Crack Propagation Behavior on Metal Laminate of FMLs After a High Tensile Overload Under High Constant Amplitude Load

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The crack propagation behaviour on the metal laminate of the FMLs is investigated under constant amplitude loads, which is higher compared to the fatigue strength of the metal laminate, and the subsequent crack propagation behaviours after being highly overloaded. The observation was carried out on the FMLs with the various surface roughness of the metal laminate at the interface between the metal and fibre-reinforced composite laminate. The overload leads to delay of the crack propagation following the overload, and the higher surface roughness increases the number of delay cycles. The overload together with the surface roughness affects stress condition in front of the crack tip and the crack tip condition as well as the compressive residual stress in front of the crack tip after the overload. In addition, the higher surface roughness strengthens the shear strength of the interface leading to the delamination caused by cyclic loads to be more difficult to take place. Therefore, the delay cycles after the overloading become longer.

Keywords : crack, propagation, delay, overload, laminate, roughness.

1. INTRODUCTION

Nowadays, kinds of composites have replaced gradually the role of conventional material, such as metals in lightweight structures. It cannot be inevitable that a structure has to be satisfied with the strength, durability, safety and low cost. In most cases, structures carry dynamic loads, and they are rare to be subjected to static loads. The approach using the strength of the material design assumes a material to be homogenous, continuum and isotropic. Because of that, the safety factor in this approach is merely determined by the comparison of the material strength to the applied load. The comparison value is at least greater than 1 in the case of structures loaded statically. However, in the case when dynamic loads are applied to structures, and to be safe, the magnitude of the dynamic loads should be less than one-third to half of the strength of materials [1, 2]. It is difficult to obtain a material, which is free from defects such as flaws or crack-like defects. Even, the stress raiser such as holes for joining and notches or notches-like are difficult to be avoided on members of structures, and the interaction among them may lead to the crack initiation, especially when those are loaded under dynamic loads [3, 4]. The strength of the material method will endanger the safety of structures because the method does not consider defects contained by a material in the structure. Instead of the strength of the material method, the fracture mechanic method is used

to design a structure in which the material contains the defects. This method can evaluate the safety of structures although the defects exist in the material or the defect is assumed to be present [2]. The existence of defects may also take place in composites [5-7].

A composite is defined as the combination of at least two kinds of materials in which one of them reinforces the other [6, 8]. The strength of composites depends on the material composing composites. The kinds of composites mostly used for structures is the fibre metal laminates (FMLs) composite. This composite combines a lightweight metal with a high strength fibre. The lightweight metal of aluminium is often selected to be combined with the carbon or glass fibres to make the composite [6, 8]. The tensile strength of the aluminium is much lower than those fibres. In this case, the fibres act as the reinforcement of the composites. The tensile strength of the composite will be somewhere between the tensile strength of the aluminium and the fibres. In spite of that, compared to the aluminium, the composite will have better properties such as higher tensile strength to weight ratio [6]. In a design process of a structure, a designer may consider only the strength of the composite without considering the strength of material constituent of the composite. The consideration will be no problem if that structure carries static loads only. However, when a structure is subjected to dynamic loads, that consideration will endanger the safety of a structure because in the dynamic case, the capability of the composite depends on the properties of the constituent material composing the composite [5, 7, 9-12]. In general, the magnitude of the dynamic loads allowed to be carried by a structure has to be lower than the static loads, and it may be less than half of the static strength of material [1]. A failure caused by dynamic loads may occur on the metal laminate of FMLs

[5]. The failure begins by the crack initiation on the metal laminate, and then the crack grows under the dynamic load before completely fracturing as reported in the previous investigations [5, 7, 9-12]. The crack initiation under dynamic loads taking places on the metal laminate of the FMLs is similar to what occurs on the monolithic metal. However, if the crack grows as the long crack, the crack growth rate of the metal laminate is lower than that on the monolithic metal because of the fibre-bridging effect taking place behind the crack tip [7, 9-12]. The fibre-bridging effect may reduce the crack growth rate on the metal laminate because the load over the crack region behind the crack tip is transferred to the laminate of the fibre reinforced composite. The transferred load leads to shear stress to develop at the interface between the metal and the fibre reinforced composite laminate [5]. Because the shear stress is also dynamic, it causes gradually delamination to take place at the interface originated at the region just behind the crack tip. If the delamination develops over the crack, behind the crack tip, the fibre-bridging effect will reduce too. As a result, the crack growth rate will increase [5, 7]. The development of that delamination is affected by the shear strength of the interface.

In design practice, it should be noticed that the strength of a composite alone is not enough as consideration if a composite carries the dynamic loads. The strength of every constituent of a composite should be known [2, 6]. However, it is possible that the design considerations base on only the strength of a composite, hence, the load carried by the every of a composite constituent may be too high if the dynamic loads are applied to a composite. Although the dynamic loads are lower than a composite strength, cracks may initiate on a certain site of composite constituents [5]. This phenomenon also occurs in the FMLs. In this case, the crack occurs on the metal laminate only because its strength is much lower than that of the fibres, and the fibre-reinforced composite laminate is still intact if the fibre is carbon or glass [5]. Besides kinds of laminate materials, the strength of the FMLs is also affected by the interfacial strength between the metal and the fibre-reinforced composite laminate. The interfacial strength depends on the adhesive and the surface roughness of the metal laminate at the interface [12-15].

