Reliability Assessment of Non-Destructive Inspection Using Additively Manufactured Artificial Defect Specimens

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ABSTRACT

Various non-destructive inspection (NDI) techniques are being utilized to detect cracks early for the flight safety of aircraft structures, but it is difficult to obtain actual cracked parts to verify them. In this study, artificially defective specimens were manufactured using 3D printing technology to solve this problem. The manufactured specimens were subjected to various destructive/non-destructive tests, including eddy current testing, to quantitatively evaluate the detection performance according to the defect size of the specimen. The results of this study can be applied to the reliability evaluation of NDI and structural reliability analysis, and in particular, it is expected to contribute to overcoming the difficulties of experimental data collection and developing a highly reliable defect detection model.

INTRODUCTION

According to MIL-HDBK-1823A [1], a minimum of 40 samples is required to evaluate the reliability of non-destructive inspection (NDI) for crack detection in aircraft structures. According to the International Atomic Energy Agency's NDT specimen fabrication guidelines, sample specimens are usually fabricated by inserting artificial defects in various ways. For example, gas pores generated during the welding process or intentionally inserted non-metallic inclusions. However, these conventional methods have limitations in fabricating specimens with complex internal shapes or when precise defect control is required.

To overcome these limitations and obtain these desired data, artificial defect specimens were fabricated using powder bed fusion (PBF)-based 3D printing technology [2], and experiments were conducted. Defect signals were collected through

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eddy current inspection, and defect characteristics were evaluated through non-destructive and destructive tests. Non-destructive examinations were performed using computed tomography (CT) and computed radiography (CR), and the specimens were physically opened to compare actual crack lengths. Based on the experimental data, probability of detection (POD) analysis was conducted to assess the reliability and limitations of defect detection. Finally, the length at detection (LaD) was derived from each inspector's signal analysis [3].

This paper consists of experiments, results and discussion, and conclusion. The experimental part describes the method of fabricating artificially defective specimens, the POD calculation method, and the crack size estimation process. The results and discussion part derives the POD curve and LaD based on the eddy current test and crack length measurement results. This analysis can be used to quantify the NDI system's defect detection performance and to establish maintenance strategies and structural health monitoring systems for aircraft structures.

EXPERIMENTAL

Fabrication of specimens

Artificial defect specimens were fabricated using AlSi10Mg, an aluminum alloy widely used in aircraft structures. A metal 3D printer was used to fabricate the specimens, and the PBF method, one of the additive manufacturing technologies, was applied [2]. AlSi10Mg is a material that provides excellent layer uniformity and high shape precision in the field of metal additive manufacturing, and has properties suitable for simulating defects and fabricating high-precision specimens.

The fabricated specimens were classified into specimens with edge defects and specimens with center defects depending on the location of the defect. The edge defect specimens are designed from 1 to 6, and the center defect specimens are prepared from 7 to 12. The specimen design considers various locations of defects that may occur in actual aircraft structures.

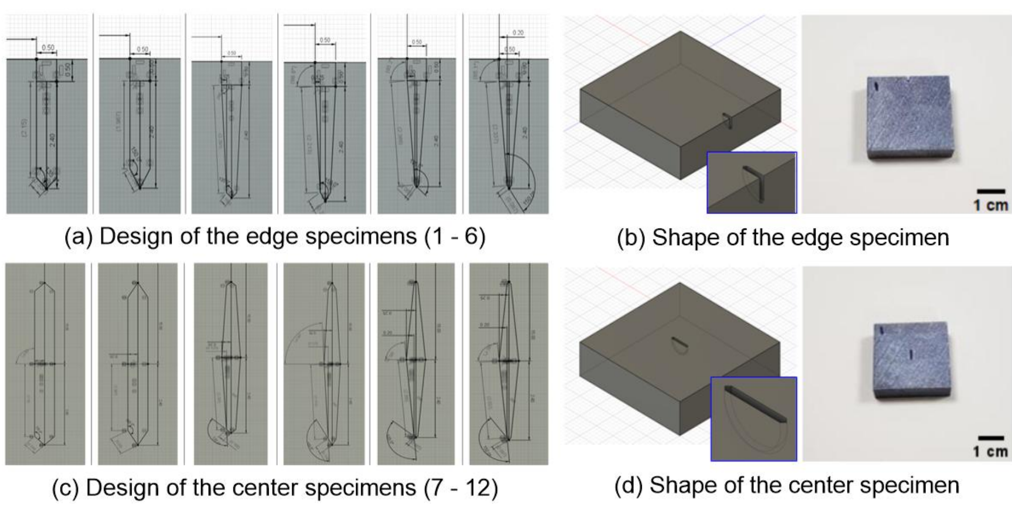


Figure 1. Artificial defect specimens.

