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Mekanika: Majalah Ilmiah Mekanika

Surface Roughness and Fiber Angular Orientation Analysis Toward Laminated Composite Crack Propagation

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Abstract

In this study, fatigue testing of fiber metal composites was carried out to determine the rate of crack propagation so that the age of the fiber metal composite specimen was known. The independent variable in this research is the angular orientation of the carbon fiber and the surface roughness of the aluminium with the dependent variable response is the bridge crack rate. The manufacture of fiber metal laminates specimens uses the Vacuum Assist Resin Infusion (VARI) method, which uses a vacuum pump as a means to flow the resin from the reservoir to the mold. Fatigue testing is performed using the stress amplitude method. That is, the value of the load when the tensile test is one third of the tensile strength. After the fatigue test was carried out, the results were obtained on specimens with an angular orientation of 0/90° fibers, the crack propagation rate slowed down with a cycle value of 90,000 in specimens with a surface roughness value of 2.128 µm then decreased cycles on specimens with a value of 2.887 µm, namely 11,000 cycles.

1 Introduction

In developments in the field of technical materials, most metals are processed into household utensils, tableware and drinking utensils, ornaments and weapons of war such as swords, armors and shields at the beginning of the discovery of metal by mankind, which was around 6,000 Before Century **(**BC**)** [1]. However, with the development of science and technology, metals are then processed for industry. The automotive industry is one of the industrial fields that uses a lot of metal as raw material for its production. Such as in the manufacture of car frames, motorcycle frames, car bodies, auto and motorbike parts and components of motor vehicle engines. Besides being widely used in the automotive industry, metal is also widely used as a building construction material. Military defence is also an industry that uses metal as raw material for production, such as making tanks, cannons, rifles, and others. The use of metals for engineering and industrial processes is indeed quite attractive as a raw material. Almost all industries use metal as raw material, but metal also has several drawbacks to be used as a material in engineering and industrial processes. The disadvantages of metal are that they are corrosive. To overcome the shortage of corrosive metals, composite has recently become a material that is widely used as raw material for production.

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Composites that have corrosion resistant properties and are generally lighter than metal are starting to be widely used as materials in industrial and engineering processes**.** Composites are materials that are composed of a mixture of two or more materials that have different chemical and physical properties which will produce new materials that have different properties from the constituent materials [2]. The constituent material of the composite consists of four components, namely the matrix, the reinforcing material, the filler material and the additive material shown in Figure 1.

Figure 1. The composite illustration

Carbon Fiber (CF) or carbon graphite is a material which consists of very thin fibers about 0.005-0.010 mm and consists mostly of carbon atoms. The carbon atoms are bonded together with microscopic crystals that are parallel to the long axis of the fiber. This is what makes carbon fiber a very strong fiber for a fiber of its size. Several thousand carbon fibers are spun together to form a single thread, which can be used on its own or woven into cloth. [3] Carbon fiber has many different spun patterns and can be combined with plastic resin and molded to form composite materials such as Carbon Fiber Reinforced Plastic (CFRP) to make materials that have a high strength-to-weight ratio. The density of carbon fiber is also lower than that of steel, making it ideal for applications requiring lightweight materials. From this description, it shows that carbon fiber has the potential as a reinforcement or core in composites.

Fatigue or fatigue according to is defined as the process of permanent, progressive localized structural change in conditions that produce fluctuations in strain and stress below its tensile strength and at one point or many points that can peak into a crack or fracture as a whole after certain fluctuation [4]. There are three phases in the fatigue fracture, specifically;

1. Crack initiation. The fatigue mechanism generally starts from the crack initiation that occurs at weak material surfaces or areas where concentration occurs surface tension (such as scratches, notches, hole-pits etc.) due to presence repeated loading.
2. Crack propagation. This crack initiation develops into microcracks. Propagation or the combination of these microcracks then forms the macrocracks that will be leading to failure.
3. Fracture. Fracture occurs when the material has undergone a stress cycle and strain that produces permanent damage.

To find out the process of the three phases above, it is necessary to do a fatigue test. Fatigue testing can be used to see the resistance of a material to dynamic or repetitive loading where the load is below its yield strength. The fatigue strength is influenced by many variables, including: specimen size, specimen shape, final work, type of load/stress. By using a variable load or voltage, it produces different cycles, so that an S-N graph can be made (see Figure 2).