In the present study, due to possibilities that the FMLs carries dynamic loads, which is considered to be high compared to the fatigue strength of the metal laminate, the crack growth behaviour on the metal laminate was investigated under cyclic loads with high amplitude. Because the interfacial strength between the metal and fibre-reinforced composite laminate influences the crack growth, the crack growth was also observed on the metal laminate with various interfacial surface roughness. Besides, the study carried out the observation of the transient crack growth behaviour under highly constant amplitude loads following a high single tensile overload.

2. METHOD OF STUDY

Figure 1 shows the setup of the vacuum assisted resin transfer moulding (VARTM) technique, which was used

to make the specimens of FMLs composites. This technique was carried out in the condition of laboratory room temperature. In the present works, Fig.2 shows the sequence of the laminates of the FMLs arranged as this manner in the specimen mould (e) of Fig.1. The woven carbon-fibre orientation was directed to $0^0/90^0$ to the load direction. The example of the woven carbon-fibre orientation is shown in Fig.3. The resin-epoxy was used as adhesive to make the FMLs composite. To make the specimens using the VARTM technique, the mixture of epoxy-hardener with ratio 2:1 was poured into the container (a), and then the mixture filled up the specimen mould after being sucked by the vacuum pump (h). Afterwards, if the mould had been filled up completely by the epoxy, the vacuum pump was turned off, and then it was left for 12 hours for curing as recommended by the epoxy manufacturer. The double-edge crack type of specimen for the fatigue test was selected, thus, the sharp notch with 3.0 mm in length and 0.2 mm in width was cut carefully by a saw at every edge of the specimen as shown in Fig 2. The length of 50 mm from both ends of the specimen was used for gripping on the testing machine. The specimen thickness obtained by using VARTM technique is 1.3 mm on average for one layer woven carbon fibre.
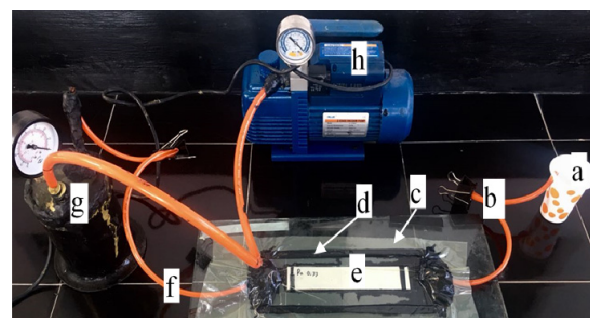
a. Container   e. Specimen mould
b. Inlet tube   f. Outlet tube
c. Film bag   g. Epoxy trap
d. Sealant   h. Vacuum pump

Figure 1. Vacuum assisted resin transfer molding (VARTM)
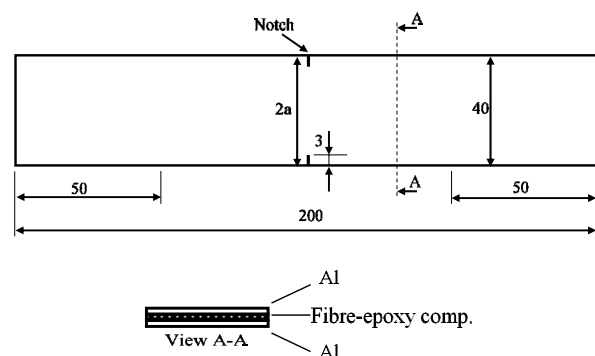

Figure 2. The shape and the dimension of the FMLs specimen (mm)

The commercial aluminium with the thickness of 0.35 mm was selected as the metal layer of the FMLs, and the yield and ultimate tensile strength of the aluminium were 70 and 78 MPa., respectively and the maximum elongation was 0.5 % after being heat-treated at 300^OC for an hour and cooled in the furnace. Before heat treated and shaped, as specimens shown schema-

tically in Fig. 2, to vary the level of the surface roughness of the monolithic aluminium, the sandblasting process was carried out on the surface of the 20 cm x 20 cm of the monolithic aluminium sheet. The size of the sand particle stated in the mesh number was 70. The process was carried out with the scanning speed of 20 mm/s and the pressure of 5.0 bar. The distance from the sandblasting nozzle to the aluminium surface was 1 m. The scanning was conducted once up to three times to obtain different surface roughness (*Ra*), respectively, and the levels of *Ra* obtained were 1.68, 1.78, and 1.93 μm, on average. The surface roughness test was carried with a surface roughness tester in the measuring range 0.005~16 μm. The average tensile strength of a single carbon-fibre taken from the woven carbon-fibre as shown in Fig. 3 is 1.27 GPa., and the maximum elongation is 2.75%.
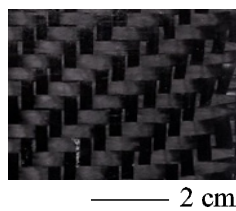

