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ARALL재의 개발과 이의 피로파괴거동에 관한 연구

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A Study on the Fatigue Behavior of ARALL and Manufacturing of ARALL Materials

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ABSTRACT

섬유강화금속적층재(Fiber Reinforced Metal Laminates, FRMLs)는 고강도금속과 섬유강화복합재료(Fiber Reinforced Composite Materials)를 적층한 새로운 종류의 하이브리드 재료이다. 국산 아라미드 섬유인 헤라크론(Heracron, 코오롱)과 국내 복합재료 제작기술(한국화이바)을 사용하여 섬유강화금속적층재를 제작하고, 이를 HERALL(Heracron Reinforced Aluminum Laminate)이라 명명하였다. HERALL(Heracron Reinforced Aluminum Laminate)의 피로균열성장특성 및 피로균열진전 방해기구를 ARALL(Aramid-fiber Reinforced Aluminum alloy Laminates) 및 Al 2024-T3과 비교해석하였다. HERALL과 ARALL은 균열진전을 저지하는 아라미드 섬유로 인해 뛰어난 피로균열성장특성 및 피로저항성을 보여주었다. 아라미드 섬유의 균열브리징으로 인한 K_{max}의 감소량과 Al 2024-T3의 균열닫힘으로 인한 K_{min}의 증가량을 구할 수 있는 응력-COD 법을 사용하여 실제로 균열성장에 영향을 준 유효응력확대계수범위를 측정하였다. 균열선단으로부터 균열을 가공하면서 COD 변화량을 측정하여 균열브리징 영역을 구하였다.

Key Words : FRMLs(섬유강화금속적층재), ARALL(아랄), HERALL(헤랄), ARAMID(아라미드), HERACRON(헤라크론), CRACK BRIDGING(균열브리징), CRACK CLOSURE(균열닫힘)

1. INTRODUCTION

Aluminum alloys are usually used in the majority of aircraft industry. However, in the design of aircraft using aluminum alloys, fatigue behavior proves to be a limiting factor. Recognizing the severe limitations imposed on the use of aluminum by fatigue, Vogelesang and Marissen at the Delft University of Technology developed a composite material based on aluminum skins covering piles of aramid fiber reinforced epoxy and named "FRMLs(Fiber Reinforced Metal Laminates)". The trade name of fiber reinforced aluminum laminate material is ARALL®(aramid-fiber reinforced aluminum-alloy laminates). In the case of using ARALL in aircraft structure, up to 60% higher strength and 15~20% lower density has been predicted.(1)~(8)

The fatigue crack growth resistance of the FRMLs is primarily associated with extensive crack bridging from unbroken fibers in the wake of the crack. The fibers of high strength in the adhesive bond layers act as crack-bridging and restrain crack opening. The studies on the crack-bridging have been

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concentrated on that of fiber reinforced composite materials.[9]

The primary objective of the present work is to make FRMLs using Heracron and epoxy resin, that were made by KOLON and Han Kuk Fiber in KOREA, and to measure quantitatively the magnitude of crack-tip shielding by crack bridging as well as crack closure in FRMLs.

2. EXPERIMENTAL PROCEDURE

2.1 Making of HERALL

The prepreg used in HERALL(HEracron-fiber Reinforced ALuminum alloy Laminate) is made by impregnating Heracron fiber. This prepreg consists of an epoxy based adhesive system impregnated with uniaxial heracron fibers, in a 50/50 fiber adhesive weight ratio. Making process is shown as Fig. 1～4 and the fiber direction is aligned in parallel to the rolling direction of 2024-T3 aluminum sheet. Curing is achieved at 121℃.