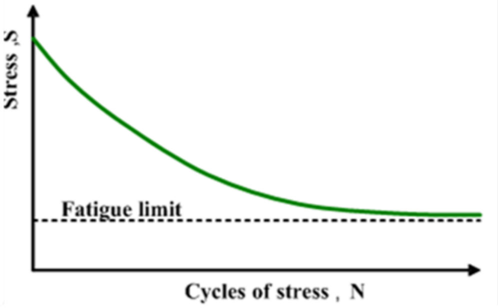


Figure 2. The S-N curve

Fatigue testing is generally carried out by applying a uniaxial stress or dynamic load. The given dynamic level varies, it can be pull-pull, pull-compress and compress-compress. Figure 3 shows a repeated tensile stress cycle with maximum stress (S_{max}) and minimum stress (S_{min}). To produce the composites in this research uses the Vacuum Assist Resin Infusion (VARI) method. VARI is a method of making composite materials that uses low pressure applications to regulate the passage of resin into lamina. The material that becomes the matrix is placed in a mold, then a vacuum process is carried out to pull the resin flow into the mold.

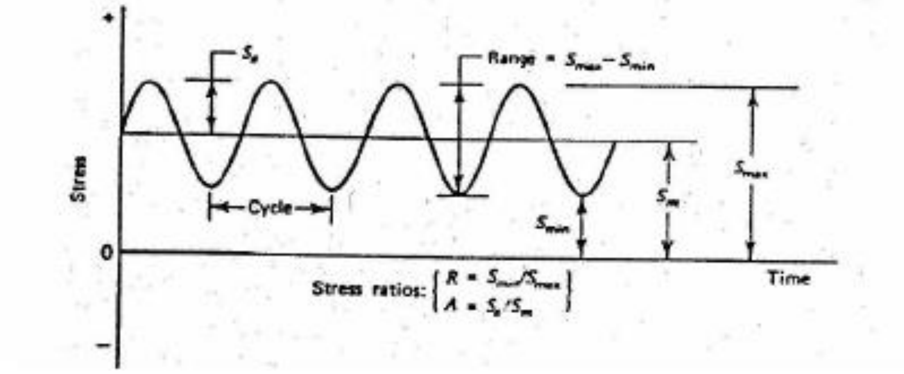


Figure 3. Load cycle with constant amplitude

The VARI method produces composite materials that have a high fiber-resin ratio compared to the hand lay-up method. The hand lay-up method uses the manual method to flow the resin, whereas in the VARI method the resin flow is carried out by a constant vacuum pressure. The use of this constant vacuum pressure which regulates the distribution of resin to remain in a certain amount. This results in a high fiber-resin ratio resulting in a strong and lightweight composite material. Some of the basic steps in the VARI process are as follows:

1. The fiber which functions as a filler is placed in a mold covered with a vacuum bag
2. Liquid resin functions as a matrix poured in a container connected to the mold and vacuum machine
3. The air pressure inside the mold is lowered by the vacuum machine
4. The resin is dispensed under low pressure
5. The curing process is carried out after the resin forms the lamina

The VARI method is classified into two types, namely the Surface Infusion method and the Interlaminar Infusion method [5] (shown in Figure 4). In the surface infusion method, the resin is passed over the surface of the lamina, with the greatest disadvantage being the cost due to the preparation of machine operation, and the increasing complexity if this method is applied on a large scale. Whereas in the interlaminar infusion method, the resin is flowed through the space between the lamina. The Interlaminar Infusion method has many advantages when applied on a large scale. The resin flows between the laminae so that the thickness of the resin is maintained in the space between the laminae. In addition, the resin flow process is faster because it passes through a space that has been maintained in thickness. This more sustainable process also causes less waste material to be wasted.

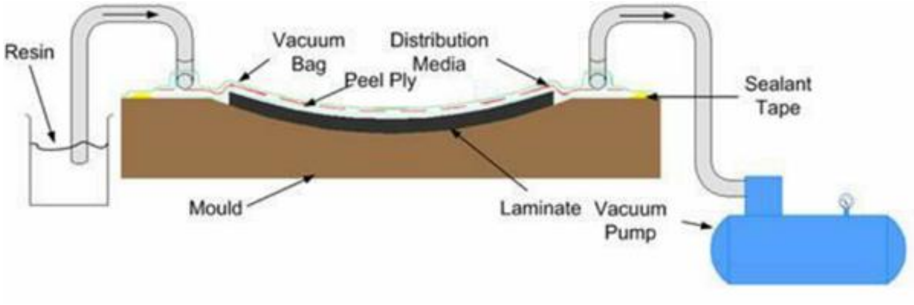


Figure 4. The VARI method

2 Experimental Methods

2.1 Materials

2.1.1 Carbon fiber

The fiber used in this research is carbon fiber with twill woven type with the following specifications:

Used yard : TR 30S-3L
Product number : C520-3K
Weave : 2/2 Twill
Arbon thickness : 0.25±0.02 mm
Carbon fabric weight : 204±2
Width : 1,500 mm

2.1.2 Resin epoxy and hardener

For the matrix in this research using epoxy resin 174/Eposchon-A and Versamide 140/Eposchon-B (hardener).