— 2 cm

Figure 3. An example of woven carbon fibre

By means subjecting the specimen of the FMLs to the fatigue loads on the servo-hydraulic fatigue machine with capacity 50 kN, the observation of crack propagation behaviours on the FMLs was carried out. As shown in the Fig.2, the crack length, 2*a*, was measured including the notches at both sides of the specimen. In the present investigation, the three specimens were tested in the fatigue test, respectively, for every FMLs with different interfacial surface roughness of the aluminium laminate, hence, the crack propagation behaviour presenting here is based on the average of them. Fig. 4 shows representatively the fatigue-load pattern when the stress ratio, *R*, is 0. The stress ratio is defined as the ratio of the minimum ($S_{min.}$) to maximum constant amplitude stress ($S_{max.}$). The single tensile overload ($S_{ovl.}$) was applied when the average of semi crack-length, *a*, had reached 8 mm. In the fatigue test, the specimens were subjected to the constant amplitude stress with a frequency of 6 Hz., the $S_{max.}$ and $S_{ovl.}$ was determined to be 60 MPa. and 120 MPa., respectively. In comparison to the yield strength, the constant amplitude load is considered to be high because the comparison of the constant amplitude load to the yield strength is higher than 0.5, which is a limitation allowed in a structure subjected to fatigue load [1, 2]. Even, the single tensile overload is beyond the ultimate strength of the monolithic aluminium. Hence, it is the reason in the present study that the fatigue load is called a high constant amplitude load and high single tensile over-load. To observe the crack propagation, the digital microscope with a maximum magnification of 200x was used. The microscope was travelled above the surface of the specimen on which the crack was expected to occur. To be observable, the surface of the metal laminate was polished by an emery paper to obtain a mirror-like surface.

Because the crack propagation behaviour following a single tensile overload depends on the stress condition in the zone just in front of the crack tip, the stress

condition in that zone was investigated. The investigation was conducted by computer simulation, and it was aided by ANSYS software. Hence, the simulation carried out was based on the software code. Fig. 5 shows the meshing model in the simulation. The detail of A in that model shows the zone in the vicinity of the crack tip. The white arrow points the zone in front of the crack tip, and the zone is meshed as that manner because the stress concentration takes places in that zone. Because the stress distribution in front of the crack tip of the metal laminates relates to the delamination taking place over the crack wake [7, 9-11], the shape of the delamination is modelled as semi ellipse as proposed by Yi H. *et. al.* [9] as pointed by the blue arrows. The simulation models the stress distribution when the semi-crack length, *a*, was propagated to be 8 mm in length in which the single tensile overload was applied. The evaluation of the stress distribution in front of the crack tip was carried out when the model was overloaded and at the zero loads after overloading because the stress condition developing after the overloading affects the following crack propagation behaviour [16-18].
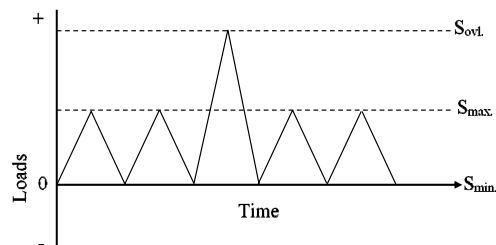

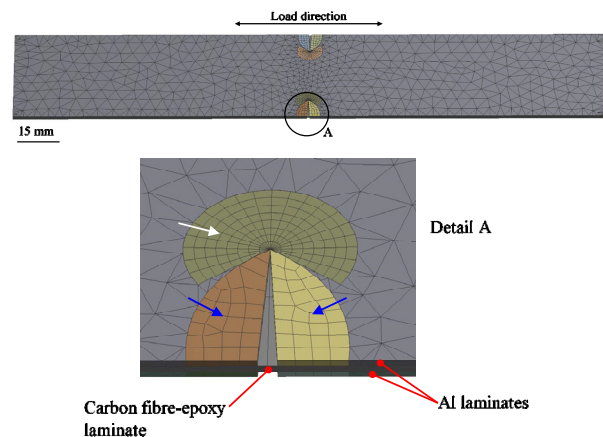**Figure 4. An example of representative of fatigue-load pattern**

Figure 5. Finite element mesh used in simulation

The crack propagation on the FMLs occurs only on the metal laminates and the fibre reinforced composite is still intact [5, 7, 9-11]. Because of that, the stress carried by the metal laminates over the crack region is transferred to the fibre reinforced composite laminate, and the transferred stress leads to the shear stress developed at the interface between the metal laminate and the fibre reinforced composite laminate. The shear stress takes place over the crack wake behind the crack tip [5]. The shear stress affects the crack opening level of the crack at the metal laminate [5, 7]. Compared to the crack taking place on the monolithic metal, the crack propagation rate is lower on the metal laminates of the