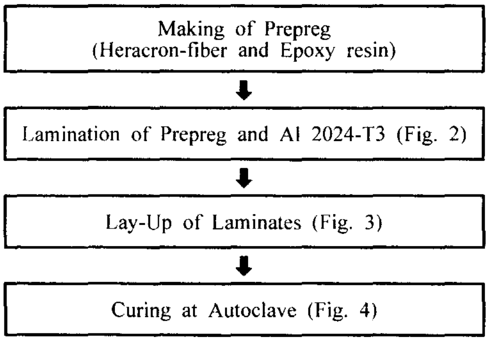

Fig. 1 Process of making HERALL

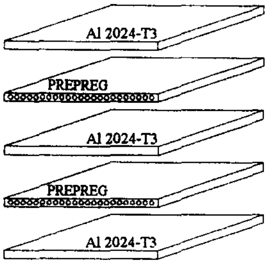

Fig. 2 Lamination of Prepreg and Al 2024-T3

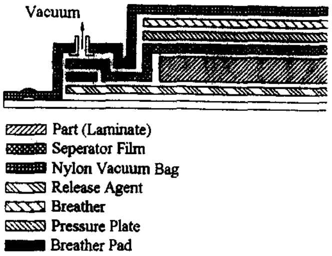

Fig. 3 Lay-Up of Laminates

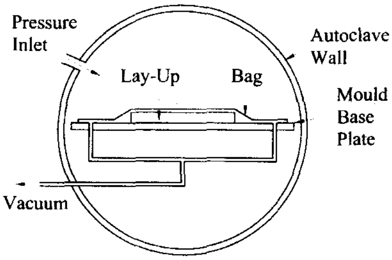

Fig. 4 Curing at Autoclave

2.2 Fatigue Test

The mechanical properties of materials used in this study is shown as Table 1. Fatigue test were performed using Shimadzu Fatigue Testing Machine, in accordance with ASTM Standard E647-91 and CCT specimen was used.

Table 1. Mechanical Properties of FRMLs and Aluminum Alloy

Mechanical Properties	HERALL	ARALL	Al 2024-T3
Ultimate Tensile Strength, MPa	507.8	569.7	412.7
Tensile Yield Strength, MPa	347.3	347.3	347.3
Tensile Modulus, GPa	67	64	72
Poisson's Ratio	0.32	0.32	0.24
Tensile Strain to Failure, %	2.0	2.5	13.2

The condition for fatigue test is as follows.

Maximum Stress : 231.6MPa
Stress Ratio : 0.1
Fatigue Wave : Sine Wave 10Hz
Constant Amplitude
Initial Crack Length : 13.5㎜
Final Crack Length : 37.5㎜

The length of fatigue crack was measured using traveller microscope and crack length vs cycles was analyzed by Secant method.

2.3 Measurement of Effective Stress Intensity Factor

The crack bridging of FRMLs decreases the maximus stress and the crack closure of FRMLs increases the minimum stress. The effective stresses which actually influence on fatigue crack growth of FRMLs are the effective maximum stress due to crack bridging and the effective minimum stress due to crack closure. The effective maximum stress in cycles which actually influences on fatigue crack growth due to crack bridging is measured by using the difference of COD(Crack Opening Displacement) between FRMLs and metal sheet which belongs to the same kind of metal used in FRMLs.(5) Under the equivalent fatigue stress, the COD of metal is larger than that of FRMLs crack-bridged by fibers. The effective maximum stress is measured from COD-Stress diagram. In maximum COD of FRMLs, the stress of metal is the effective maximum stress caused by crack bridging(Fig. 5~6).

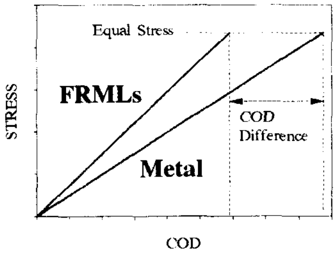

Fig. 5 COD Difference in FRMLs and Metal under Equal Stress

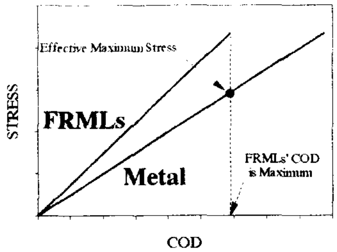

Fig. 6 Effective Maximum Stress

The effective minimum stress in cycles which actually influences on fatigue crack growth is a crack opening stress. Crack opening stress is measured by using Paris' compensation method.(10)(11) The experimental block diagram for measuring an effective maximum stress and an effective minimum stress used in this study is shown as Fig. 7.

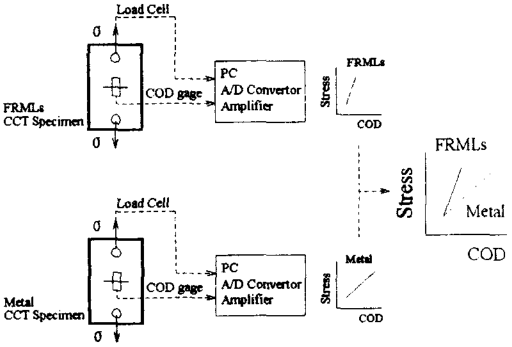

Fig. 7 The Experimental Block Diagram

2.4 Measurement of Crack-bridging Zone

In order to determine the location and size of the bridging zone of unbroken fibers behind the crack tip, experiments were performed where the wake of the crack was progressively removed while simultaneously monitoring the change in COD of FRMLs. The experiment was conducted on an arrested crack that had been cycled for 10^7 cycles at an apparent threshold. Using a fine saw, a 1㎜ wide slot was machined from the V-notch along the dormant crack to within 0.2㎜ of the crack tip. Approximately every 1㎜, the COD was measured using COD gage mounted on the center of specimen, while monitoring the length of the slot length and remaining portion of the crack with a travelling microscope. The threshold of ΔK in HERALL and ARALL was all $7.7 MPa \cdot m^{1/2}$. Slotting fibers bridging the crack of metal layers increase COD of FRMLs. In machining FRMLs using a fine saw, the crack bridging zone is where the COD increase sharply.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Fatigue Crack Growth Behavior

The results of the constant-amplitude fatigue crack propagation tests on monolithic aluminum and FRMLs are shown in Fig. 8 ~ 10. Fatigue crack propagation in the monolithic aluminum is faster than that in FRMLs. This indicates that the fatigue crack growth resistance of FRMLs is extremely higher than that of monolithic aluminum.