2.1.3 Aluminium

For the outer structure of this material using aluminium. With a thickness of 0.5 mm and the type of aluminium is Al 1100.

2.2 Method

2.2.1 Independent variable

The independent variable in this study is the angular orientation of the carbon fiber with the magnitude of the fiber angle, i.e.,

1. 0/90°
2. 45/45°

Then the second independent variable is surface roughness (R_a) with the magnitude of the surface roughness. Surface roughness on aluminium plate is obtained by using the sandblasting method, i.e.,

1. 1.675 µm
2. 1.783 µm
3. 1.936 µm
4. 2.128 µm
5. 2.887 µm

2.2.2 Dependent variable

The dependent variable in this study is crack propagation on Fiber Metal Laminates (FML) composite.

2.2.3 The manufacturing process of the composite specimen

The steps for making the test specimen are following the American Society Testing and Material (ASTM) D638-03 tensile test specimen and the ASTM D3479 fatigue test using laminate composites with the vacuum method, show in below.

1. Prepare materials (an aluminium plate that has been given surface roughness, carbon fiber that has been cut, epoxy, hardener, and composite making equipment using the vacuum method).
2. Lubricate the base/mold with grease to prevent the specimens from sticking when unloading.

3. Construct a composite FML structure with aluminium as the outer layer and as the core is a carbon fiber composite with a variety of fiber angles.
4. Prepare flow media and mesh with predetermined dimensions.
5. Arrange the FML structure on the base and wrap it with a vacuum bag.
6. Turn on the vacuum pump as a trial to make sure there are no leaks in the vacuum bag, if a leak occurs then the pressure on the pressure gauge will drop.
7. Prepare epoxy resin and hardener with a ratio of 2:1.
8. If there are no leaks, then start the process of suction the resin dough into the vacuum bag that has been prepared previously.
9. Drying the composite at a temperature that has been isolated in a vacuum bag.
10. After drying, the specimen can be unloaded.

Figure 5. The manufacturing process of the composite using the VARI method

2.2.4 The tensile test specimen

Tensile specimens according to ASTM D638 were made using the VARI process with the following dimensions is presented in Figure 6 [8].

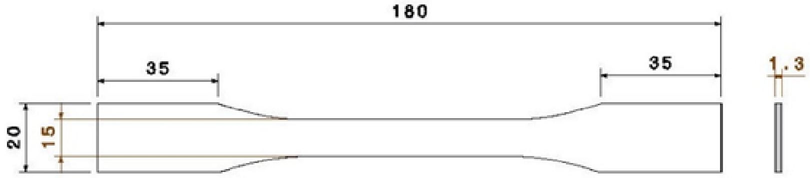


Figure 6. Dimensions of fiber metal laminates tensile test in millimeters (mm)

2.2.5 The fatigue test specimen

Tensile specimens according to ASTM D3479 were made using the VARI process with the following dimensions is presented in Figure 7 [9].

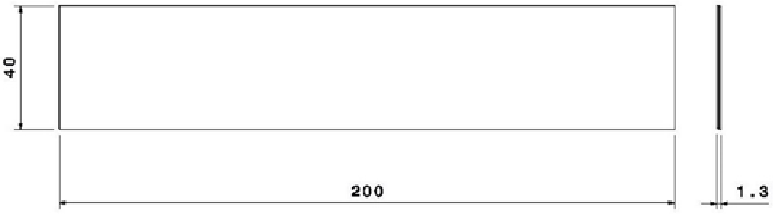


Figure 7. Dimensions of fiber metal laminates fatigue test in millimeters (mm)

2.2.6 The crack propagation measure

The crack propagation measure steps are shown as follows:

1. Apply load the FML specimen using a fatigue testing machine with a specified cycle.
2. After the cycle is reached in the first step, measure the cracks that occur using the DinoCapture software.
3. Perform the same steps for each subsequent cycle.

3 Results and Discussion

3.1 Fatigue test of fiber metal laminates

The fatigue test in this study was carried out to observe the crack propagation rate of metal laminates fiber specimens for each variation of surface roughness and angular orientation of the fibers. By carrying out this fatigue test, the number of cycles data of the metal laminates specimen for each surface roughness variation and fiber angular orientation variation is shown in Table 1. The results of fatigue testing of fiber metal laminates specimens with an angular orientation of 45/45° fibers are shown in Table 2.