FMLs [7, 9, 12, 13]. It is caused by the bonding strength at the interface of the FMLs. The crack opening level indicates the stress distribution in front of the crack tip and the stress intensity factors [16-18]. The shear stress leads to the delamination of the interface over the crack wake behind the crack tip. The delamination may increase the stress concentration in front of the crack tip and the stress intensity factors [5, 9, 11], and these can be indicated by the crack opening level [5, 16, 17]. In the present study to detect the crack opening, the displacement of the notch mouth was measured by the extensometer with 50 mm gauge length, 5 mm measuring range and accuracy 1μm. The measurement was conducted by connecting the extensometer to the region over the notch by the links as depicted in Fig. 6.
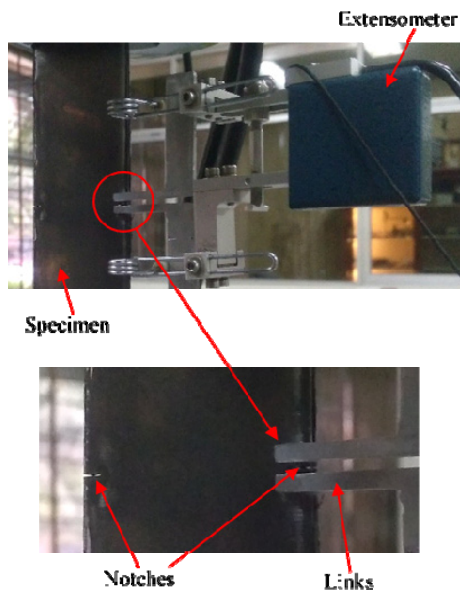

Figure 6. The extensometer arrangement on a fatigue test specimen

3. RESULTS

Figure 7 shows an example of the crack propagation on the metal laminate of FMLs after the crack had propagated from both notch roots, and it met in the mid of the specimen. The example is on the specimen when the interfacial surface roughness is 1.68 μm. The specimen does not separate because the carbon fibre-epoxy composite laminate is still intact. This phenomenon is similar to previous works [5, 7, 9-11, 13, 15]. Fig. 8 shows the crack propagation behaviour plotted in the semi-crack length, a, vs. the number of cycles, N. The surface roughness of 0.33 μm represents the FMLs on which the surface of aluminium at the interface was not sand-blasted. The figure shows that for baseline cases, the fatigue life on the rougher surface is longer. The overload retards the crack propagation, and the retardation is more profound on the specimen with the higher surface roughness.

The crack propagation rate, da/dN vs. semi-crack length, a, is shown in Fig.9. After the overload, the crack propagation rate decelerates to minimum rates and then converges gradually to the rate as before the overload. The increasing of the interfacial surface roughness, R_a, leads to the minimum rate to be lower. The deceleration

after the overload relates to the affected overload zone just in front of the crack tip. After the overloading, the cyclic loads was resumed to the constant load. The crack would propagate in that zone. The deceleration is caused by the retardation of the crack propagation when the crack traverses to that zone. Therefore, it causes fatigue life to be longer than the baseline. The relation of the affected overload zone and the retardation will be discussed in detail in the next section.
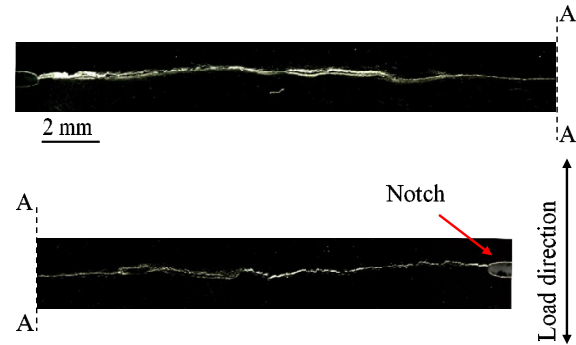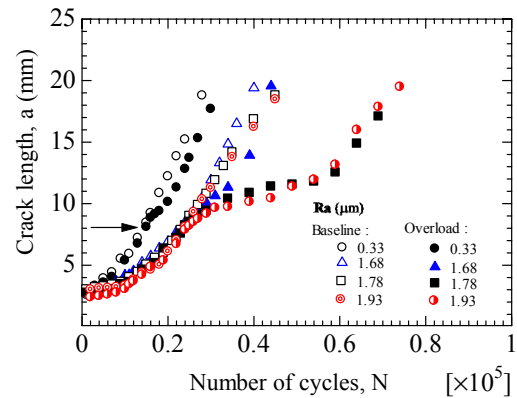

Figure 7. An example of crack propagation on FMLs.

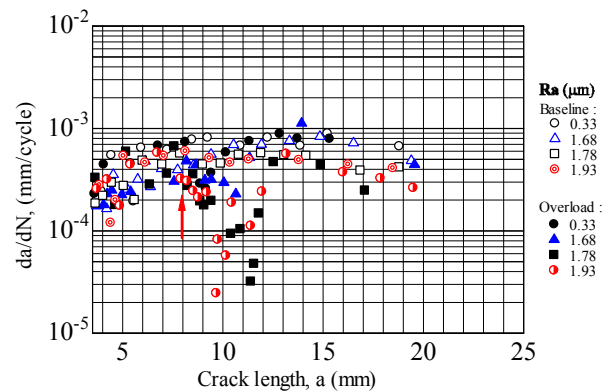Figure 8. The crack propagation behaviour, a vs. N