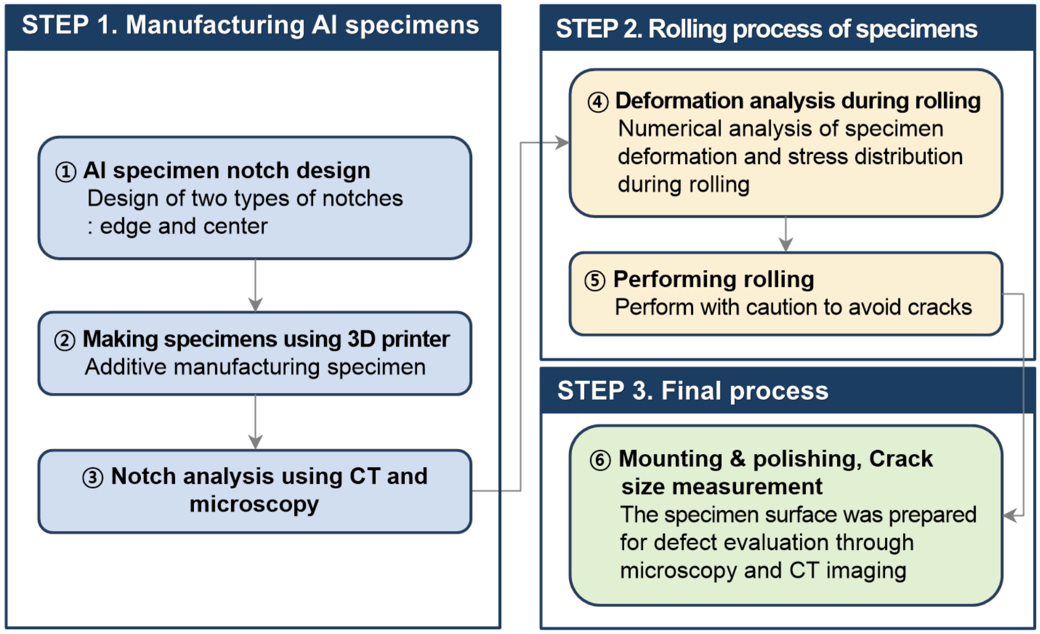


Figure 2. Specimen fabrication flowchart.

The specimen fabrication and processing procedure is largely divided into three stages. In the first stage, two types of notches were designed according to the edge and center positions, and the specimens were fabricated using a metal 3D printer. The initial notch shape of the fabricated specimens was analyzed using computed tomography and an optical microscope.

In the second stage, a cold rolling process was performed to close the defects in the specimens. Before rolling, numerical analysis was performed using Abaqus software to predict the deformation and stress distribution of the specimens. Through this, the optimal rolling conditions were derived to prevent excessive deformation or additional cracks. The rolling process was repeated several times to prevent cracks in the specimens, and the experimental results showed that the notches were completely closed through rolling. The slight specimen deformation that occurred during the rolling process was corrected through a subsequent compensation process.

In the third stage, the specimens were mounted and polished to precisely machine the surface. Through this process, variables that may occur during the eddy current inspection process were controlled, and the defect signals could be measured more accurately. Finally, NDI was performed on the prepared specimens to secure basic data for subsequent defect signal analysis and detection probability calculation.