Table 1. Cycle data from the fatigue test of specimens with an angular orientation of 0/90°

Surface roughness (R_a) (μm)	Displacement ratio (R)	Cycle
0.33	0	25,000
1.68	0	40,000
1.78	0	740,000
1.93	0	90,000
2.128	0	90,000
2.887	0	11,000

Table 2. Cycle data from the fatigue test of specimens with an angular orientation of 45/45°

Surface roughness (R_a) (μm)	Displacement ratio (R)	Cycle
0.33	0	440,000
1.68	0	40,000
1.78	0	25,000
1.93	0	4,000
2.128	0	7,000
2.887	0	60,000

In addition to knowing the data on the number of cycles of each fiber metal laminates specimen, this test also aims to determine the crack propagation of the specimen for each variation of surface roughness and fiber angular orientation. To find out the rate of crack propagation of fiber metal laminates specimens, it can be seen in the following sample data (see in Table 3):

Table 3. Sample data of cycling number and crack length after fatigue test

Number of cycles	Crack length (mm)		Average crack length (mm)
	Left	Right	
5000	1.247	1.507	4.377
10000	2.207	2.444	5.3255

In the fatigue test, the point is to determine the rate of crack propagation of the specimen with a small but repetitive load, or material is subjected to cyclic loading. Then the two sides of the notch are measured and the average crack length is calculated. To find the average crack length (*a*) for each cycle when testing is carried out, it can be calculated using Equation 1.

$$a = \frac{\Sigma\, notch\ length + \Sigma\, crack\ length}{2} \tag{1}$$

Then, to find out the crack propagation rate (*da*/*dN*) for each cycle when testing can be calculated using Equation 2. (sample calculation is taken on cycle 10,000)

$$\frac{da}{dN} = \frac{a_n - a_{n-1}}{N_n - N_n - 1} \tag{2}$$

Therefore, for the crack propagation rate (*da*/*dN*) in the 10,000th cycle of fiber metal laminates specimens under fatigue test is 0.0001897 mm/cycle. Likewise, several other cycles can be calculated using the same method to determine the rate of crack propagation.

3.2 Effect of surface roughness and fiber angle orientation 0/90°

The discussion in this study is focused on the effect of aluminium surface roughness and carbon fiber angular orientation on the rate of crack propagation in fiber metal laminates specimens. To determine the effect of surface roughness and fiber angle orientation of 0/90° on the rate of crack propagation, it can be seen in the following figure:

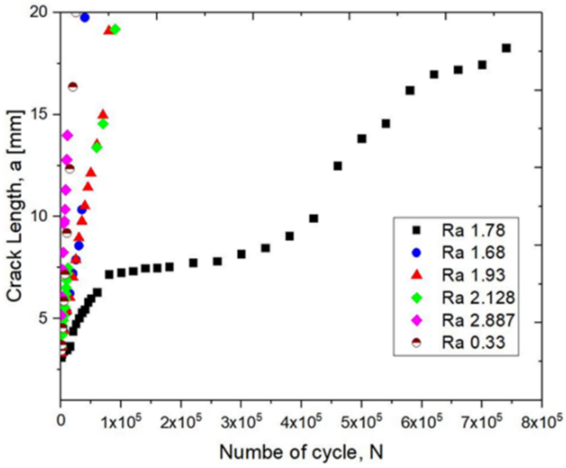


Figure 8. Relationship of the number of cycles to the crack length of the fiber metal laminates specimen for each variation of surface roughness (R_a) and fiber angle orientation 0/90°

The graph in Figure 8 explains the relationship between the number of cycles to the crack length of the metal laminates specimen for each surface roughness variation (*Ra*) with the fiber angular orientation 0/90°. In the graph, it can be observed that specimens with a value of *Ra* 0.33 µm are fractured in the 25,000 cycles, specimens with a value of *Ra* 1.68 µm are fractured in the 40,000 cycles then specimens with a value of *Ra* 1.93 µm, *Ra* 2.128 µm, and *Ra* 2.887 µm have decreased age of the specimen. characterized by the decreasing number of cycles in the fiber metal laminates specimen. Specimens with a *Ra* value of 1.93 µm were fractured in the 90,000 cycles, specimens with a *Ra* value of 2.887 µm were fractured at cycle 11000. In Figure 8, the graph of the relationship between the number of cycles and the crack length of the metal laminates specimen is explained. In this study, in addition to knowing the relationship between the number of cycles and the length of the crack, it was also observed how the effect of surface roughness (*Ra*) and fiber angle orientation 0/90 ° on the rate of crack propagation. The fiber metal laminates specimen is shown in Figure 9.