Figure 9. Crack propagation rate a vs. da/dN

The number of cycles required by the crack tip to traverse the affected overload zone is called the number of delay cycles, N_d, and it is defined as shown in Fig. 10 [17, 18]. In the present study, Fig. 11 shows the number of delay cycles observed on the surface of the aluminium laminate of the FMLs composite. The effect of the surface roughness to the number of delay cycles is profound when the surface roughness increases up to 1.78 μm, and after that the effect is not profound. This relates to the stress distribution in front of the crack tip and the stress condition at the interface.
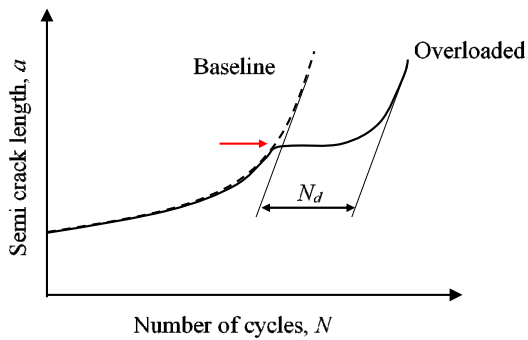
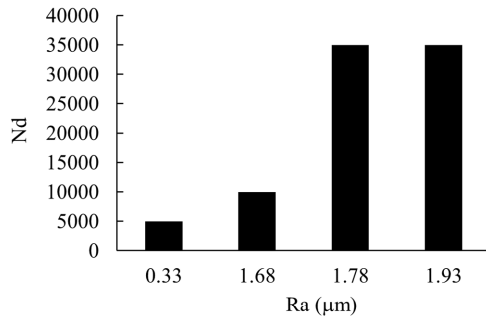**Figure 10. The definition of the number of delay cycles**

Figure 11. The number of delay cycles, N_d vs. surface roughness, R_a.

4. DISCUSSION

The delay cycles associated with the overload in the present study similar to those found in the previous reports [5, 7, 16-19]. The crack propagation following the overload relates to the residual stress state just in front of the crack tip. If the compressive residual stress state develops just in front of the crack tip, the stress state delays the crack propagation [16, 19]. In contrast to that, if the tensile residual stress develops, the crack propagation accelerates. In this case, the fatigue life is shorter than the baseline, and it will endanger structure integrity [19]. As in this study the crack growth was observed only on the aluminium laminate, the stress state in the crack tip on the laminate after the over-loading was investigated. Fig. 12 is an example of stress contour on the specimen with surface roughness 0.33 µm when it is overloaded (S_{ovl}). It can be seen from the figure that the stress distribution is not the same for every laminate. The carbon fibre-epoxy composite laminate carries stress to be higher than the aluminium laminate as indicated by the stress contour in red colour. The blue colour region at the aluminium laminate, which is behind the crack tip and over the crack wake indicate that the stress is in the compressive state. This means that the stress state on the aluminium laminates on which the delamination occurred at the interface is in the compressive state when it is loaded at overload point. The colour shifts gradually from the blue to the green one at which delamination does not occur, and the green colour indicates the stress state to be in the tensile state. The stress concentration takes place in the small region just in front of the crack tip as indicated by the yellow colour region on the aluminium laminates. Fig. 13(a) and 13(b) summarize the stress magnitude and the stress state in the region just in front of the crack tip when it was loaded at the overload point, and after

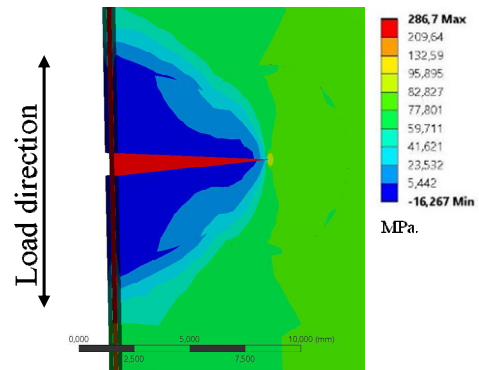being unloaded from the overload point to zero loads, respectively.

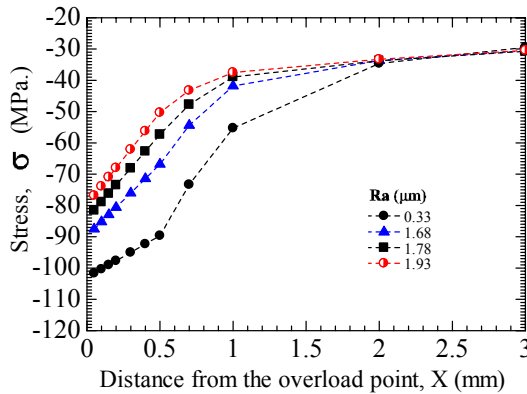**Figure 12. An example of stress contour at the point of the overload (S_{ovl}) and R_a = 0.33 µm.**

Figure 13(a) shows the magnitude of the stress distribution in front of the crack tip on the aluminium laminate with various interfacial surface roughness at the point of overload, respectively. Since the crack tip causes the stress concentration, the magnitude of the stress is higher than elsewhere just in front of the crack tip before decreasing gradually as the distance from the crack tip, X, increases. The stress magnitude on the FMLs with R_a of 0.33µm is the highest, and the stress magnitude decreases as the value of the R_a increases. Upon unloading from the overload point to zero loads the state of the stress distribution changes from the tensile to the compressive, as shown in Fig. 13(b). In this case, although the load is zero, the stress still exists with the compressive state, thus, it indicates that the residual compressive stress develops in the region affected by the overload just in front of the crack tip. The negative sign in Fig. 13(b) indicates that the stress state is compressive. The FMLs with R_a of 0.33µm has the lowest value of the stress just in front of the crack tip, and the value becomes higher at the higher value of R_a. The crack propagation behaviour after overloading depends on the residual stress state developing in the affected overload zone [16-19]. The crack propagation is delayed if the residual compressive stress develops in that zone as shown in Fig. 13(b). It leads to the deceleration of the crack propagation rate, and the fatigue life is longer than the baseline [19]. The lower residual compressive stress should cause the fatigue life to become longer [9]. However, in the present study, in the case of R_a of 0.33µm, which has the lowest residual compressive stress, its fatigue life is the shortest compared to the other cases. This is possible because the crack tip condition upon the overload also affects the crack propagation behaviour when the cyclic loads are resumed to the constant amplitude loads [18-20].

