A Fracture Mechanics Approach to the Water Jet Drilling of Composite Materials

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Abstract: Water jet machining of composite materials surpasses the conventional solid tool machining with respect to tool wear, thermal damage and environmental protection. Nevertheless, delamination during water jet drilling is a primary concern in applying this advanced technique. In the present work, mechanisms of delamination are recognized, and the phenomenon is modelled by using linear elastic fracture mechanics (LEFM) and circular plate bending theory. In this work a theoretical model is developed in which water jet force is identified as the main cause of delamination damage. By using this model, the critical water pressure leading to the onset of delamination is predicted. The approach is justified by existing experimental data from independent researchers with good agreement. The model contains the composite material parameters such as the fracture toughness of the fibre and matrix as well as the fibre volume fraction. The model also includes an analysis to assess the critical length of the fibre below which fibres tend to be pulled out of the matrix rather than to be fractured.

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1. Introduction:

Water jet machining has become a standard cutting mechanism in a wide variety of industry. Most non-metals could be cut rapidly and efficiently with a water jet. Examples of these materials are: composites, wood, plastic, cloth and rocks of medium hardness. The advantages offered by water jet include minimal or no dust, high cutting speed, multidirectional cutting capability, no dulling of cutting tool and no thermal or deformation stresses [1-3]. In the other side, machining of composites with conventional tools is associated with inherent problems such as tool wear and thermal damage [4-5]. Water jet cutting uses high pressure water instead of a solid tool and hence eliminates the above mentioned problems.

In water jet machining, materials are removed by the impingement of a continuous stream of high energy water beads. The machined chips are flushed away by the water. Similarly to solid tools, the water jet exerts machining force on the workpiece during cutting. This force is transmitted by the water beads clashing with the cut. The magnitude of the force is determined by the jet velocity, which can be calculated from the water pressure supplied by the machine [6].

There are also some limitations of water jet machining. The first limitation arises from the difficulties in machining hard materials such as metals, ceramics and hard rocks and this could be overcome by the use of abrasive water jet machining [7]. The second limitation is the delamination which occasionally occurs during the machining of composite materials. Since the material removal by water jet is driven by high water pressure the workpiece is subject to mechanical force and in certain cases damage is caused by this force.

Most of the previous work was in the field of manufacturing processes and mechanical properties. Some work was performed on machining [8-10]. However, little attention was given to the damage induced by machining. It was reported in [11] that damage in exit occurs due to the jet force acting perpendicular to the laminae and the effects of process parameters, thickness and composition of the material were studied experimentally. Hashish [12] found that the hole piercing of composite laminates by high pressure water jet resulted in fracture, cracking or delamination. He explained that the shock loading of water and hydrodynamic pressurization are responsible for the damage. The delamination fracture damage was considered in [13] during the end milling of holes in 'GFRP' composites. Little attention was given to the damage induced by machining using non-conventional methods for cutting composite materials.

The presence of delamination reduces the stiffness and the strength of a laminate and hence its load carrying capacity. Delamination can also be the limiting factor in the use of composite materials.

In this work a model will be derived for evaluating the critical pressure of delamination fracture damage induced during the water jet drilling of composite laminates. The material properties will be considered in the model and the results will be compared with other investigators experimental results. The analysis well be extended to estimate the critical fibre length below which the fibre tends to be pulled of the composite rather being fractured.

2. Theoretical Model

In water jet drilling of composite laminates there is a thrust jet force acting perpendicularly to the lamina that show flexural bending in response. The lamina under the water jet thus tends to be pushed away from the inter-laminar bound around the hole. As the jet advances to the end, the uncut thickness decreases and the resistant to deformation weaken. At a certain point the thrust jet force causes such a deformation that the inter laminar bond strength can no longer hold and delamination around the hole exit occurs. This happens before the lamina is completely pierced by the water jet.

Figure (1) illustrates this mechanism. Variable process parameters, such as water jet diameter and pressure, can affect the occurrence of delamination by changing the magnitude of the thrust jet force. The flexural rigidity and the opening-mode delamination fracture of the composite laminate on the other hand determine the material response in the form of delamination and separation of lamina during jet drilling [11, 12].

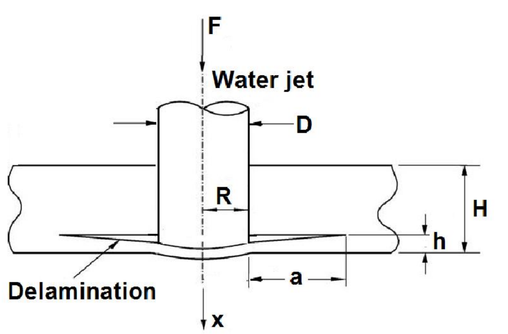

Figure (1): A schematic drawing for the circular plate model of delamination fracture analysis.