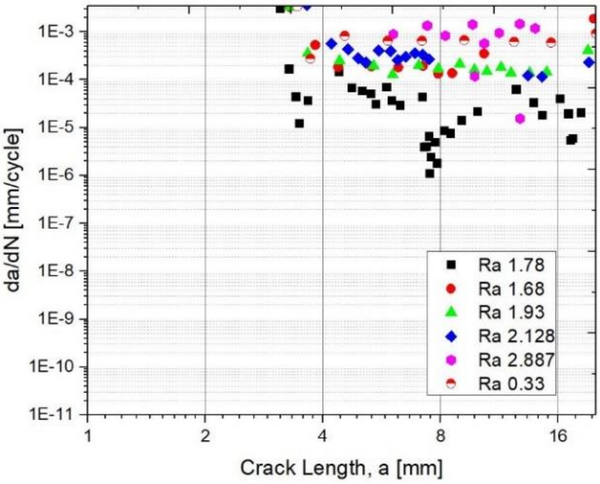


Figure 9. Relationship between the average crack length (*a*) to the crack propagation rate (*da*/*dN*) of the fiber metal laminates specimens for each surface roughness variation with an angular orientation of 0/90°

Figure 9 explained the relationship between the average crack length (*a*) and the crack propagation rate (*da*/*dN*) of the metal laminates specimens for each surface roughness variation (*Ra*) with fiber angular orientation 0/90°. Apart from decreasing specimen age, surface roughness also affects the rate of crack propagation of fiber metal laminates specimens. Fiber metal laminates specimens with a value of *Ra* 0.33 µm, *Ra* 1.68 µm, *Ra* 1.78 µm, the higher the surface roughness value, the crack propagation rate decreased, but on the fiber metal laminates specimens with a value of *Ra* 1.93 µm to *Ra* 2.887 µm crack propagation rate was even faster. By using the stress amplitude method in the fatigue test, the load received by the specimen depends on the tensile strength value for each variation of surface roughness. This is the basis for determining the loading value when fatigue testing is carried out. The value of fatigue loading can be determined by Equation 3. The loading magnitude during fatigue testing of fiber metal laminates specimens based on the calculation of the fatigue load can be seen in Table 4.

$$Load = \frac{{}^{1}/_{3} \times UTS \times A}{2} \tag{3}$$

Where,

UTS : Ultimate tensile strength
A : Cross-section area

Table 4. The magnitude of the specimen fatigue test loading for each variation of *Ra* and angular orientation of the fiber 0/90°

Surface roughness (*Ra*) (µm)	**Ultimate tensile strength (MPa)**	**Load (kN)**	**Number of cycles**
0.33	195.8	1.3	25,000
1.68	199.1	1.36	40,000
1.78	253.4	1.7	740,000
1.93	265.8	1.8	90,000
2.128	271.4	1.86	90,000
2.887	282.3	1.9	11,000

Table 4 shows that the higher the *Ra* value, the higher the tensile strength value as well as the higher the loading when fatigue testing is carried out. The number of cycles when testing increased for specimens with a value of *Ra* 0.33, 1.68, and 1.78 µm with loading values of 1.3, 1.36, and 1.7 kN, respectively. Then for specimens with a value of *Ra* 1.93, 2.128, and 2.887 µm with loading values above 1.7 kN, the number of cycles decreased. The loading value that is too high affects the fiber metal laminates specimen. The loading value that is too high makes the age of the material lower, which is indicated by the decreasing number of cycles during fatigue testing and the high rate of crack propagation.

3.3 Effect of surface roughness and fiber angle orientation 45/45°

Two variables of fiber angular orientation were used in this study, namely the angular orientation of the fiber 0/90° and 45/45°. To determine the effect of surface roughness and angle orientation of the 45/45° fibers on the crack growth of fiber metal laminates specimens, is shown in Figure 10.

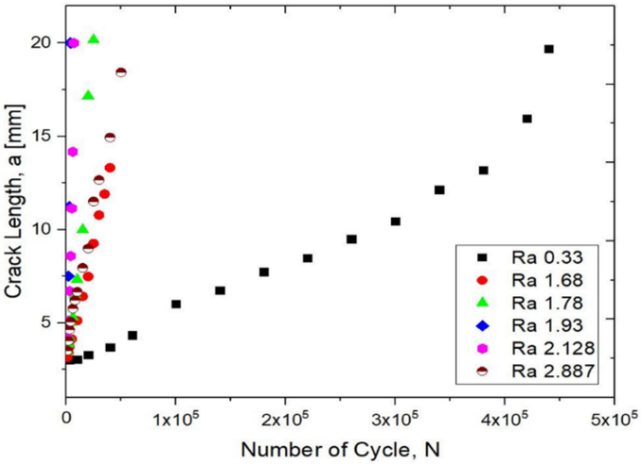


Figure 10. Relationship of the number of cycles to the crack length of the fiber metal laminates specimen for each variation of surface roughness (*Ra*) and angle orientation 45/45°

Figure 10 explained the relationship between the number of cycles to the crack length of the metal laminates specimen for each surface roughness variation (*Ra*) with the angular orientation of the fiber 45/45°. A graph in Figure 5.3 specimens with a value of *Ra* 1.93 µm fractured in the 4,000 cycles, specimens with a *Ra* value of 2.128 µm was broken in the 7,000 cycle and specimens with a value of *Ra* 2.887 µm were fractured in the 60,000 cycles. To determine the effect of surface roughness (*Ra*) and fiber angle orientation 45/45° on the crack propagation rate of fiber metal laminates specimens can be seen in Figure 11.