Figure 14 shows qualitatively examples of the crack tip advancement, Δa, at the point of the overload. The figure indicates that the advancement depends on the surface roughness of the aluminium at the interface. The green dashed-line and red indicate the crack tip position before and after at the point of the overload, respectively. When the value of R_a is 0.33 µm, the over-load advances the crack tip to be furthest than other cases. It is caused by the stress concentrating just in front of the crack tip being highest compared to other

cases. Because of that, it may affect the residual stress in front of the crack tip. Hence, it causes the number of delay cycles to be the lowest. The increasing value of R_a leads to advancement, Δa, to become shorter. The shorter of Δa is plausible that it does not affect profoundly the residual stress developing in front of the crack tip. Therefore, the shorter advancement of the crack tip leads to the increase of the number of delay cycles, N_d.
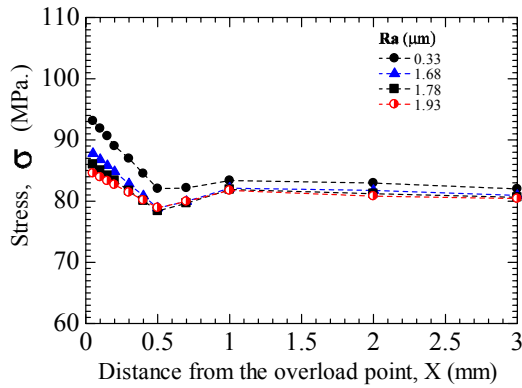

(a) At the point of overload


(b) At zero load after overloading

Figure 13. An example of stress contour at the point of the overload ($S_{ovl.}$) and R_a = 0.33 μm

It is well known that in the case of monolithic metal, the crack propagation behaviour is associated with the crack opening displacement [18]. The crack opening displacement may also indicate the residual stress state in front of the crack tip. The crack propagation behaviour in the metal laminates of the FMLs is similar to that in the monolithic cases, however, in the metal laminates of the FMLs, the crack propagation is affected by the bridging stress [5, 7]. The bridging stress is transferred to the interface between metal and fibre-epoxy composite laminate as the shear stress over the crack surface behind the crack tip. The shear stress leads to the delamination on the region over the crack surface. If the delamination occurs, the crack propagation is accelerated. Therefore, the shear strength of the interface can determine whether or not the delamination takes place easily. In the present study to indicate that the surface roughness affects the shear strength of the interface, the displacement of the notch mouth, Δ, was detected instead of crack tip opening displacement for convenien for convenien. Fig. 15 shows various displacements of the crack mouth when the crack was growing. The red

arrow indicates when the overload was applied, and the black arrows point the displacement for every surface roughness of the aluminium laminate. Before the overload, the displacement is almost the same for all cases. However, in the case of R_a is 0.33 μm, the displacement is slightly higher than the other. At the overload point, the displacement of R_a of 0.33 μm is the highest. The displacement is lower as the surface roughness is higher. After being overloaded, the displacement returned almost to the same level as before being overloaded but this is an exception in the case of R_a is 0.33 and 1.68 μm at which the displacement increases as the crack grew. This displacement is plausible to indicate that delamination may be vulnerable to take place on the surface roughness of 0.33 and 1.68 μm. Therefore, the crack growth rate is higher in both cases, and their fatigue life is shorter than those of 1.78 and 1.93 μm.
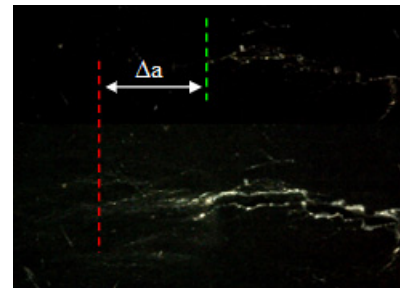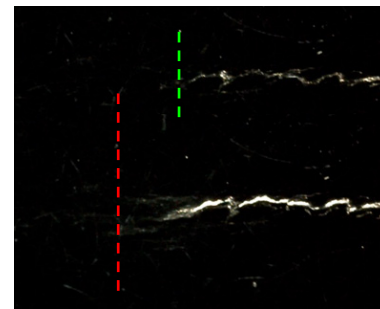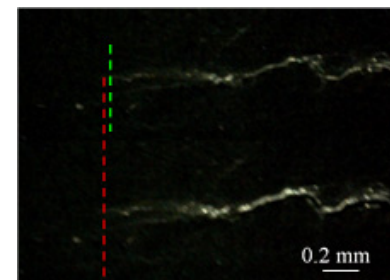

