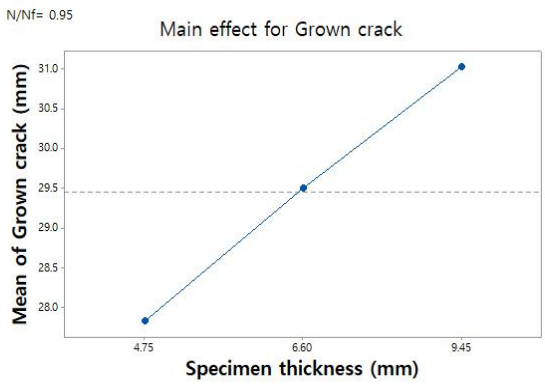
In contrast to the results obtained in the early crack propagation stage, the grown crack near the failure stage was the smallest in the 4.75 mm specimen. The smaller the ST, the faster the cracks grow in the early crack propagation stage, causing them to break before the formation of larger cracks . Thus, the ST value seems to have a significant effect on crack growth in magnesium alloys.

As shown in Fig. 5(b), the grown cracks near the failure stage increased almost linearly with the ST. Thus, a model for the grown crack was obtained by regression analysis. The regression model is presented in Eq. (1).

$$Grown\ crack = 24.806 + 0.6695\,ST \quad (1)$$



(a) Early crack propagation stage



(b) Near failure stage

Fig. 5 Main effect plot of ST on crack growth

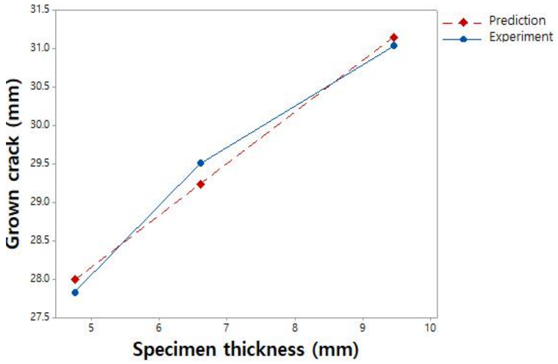


Fig. 6 Comparison plot between prediction model and experiment

The correlation coefficient (R2) of the developed model is 79.46%. The coefficient of correlation indicates the goodness-of-fit for the model. This regression model provides a detailed explanation of the relationship between the specimen thickness and crack length. Fig. 6 shows that there is agreement between the model and the experiment, with a maximum error of 0.92%.

4. Conclusion

The ANOVA method was used to assess the effect of ST on crack growths in the early crack propagation stage and near the failure stage in magnesium alloys. The variances of grown cracks were found to be equal for the three ST values both in the early stage of crack propagation and near the failure stage. The validity of ANOVA was confirmed by verifying the normal distribution and mutual independence of the residuals of the grown cracks.

The ANOVA demonstrated that ST is highly influential on crack growth characteristics in magnesium alloys. The effect of changes in ST value was also verified through the ANOM test. It was observed that for a smaller ST, cracks grow faster in the early crack propagation stage and break more quickly before the development of larger cracks. Additionally, it was found that the ST significantly affects the growth of cracks in the early crack propagation stage and near the failure stage in magnesium alloys. A regression model was also developed to predict the grown crack length near the failure stage at a given ST value.

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