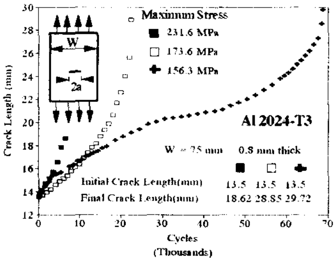

Fig. 8 Fatigue Crack Length vs Cycles of Al 2024-T3(R = 0.1)

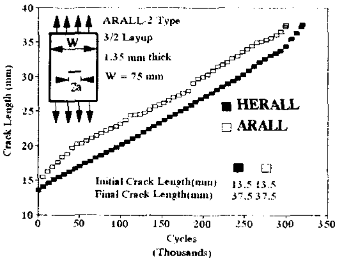

Fig. 9 Fatigue Crack Length vs Cycles of HERALL and ARALL (R = 0.1)

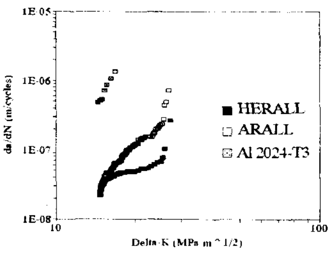

Fig. 10 Relation between Fatigue Crack Growth Rate and Stress Intensity Factor Range Comparing FRMLs with Al 2024-T3

3.2 Measurement of Effective Stress Intensity Factor

The extrinsic mechanism affects the applied crack driving force ΔK defined as eq. [1], which decreases the effective K_{max} and increase the effective K_{min}. Accordingly, the effective stress-intensity experienced at the crack tip may be defined as eq. [2].

$$\Delta K = K_{max} - K_{min} \qquad [1]$$

where ΔK = Stress Intensity Factor Range
K_{max}= Maximum Stress Intensity Factor
K_{min}= Minimum Stress Intensity Factor

$$\Delta K_{eff} = K_{br} - K_{cl} \qquad [2]$$

where ΔK_{eff} = Effective Stress Intensity Factor Range
K_{br}= Effective Maximum Stress Intensity Factor
K_{cl}= Effective Minimum Stress Intensity Factor

The effective $K_{max}(K_{br})$ due to crack bridging was measured using a COD-Stress method. The COD difference of FRMLs and metal sheet in Fig. 11 ~ 12 represents the effective stress due to crack bridging. The experimental COD-Stress curves of HERALL and ARALL are steeper than that of 2024-T3 aluminum sheet. Thus, at a maximum CODs of HERALL and ARALL, the stress of 2024-T3 aluminum sheet is the effective maximum stress. As shown in Fig.11 ~ 12, the measured effective maximum stresses of HERALL and ARALL were 163.7MPa and 166MPa, while the applied maximum stress was 231.6MPa. The measured reductions of maximum stress due to crack bridging are 29.3% and 28.3% in HERALL and ARALL.

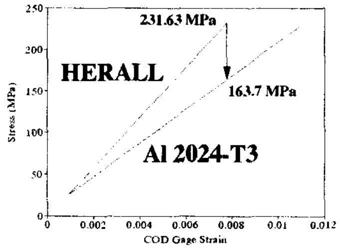

Fig. 11 Effective Maximum Stress in HERALL

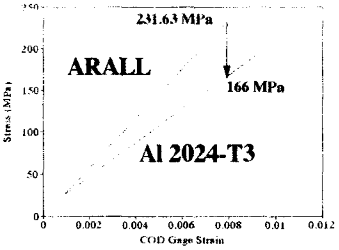

Fig. 12 Effective Maximum Stress in ARALL

In FRMLs and aluminum alloy, the principal source of crack closure arises from wedging of crack surfaces by fracture-surface asperities(roughness-induced closure), aided by that induced by cyclic plasticity in the wake of the crack tip. The effective $K_{min}(K_{cl})$ due to crack closure was measured using a COD gage mounted on the center of specimen and Paris' compensation method. The increase in the effective K_{min} of HERALL, ARALL and 2024-T3 aluminum alloy were about 11%.

As shown in Fig. 13～14, the effect of extrinsic mechanisms studied in the paper may be judged by using both crack bridging and crack closure corrections to compute ΔK_{eff} values from eq. [2].