(a) R_a = 0.33 μm
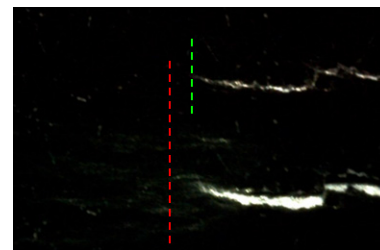
(b) R_a = 1.68 μm

(c) R_a = 1.78 μm

(d) R_a = 1.93 μm

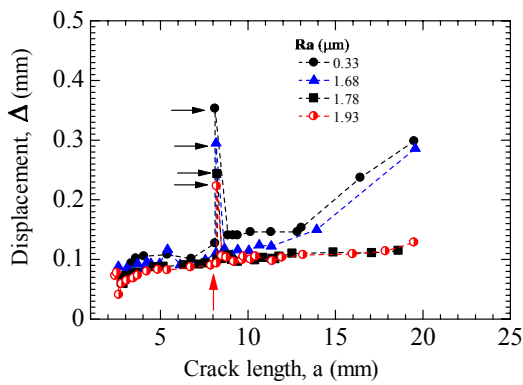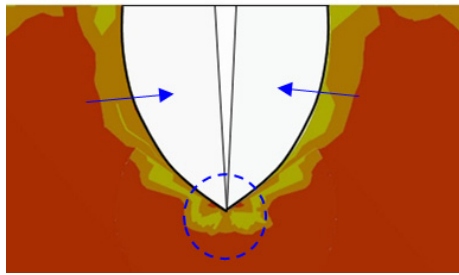**Figure 14. Crack tips advancement, Δa, during overloading when R_a is 0.33, 1.68, 1.78 and 1.93 μm**

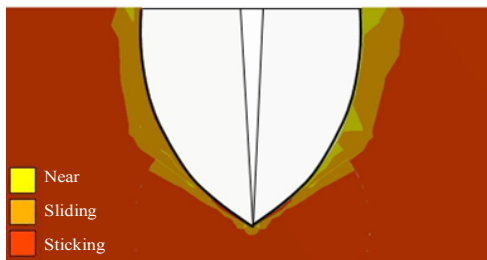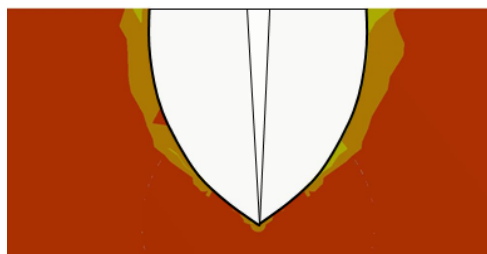**Figure 15. Notch mouth displacement, Δ, for various crack length**

(a) R_a = 0.33 μm
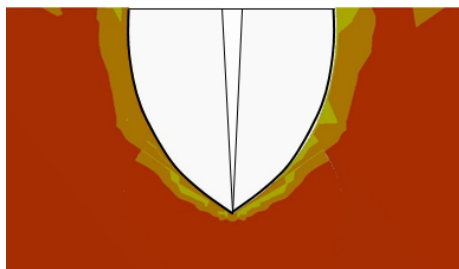
(b) R_a = 1.68 μm

(c) R_a = 1.78 μm

(d) R_a = 1.93 μm

Figure 16. The example of contours indicating bonding conditions in the region near by the crack tip when R_a is 0.33, 1.68, 1.78 and 1.93 μm

To confirm that the surface roughness affects the interface between the aluminium and the fibre-epoxy laminate, Fig. 16 shows examples indicating bonding

conditions in the region near the crack tip. The blue arrows indicate the region at which the delamination takes place, and the dashed line circle is the region affected by the overload. The bonding conditions are divided into three categories, those are near sliding, sliding and sticking. For the region encircled by the dashed line circle, the region is dominated by the near sliding and sliding condition. The region becomes smaller as the surface roughness becomes higher. These conditions indicate that the delamination in the case of surface roughness 1.78 and 1.93 μm is more difficult than that of 0.33 and 1.68 μm cases. As a result, previous cases have the fatigue life longer than the former cases.

5. CONCLUSION

The present study concludes the following;

1. The overload delays the crack propagation observed on the metal laminate, and the number of delay cycles increases on the higher surface roughness.

2. The increasing of the number of delays cycles is associated with the stress concentration and the compressive residual stress developing in the overload affected region in front of the crack tip.

3. The lower compressive residual stress develops on the metal laminate with the lower surface roughness if the crack tip is assumed to not advance upon overloading. However, upon overloading the crack tip advances, and it causes the transient acceleration of the crack. The acceleration is lower for the higher surface roughness.

4. The notch mouth displacement indicates that the higher surface roughness causes the interfacial shear strength between the metal laminate and the carbon fibre-epoxy composite to be higher. Hence, it leads to the delamination caused by cyclic loads to be more difficult to take place. Therefore, the delay cycles after the overload become longer.

REFERENCES

[1] Stephens, R.I.: *Metal fatigue in engineering*, John Wiley & Sons, New York, 2001.

[2] Barsom, J.M.: *Stress analysis for members with crack*, ASTM, Philadelphia, 1999.

[3] Kastratovic, G., Vidanovic, N., Grbovic, A. and Rasuo, B.: Approximate determination of stress intensity factor for multiple surface cracks, FME Transactions, Vol. 46, No. 1, pp. 39-45, 2018.