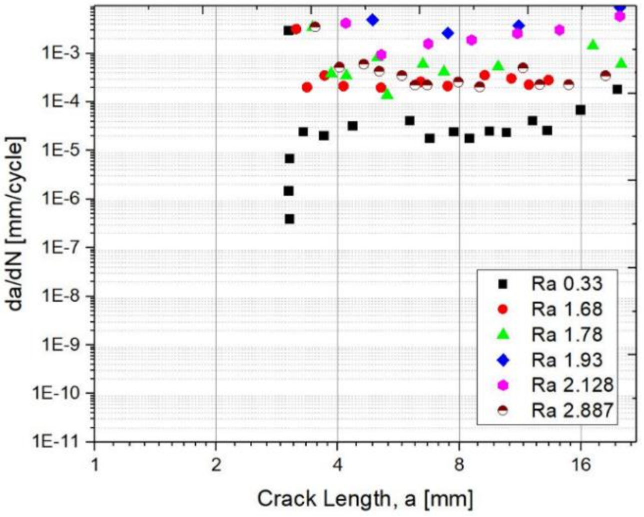


Figure 11. Relationship between the average crack length (*a*) to the crack propagation rate (*da*/*dN*) of fiber metal laminates specimens for each surface roughness variation with fiber angular orientation 45/45°

Figure 11 explained the relationship between the average crack length (*a*) and the crack propagation rate (*da*/*dN*) of the metal laminates specimens for each surface roughness variation (*Ra*) with the fiber angular orientation 45/45°. Variations in surface roughness in this study affect the cracking rate of fiber metal laminates specimens. In fiber metal laminates specimens with a fiber angle of 45/45°, the higher the surface roughness value or the coarser the aluminium surface, the bridge crack rate tends to increase. Then in specimens with a surface roughness value of 2.887 µm, the crack propagation rate was below the specimen with a surface roughness value of 1.93 µm and *Ra* 2.128 µm. This happens because the loading value during the fatigue test equates to the value of the specimen loading with a surface roughness of 2.887 µm with an angular orientation of 0/90° fibers. This is done because if the loading value is adjusted to the actual loading value of the specimen with a surface roughness of 2.887 µm and angular orientation of 45/45°, the crack propagation rate will be difficult to observe. After all, the data recorded is small. After all, the loading value is too large. The loading value during the fatigue test of fiber metal laminates specimens with an angular orientation of 45/45° fibers based on the formula for calculating the loading values discussed previously can be seen in Table 5.

Table 5. The loading value during the fatigue test of the specimen for each variation of *Ra* angular orientation 45/45°

Surface roughness (*Ra*) (µm)	**Ultimate tensile strength (MPa)**	**Load (kN)**	**Number of cycles**
0.33	72.4	0.4	440,000
1.68	187.3	1.2	40,000
1.78	210	1.4	25,000
1.93	357	2.4	4,000
2.128	361	2.47	7,000
2.887	282.3	1.9	60,000

In Table 5, it can be observed that the higher the surface roughness value, namely the specimens with a *Ra* value of 0.33 µm to *Ra* 2.128 µm, the higher the tensile strength value which causes the higher the loading value when the fatigue test is carried out. The higher the *Ra* value in the specimen with a fiber angle orientation of 45/45°, the age of the specimen is the lower, this is because the load given to the specimen is also greater. Loads that are too large can affect the fiber metal laminates specimens which affects the lower the age of the material, which is indicated by the decreasing cycle value during fatigue testing and the high rate of crack propagation that occurs. However, the specimen with a *Ra* value of 2.887 µm, the cycle increased with a value of 60,000 cycles because during this test the loading was adjusted to the specimen loading value of *Ra* 2.887 µm with a fiber angle orientation of 0/90°. Because the load given is adjusted to the actual loading value of the specimen *Ra* 2.887 µm with an angular orientation of 45/45° fibers, which is 2.5 kN, the crack propagation rate cannot be observed because of the few data recorded.