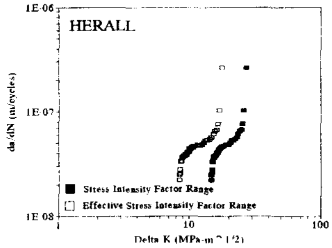

Fig. 13 Effective Stress Intensity Factor Range of HERALL

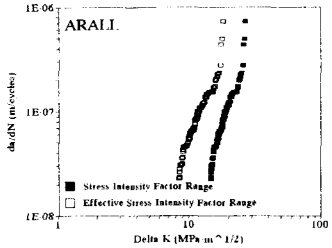

Fig. 14 Effective Stress Intensity Factor Range of ARALL

3.3 Crack Bridging Zone

As noted above, the crack bridging zone is where the COD sharply increase in machining FRMLs using a fine saw. The results of measuring COD gage signals in machining a 1㎜ wide slot are as shown in Fig. 15～16. The COD increased sharply as the last 4㎜ of wake were removed. This indicates that the fibers in this region were originally intact across the fatigue crack and were bridging cracks of 2024-T3 aluminum sheet.

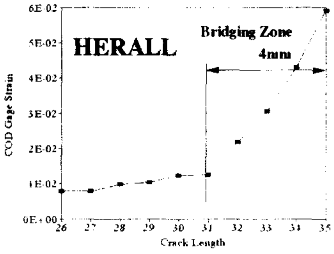

Fig. 15 Crack-Bridging Zone Length of HERALL

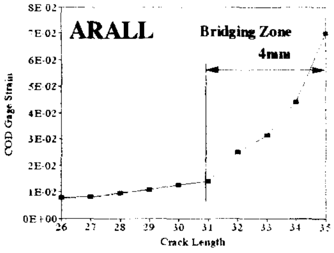

Fig. 16 Crack-Bridging Zone Length of ARALL

4. CONCLUSIONS

Based on an experimental study of fatigue crack propagation and extrinsic mechanisms in FRMLs and a 2024-T3 aluminum alloy, the following conclusions can be obtained.

1) The fatigue resistances of HERALL and ARALL were vastly superior to that of 2024-T3 aluminum alloy.
2) The reductions of effective maximum stress of HERALL and ARALL due to crack bridging

were about 29.3% and 28.3% of maximum stress.

3) The lengths of crack bridging zone of HERALL and ARALL was all about 4㎜.
4) The increase of minimum stress intensity factor in FRMLs were 11% of minimum stress intensity factor.

REFERENCES

1. Anderson T.L., Fracture Mechanic, Fundamentals and Applications, CRC Press, 1991.
2. Glyn Lawcock, Lin Ye and Yiu-Wing Mai, "Novel Fiber Reinforced Metal Laminates for Aerospace Applications - A Review, Part I - Background and General Mechanical Properties," SAMPE Journal, Vol. 31, No. 1, pp. 23-31, January/February 1995.
3. Marissen R. and Vogelessang L.B., "Development of a New Hybrid Materials; Aramid Reinforced Aluminum Laminate(ARALL)," SAMPE Conference, Cannes, 1981.
4. Marissen R., "Fatigue Crack Growth in Aramid Reinforced Aluminum Laminates (ARALL) Mechanisms and Predictions," DFVLR, Institut für Werkstoff-Forschung, DFVLR-FB-84-37, 1984.
5. Marissen R., "Flight Simulation Behavior of Aramid Reinforced Aluminum Laminates(ARALL)," Engineering Fracture Mechanics, Vol. 19, No. 2, pp. 261-277, 1984.
6. Marissen R., "Fatigue Crack Growth Predictions in Aramid Reinforced Aluminum Laminates (ARALL)," ICAS and AIAA, pp. 801-807, 1986.
7. Ritchie R.O., Weikang Yu and Bucci R. J., "Fatigue Crack Propagation in ARALL® Laminates; Measurement of the Effect of Crack-Tip Shielding from Crack Bridging," Engineering Fracture Mechanics, Vol. 32, No. 3, pp. 361-377, 1989.
8. Vogelessang L.B., "Development of a New Hybrid Material(ARALL) for Aircraft Structures," Seminar at University of Manchester, Institute of Science, 1982.
9. Marshall D.B., Cox B.N. and Evans A.G., "The Mechanics of Matrix Cracking in Brittle-Matrix Fiber Composites," Acta metal, Vol. 33, No. 11, pp. 2013-2021, 1985.
10. RAGHUVIR KUMAR, "Review on Crack Closure for Constant Amplitude Loading in Fatigue," Engineering Fracture Mechanics, Vol. 42, No. 2, pp. 389-400, 1992.
11. E.Elber, "The significance of fatigue crack closure in fatigue," ASTM STP 846, pp. 230-242, 1971.