Detection probability calculation

For detection probability analysis, log transformation was applied to the signal data. Log transformation was performed to adjust the distribution of data to be close to normality and to make it suitable for linear regression analysis. The transformed data was used to secure linearity between the fault length and signal size, and detection probability analysis was performed based on this. The detection probability model used in this study is as follows [1].

$$POD(a) = 1 - \Phi\left(\frac{y_{th} - \mu(a)}{\hat{\sigma}}\right) \tag{1}$$

where Φ is the cumulative normal distribution function, y_{th} is the detection threshold, $\mu(a)$ is the average signal size by crack size, and $\hat{\sigma}$ is the standard deviation of the signal size. The parameters of equation (1) can be derived from a linear model. The linear model representing the relationship between the signal and the crack length is as follows.

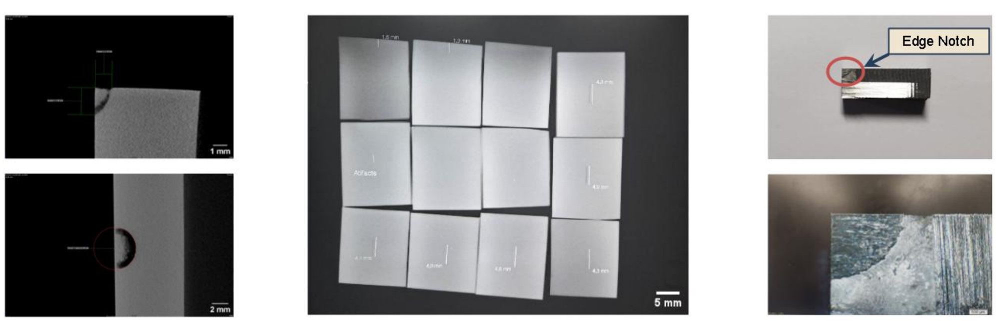
$$y(a) = \beta_0 + \beta_1 x \tag{2}$$

The detection probability curve was derived based on the defect length obtained through NDI and signal intensity data obtained through eddy current inspection. The linear relationship between the defect length and the signal intensity was confirmed through linear regression analysis of the experimental data. The noise and threshold values were applied according to the standards of the US Air Force non-destructive testing technical order [4], and the noise was set to 10 percent and the threshold value to 15 percent of the reference signal intensity. Since the reference signal intensity was set to 80 percent, the noise was converted to 8 percent and the threshold value to 12 percent and applied [5].

Crack size estimation

In this study, the defect length was estimated through non-destructive inspection of previously manufactured specimens. The NDI methods used are divided into computed tomography (CT) and computed radiography (CR). CT reconstructs the internal structure of the specimen into a three-dimensional image to precisely identify the location and shape of the defect, and CR is used to quickly detect the defect through a two-dimensional image. The length of the defects identified through each inspection method was measured using dedicated software, and through this, the defect length data based on the non-destructive testing of each specimen was obtained.

In addition, in order to increase the accuracy of the crack size estimation, the specimen was physically opened to measure the actual defect length. The cutting was performed using a metal wire cutting technique, and the cut cross-section was observed



(a) Computed tomography (b) Computed radiography (c) Destruction

Figure 3. Measurement of crack length through non-destructive and destructive methods.

using a stereoscopic microscope to precisely measure the length of the notch. The defect length obtained in this way was compared and analyzed with the results measured by the non-destructive testing. By comparing the results between the two methods, the accuracy of the non-destructive testing technique was verified and the reliability of the experimental data was secured.

RESULTS AND DISCUSSION

Eddy current testing

An acrylic base plate was manufactured for the repeatability and reproducibility of the eddy current inspection. All specimens were fixed and inspected under the same conditions. The equipment used was an Olympus Nortec 600D. The inspection frequency was set to 200 KHz according to the standards [4]. The initial gain was set to be 80% of the full screen height at a 0.020 inch notch, but some signals exceeded 100%, so the gain was adjusted by the attenuation method and the working gain was reset. The attenuation amount was calculated by the following equation.

$$dB = 20\log_{10}\left(\frac{A_1}{A_2}\right) \tag{3}$$

where A_1 represents the signal size before adjustment, and A_2 represents the signal size after adjustment. According to the reference [4], if the signal intensity increases by 6 decibels, the signal amplitude doubles, and conversely, if it decreases by 6 decibels, the signal amplitude is halved. Based on this, the working gain was adjusted to half the level of the existing signal to enable stable signal acquisition. The probe was selected as a high-frequency probe optimized for the inspection frequency. The tip diameter of the probe used was 1/8 inch, which was selected to secure spatial resolution for small surface defects and effectively detect fine cracks. The small tip diameter has the advantage of being able to precisely measure the signal change corresponding to the defect size [4].