The application of stress amplitude based on the results of this study is less suitable when applied to composites. It is possible that stress amplitude can be applied to materials that have high fatigue cycles or high fatigue cycles due to the ductility of these materials so that they are suitable for applying stress amplitudes. In crack propagation, the initial crack or crack initiation occurs in a material that is easily deformed plastic or material with low strength, after which the crack propagates until the material breaks or fails. In this study, the use of stress amplitude may be appropriate if the loading value is adjusted to the material that has the lowest tensile strength, namely aluminium alone without carbon reinforcement.

3.4 Delamination on fatigue test fiber metal laminates specimen

Delamination is a failure model in steel or composite materials with a lamina or layer structure. This failure is caused by a variety of things, for example, repeated cyclic loads, collisions (impact), or other influences that cause the layers to separate [6]. The easy-to-separate layer can significantly reduce the toughness of a material. Delamination can also occur because of the weak bond between the fibers and the matrix. Besides, the ability of the matrix to fill the space between the fibers also affects the delamination temperature (see Figure 12).

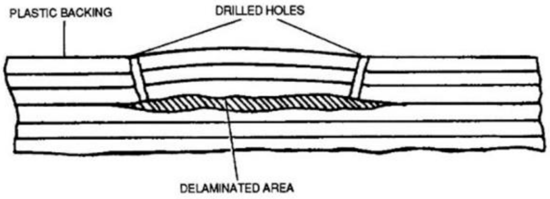
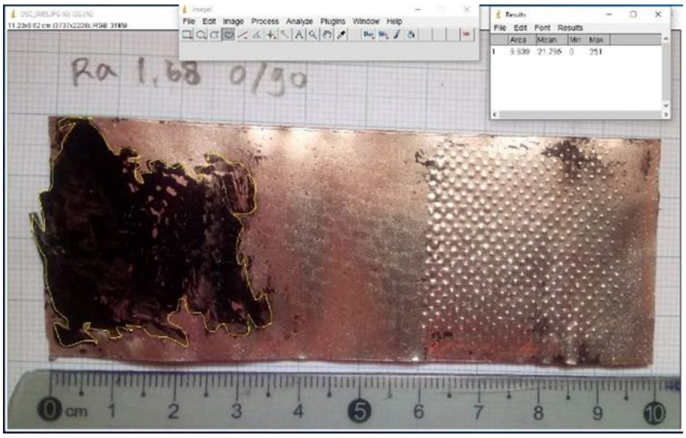


Figure 12. Delamination on composite

In this study, delamination affects the bond between layers of aluminium and carbon fiber composites in the fiber metal laminates specimens. The bond between these layers also affects the mechanical properties of the fiber metal laminates specimen. To detect delamination in a specimen, an observation is needed regarding the area of delamination that occurs in the specimen. The wider the delamination area, the lower the specimen strength and vice versa [7].

The area of delamination that occurs in the fatigue metal laminates test specimen was also observed in this study. To determine the delamination that occurs in the fatigue test specimen, the specimens that have been tested for fatigue are immersed in ink, then the area is observed with the help of ImageJ software. The image of the delamination area that occurs in the fatigue test specimen can be seen in Figure 13 (sample delamination images measured using ImageJ software on FML specimens with angular orientation 0/90°).



	Area	Mean	Min	Max
1	9.539	21.795	0	251

Figure 13. Fiber metal laminates specimen with the value of surface roughness is 1.68 µm

To determine the area of delamination that occurred in the specimen, it was measured using ImageJ software. The results of measuring the area of delamination on fatigue test specimens using ImageJ software can be seen in Table 6.

Table 6. Cross-section area delamination of the specimen with a value of fiber angular is 0/90°

Surface roughness (*Ra*) (µm)	**The cross-section area of delamination (cm^2)**
0.33	1.078
1.68	1.3
1.78	2.2
1.93	2.25
2.128	2.78
2.887	5.2

To observe the trend of how surface roughness affects the area of delamination it can be seen in the Figure 14. In addition to observing the delamination area of the specimen with an angle of 0/90° orientation, this study also observed the area of the specimen delamination with a 45/45° fiber angle orientation. Figure 15 is a picture of the delamination area that occurs in the specimen with an angular orientation of 45/45° fibers (sample delamination images measured using ImageJ software).