[4] Petrasinovic, N., Petrasinovic, D., Rasuo, B. and Milkovic, D.: Aircraft Duraluminium Wing Spar Fatigue Testing, FME Transactions, Vol. 45, No.4, pp. 531-536, 2017.

[5] René, A.: *Fatigue crack propagation and delamination growth in glare*, DUP Science, Delft, 2005.

[6] Robert, M.J.: *Introduction to composite materials-mechanics of composites materials*, Taylor & Francis, Philadelphia, 1999.

[7] Khan, S.U., Alderliesten, R.C. and Benedictus, R.: Delamination in fiber metal laminates (glare) during fatigue crack growth under variable

amplitude loading, International Journal of Fatigue, Vol. 33, No. 9, pp. 1292–1303, 2011.

[8] William, D. C. J.: *Introduction in fundamentals of materials science and engineering, an integrated approach*, John Wiley & Sons, New Jersey, 2008.

[9] Yi, H., Jianzhong, L., Xiao, H., Jiazhen, Z., and Guangquan, Y.: Delamination and fatigue crack growth behavior in fiber metal laminates (glare) under single overloads, International Journal of Fatigue, Vol. 78, No. 1, pp. 53-60, 2015.

[10] Konrad, D. and Jaroslaw, B.: Residual fatigue life of carbon fibre aluminium laminates, International Journal of Fatigue, Vol. 100, No. 1, pp. 94-104, 2001.

[11] Jianyu, Z., Lei, P., Libin, Z. and Binjun, F.: Fatigue delamination growth rates and thresholds of composite laminates under mixed mode loading, International Journal of Fatigue, Vol. 40, No. 1, pp. 7-15, 2012.

[12] Yingcai, P., Guoqing, W., Zheng, H., Maoyuan, L., Sudong, J. and Zongke, Z.: E ect of surface roughness on interlaminar peel and shear strength of CFRP/Mg laminates, International Journal of Adhesion and Adhesives, Vol. 79, pp. 1-7, 2017.

[13] Jones, A.J.K., Hu, W. and Barbara, S.: Cyclic-fatigue crack growth in composite and adhesively-bonded structures: the FAA slow crack growth approach to certification and the problem of similitude, International Journal of Fatigue, Vol. 88, pp. 10–18, 2016.

[14] Nojavan, S., Schesser, D. and Yang, QD.: A two-dimensional in situ fatigue cohesive zone model for crack propagation in composites under cyclic loading, International Journal of Fatigue, Vol. 82, No. 3, pp. 449–461, 2016.

[15] Anindito, P., Sofyan, S. A. and Hilmi, F. I.: Effect surface roughness on fatigue crack propagation behaviour of fibre Metal Laminates (FMLs), International Journal of Automotive and Mechanical Engineering, Vol. 16, No. 2, pp. 6588-6604, 2019.

[16] Anindito, P., Rudi, S., Choiron, M.A.: The effect of hold time of overload on crack propagation behavior emerging from notch root, FME Transactions, Vol. 44, No. 1, pp. 50–57, 2016.

[17] Anindito, P., Makabe, C., Miyazaki, T. McEvily, A.J.: Transition behavior of residual fatigue life after applying overload during fatigue crack growth with constant stress amplitude, Pressure vessel and piping codes and standards ASME/JSME-PVP, Vol. 480, pp. 39-44, 2004.

[18] Sadananda, K., Vasudevan, A.K., Holtz, R.L. and Lee, E.U.: Analysis of overload effects and related phenomena, International Journal of Fatigue, Vol. 21, No. 1S, pp. S233–S246, 1999.

[19] Makabe, C., Purnowidodo, A., Miyazaki, T. and McEvily, A.J.: Deceleration and acceleration of crack propagation after an overloading under negative baseline tress ratio, Journal Testing and Evaluation, Volume 33, No. 5, Pages 181–187, 2005.

[20] Makabe, C., Purnowidodo, A. and McEvily, A.J.: Effects of surface deformation and crack closure on fatigue crack propagation after overloading and under loading, International Journal of Fatigue, Vol. 26, No. 12, pp. 1341–1348, 2004.

ПОНАШАЊЕ ШИРЕЊА ПРСКОТИНЕ НА ФМ-ЛАМИНАТУ ПОСЛЕ ПРЕОПТЕРЕЋЕЊА ЗАТЕЗАЊЕМ ПОД КОНСТАНТНИМ АМПЛИТУДНИМ ОПТЕРЕЋЕЊЕМ

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Истражује се понашање ширења прскотине на влакнастом металном ламинату (ФМЛ) под константним амплитудним оптерећењем које је веће од заморне ћврстоће код металног ламината, као и потоње ширење прскотине под великим преоптерећењем. Испитивана је храпавост површине металног ламината на споју метала и влакнима ојачаног композита. Преоптерећење доводи до кашњења ширења прслине после оптерећења, док већа храпавост површине повећава број циклуса кашњења.

Преоптерећење и храпавост површине утичу на стање напона испред врха прскотине и стање врха прскотине као и на притисни заостали напон после дејства преоптерећења.

Већа храпавост површине ствара већи напон смицања на споју што доводи до ређе појаве деламинације услед цикличних оптерећења. Због тога се кашњење циклуса продужава после дејства преоптерећења.