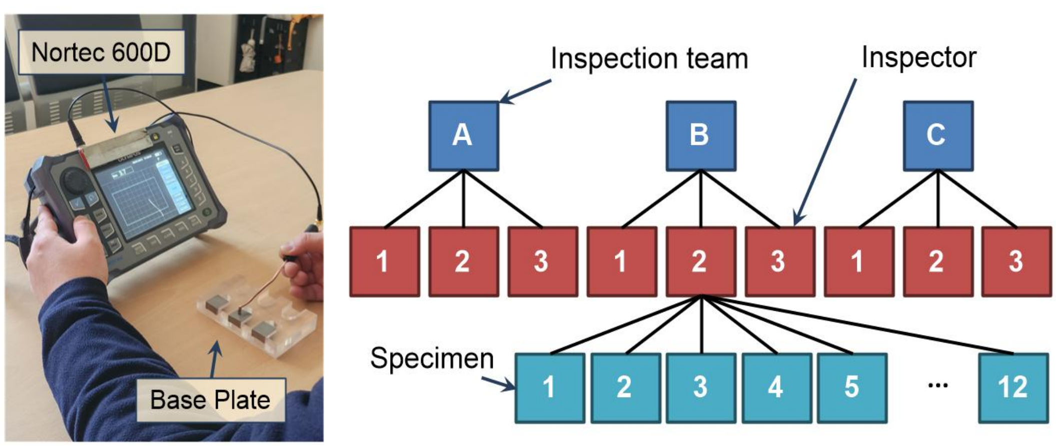


Figure 4. Experimental design (Eddy current testing).

Crack size measurement results

Some specimens were measured for crack length using physical specimen opening and CT, CR methods. However, it was difficult to obtain accurate defect lengths for some specimens due to limitations such as poor shooting quality or measurement time. Accordingly, for the remaining specimens for which crack lengths could not be measured, the crack lengths were estimated using the results of eddy current testing [6].

The method for estimating the crack length is as follows. After confirming the linearity between the signal size and the crack length in the log-log plane, the crack length of the unmeasured specimens was calculated using linear regression analysis. For specimens whose lengths could not be measured, the crack length was estimated using the average signal size measurement of each specimen from the eddy current inspection.

The analysis results showed that the defect length measured in the destructive inspection generally tended to be somewhat larger than that in the non-destructive inspection. This difference is believed to be mainly due to several factors such as the distortion of the signal-to-noise ratio that can occur during the NDI process, the lift-off phenomenon, and the difference in the detection direction. On the other hand, destructive testing is relatively less affected by these external variables, so it provides results closer to the actual defect size. Through this comparative analysis, the reliability of the non-destructive testing in this study could be additionally verified [7].

Probability of detection and detectable crack length

Fig. 5 shows the POD curve of the specimen. The POD curve was derived based on the processed defect length and the FSH value obtained through the eddy current inspection. The crack length of the unmeasured specimen was estimated based on the linear regression equation between the signal size and the crack length derived previously, and the linear regression analysis confirmed that the defect length and the eddy current inspection FSH value were linear. Since the FSH criterion was set to 80%, the noise was set to 8% (10% of 80), and the threshold was set to 12% (15% of 80).