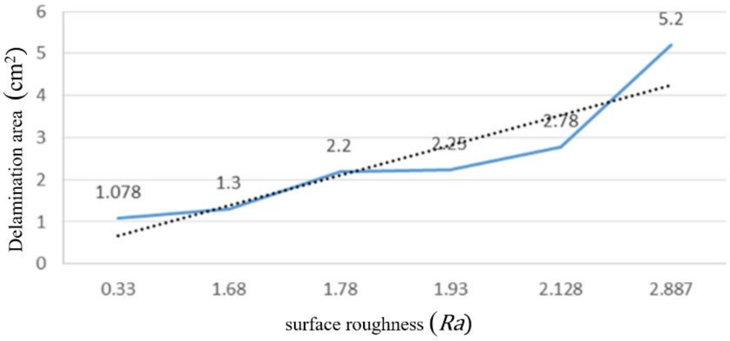


Figure 14. Relationship between surface roughness and delamination area of fiber metal laminates specimens with fiber angular orientation 0/90°

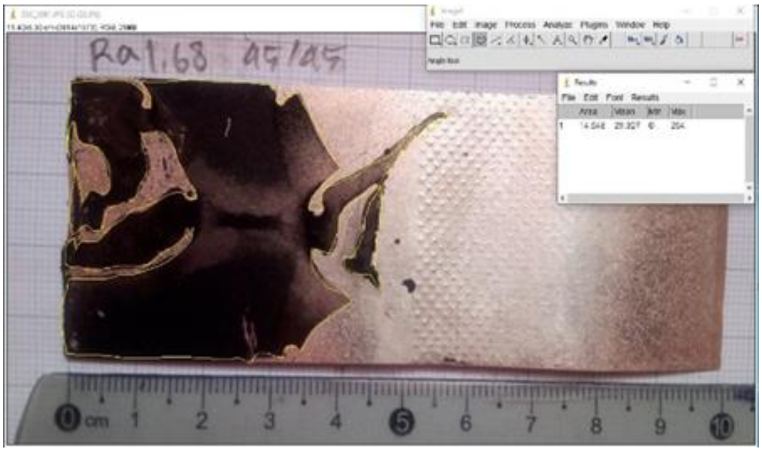


Figure 15. Fiber metal laminates specimen with the value of surface roughness is 1.68 µm

To determine the area of delamination that occurred in the specimen, it was measured using ImageJ software. The results of measuring the area of delamination on fatigue test specimens using ImageJ software can be seen in Table 7. To observe the trend of how surface roughness affects the area of delamination it can be seen in Figure 16.

Table 7. Cross-section area delamination of the specimen with the value of fiber angular is 45/45°

Surface roughness (*Ra*) (µm)	**The cross-section area of delamination (cm²)**
0.33	1.76
1.68	14.5
1.78	15.4
1.93	16.6
2.128	19.3
2.887	22.6

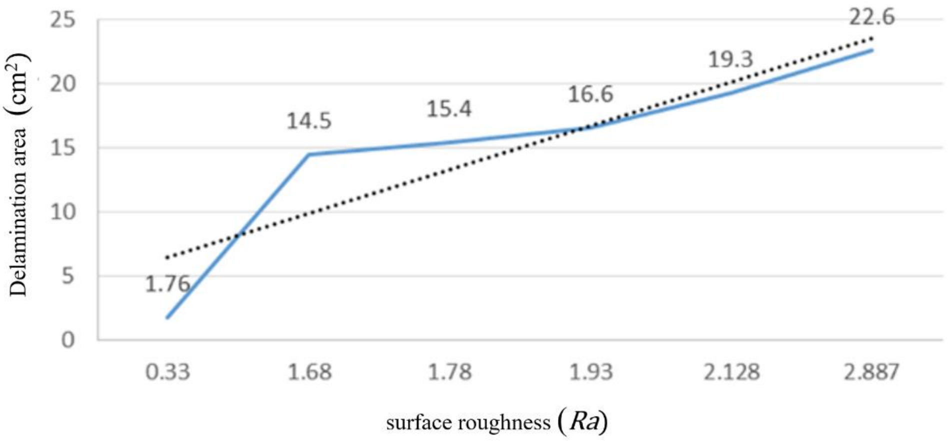


Figure 16. Relationship between surface roughness and delamination area of fiber metal laminates specimens with fiber angular orientation 45/45°

The data that has been discussed shows the phenomenon that the surface roughness value of 0.33 µm in specimens with 45/45 fiber angular orientation has the highest cycle with a value of 440,000. This shows that crack propagation at FML is affected not only because of surface roughness but also due to surface roughness. the stress concentration at the crack tip at the time of notching prior to the fatigue test. The rougher the surface, the greater the stress concentration value at the end of the notch, which is indicated by the larger area of delamination [10].

4 Conclusions

The conclusions of this study are as follows:

1. Crack propagation on Fiber Metal Laminates (FML) is influenced by several factors such as the roughness of the aluminium surface on the FML surface and also the stress concentration at the crack tip.
2. Fatigue life decreases along with higher surface roughness values. This occurs because the higher the surface roughness value, the greater the stress concentration at the crack tip in the notch, which is marked by the larger the area of delamination in the *Ra* value, which is getting coarser.
3. The area of delamination affects fatigue life.

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