Fig. 6 (a) shows the Lad of each inspector for the edge specimen. Figure 6 (b) displays the $a_{90/95}$ values, and obtains the $a_{90/95/95}$ values. Although some inspectors had deviations greater or less than the average, the overall trend was consistent. The $a_{90/95/95}$ value shown on the POD curve was 1.47 mm, showing excellent performance

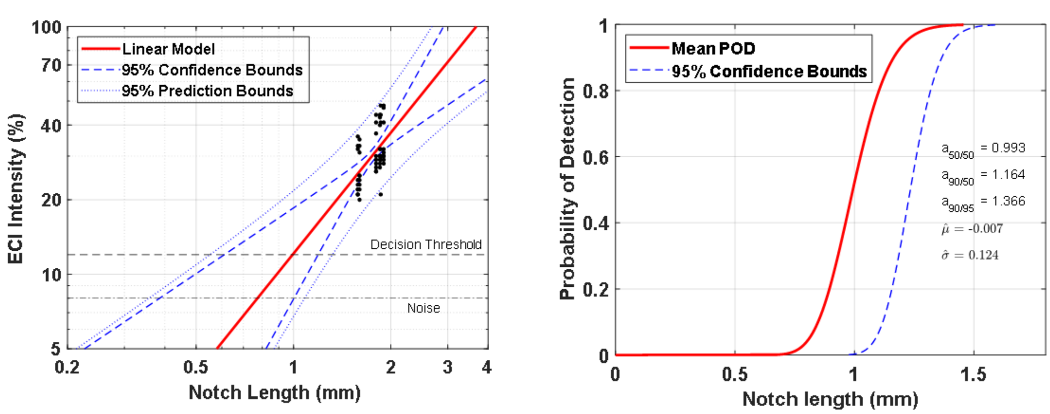
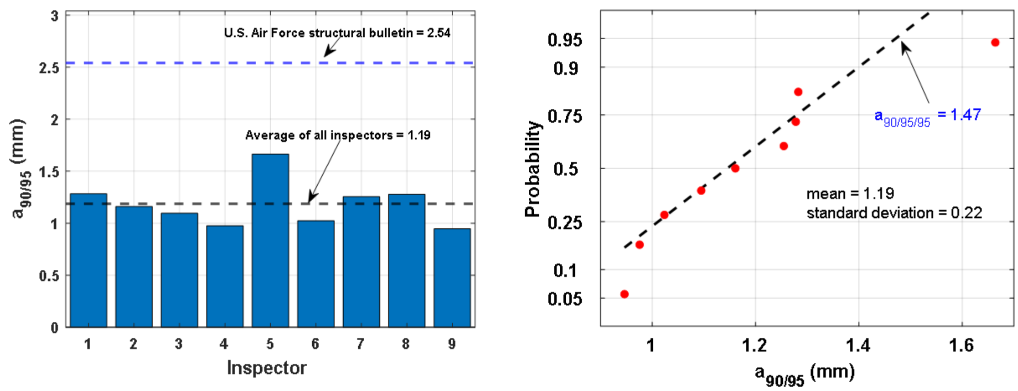


Figure 5. POD Curve analysis.



(a) Detectable crack size ($a_{90/95}$) for each inspector

(b) Normal probability plot for $a_{90/95}$

Figure 6. Detection length of individual inspectors.

compared to the US Air Force structural bulletin of 0.1 inch (2.54 mm) [8]. These results prove that the eddy current testing system used in this experiment has high defect detection performance.

CONCLUSION

In this study, artificially flawed specimens were manufactured using metal additive manufacturing technology, and the defect detection performance was quantitatively evaluated through eddy current inspection. As a result of the POD analysis, the reliable crack length detectable by eddy current inspection was confirmed to be 1.47 mm, which is better than the standard of 0.1 inch (2.54 mm) suggested by the U.S. Air Force. However, the actual crack length measured by physically cutting the specimen was approximately 2 mm, which showed some differences from the nondestructive inspection results, and thus, it was confirmed that additional research is needed to improve the reliability of nondestructive inspection.

In order to further increase the reliability of nondestructive inspection, it is necessary to perform repeated experiments under various conditions and environments and secure statistical stability through data accumulation. In particular, the utilization of the MAPOD technique is required to supplement limited experimental data and more accurately evaluate crack detection performance. MAPOD has the advantage of drastically reducing the number of physical experiments and costs by estimating the POD curve by quantifying signal variability through simulation based on physical experiment data [9].

In future studies, we plan to actively apply the MAPOD technique to systematically analyze the detection probability according to various defect types and material conditions. Through this, it is expected that a more reliable NDT system evaluation system can be established and that it will substantially contribute to the early detection of defects in aircraft structures and the establishment of maintenance strategies.

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