Based on the mechanism above, the delamination could be considered as a two-stage fracture process; the onset and the propagation. At the onset of delamination, the thrust jet force produces bending deformation which leads to lamina separation. An inter-laminar crack around the bottom of hole is thus created. At the second stage, the water pressurization together with the jet force widens this crack to final delamination damage. Having discussed the mechanisms of delamination, a model based on fracture mechanics could be derived. Since composite laminates show extremely high elasticity and a lower degree of plasticity, the simple assumption is that the use of linear elastic fracture mechanics (LEFM) is proper in the modelling [14, 15].

As shown in Figure (1) the cylinder in the middle represents the water jet which has a diameter 'D', applying thrust force 'F' downwards , while 'x' is the displacement and 'H' is the thickness of the lamina, while 'h' is the uncut depth under water jet and 'a' is the radial size of an assumed existing circular crack. As the jet cuts downwards, the uncut laminate under it are pushed and deformed elastically by the central thrust force. If the resulting strain at the tip of the crack goes beyond the critical value, delamination occurs. The equation of energy balance from (LEFM) could be written as [16]:

$$GdA = Fdx - du \tag{1}$$

Where 'G' is the energy release rate per unit area, 'A' is the area of delamination and 'u' is the stored strain energy and dA is expressed as:

$$dA = \pi(D + 2a)da \tag{2}$$

Plate bending theory for circular plate with concentrated load and clamped ends [17] is used for the following model. This assumption seems to be valid since the water jet diameter has a very small value compared with the workpiece dimension where the strain energy 'u' could be written as:

$$u = \frac{8\pi M x^2}{\left(a + \frac{D}{2}\right)^2} \tag{3}$$

Where M is the bending flexural rigidity of the circular plate and can be written as:

$$M = \frac{Eh^3}{12(1-\nu^2)} \tag{4}$$

Where 'E' is Young's modulus, 'ν' is Poisson's ratio for the composite material and the displacement 'x' is expressed as:

$$x = \frac{F\left(a + \frac{D}{2}\right)^2}{16\pi M} \tag{5}$$

The thrust force 'F' is assumed to be the product of water jet pressure 'P' and cross sectional area of the water jet, then:

$$F = \pi P R^2 \tag{6}$$

Where (R = D/2). By substituting equations 2 to 6 into equation 1, the critical water jet pressure at the onset of delamination 'P_c' could be obtained:

$$P_c = (h^{3/2})\sqrt{\frac{8EG_{IC}}{3R^4(1-\nu^2)}} \tag{7}$$

The main drawback of the above equation is the constancy of G_{IC}. Although earlier work [18] shows that G_{IC} is only a mild function of strain rate, a modification is made in this work to replace G_{IC} with another form which contains composite material parameters.

The model could be modified by representing the fracture toughness of the composite material in terms of the matrix toughness, fiber toughness and fiber volume fraction. The fracture toughness of the composite material could be represented by the following equation [19]:

$$G_{IC} = V_f G_C^f + (1 - V_f) G_C^m \quad (8)$$

where 'V_f' is the fibre volume fraction G_C^f is the toughness of the fibre and G_C^m is the toughness of the matrix. The toughness of a composite like that or any other material is a measure of energy absorbed per unit area of the crack. If the crack is simply propagating straight through the matrix and fibers, a simple role of mixtures is likely to hold. By substituting equation (8) in equation (7), then the new model will take the form:

$$P_c = (h^{3/2}) \sqrt{\frac{8E[V_f G_C^f + (1-V_f)G_C^m]}{3R^4(1-\nu^2)}} \quad (9)$$

where P_C is the critical water jet pressure at the onset of delamination. To avoid delamination, the applied water pressure should not exceed this value which is a function of material properties and the uncut thickness.

Another modification to link the new model with critical fibre length is presented in the following section. If the fibers length is less than a critical value 'X_C' they will not fracture and they must instead pull out as the crack opens. Thus, the fracture toughness of the composite material could be represented in another form containing the fibre length 'l' in the following form [19]:

$$G_{IC} = \frac{V_f \sigma_S^{m\,2}}{2d} \quad (10)$$

where σ_S^m is the matrix shear strength and 'd' is the fiber diameter, where the fibre will break at a distance from its end equals to 'X_C', Then $l = 2X_C$. By substituting this in equation (10) yields the following [19]:

$$G_{IC} = \frac{2V_f \sigma_S^m X_C^2}{d} \quad (11)$$

By substituting equation (11) in equation (7), thus, the proposed model for critical fibre length will take its final form as follows:

$$P_c = (h^{3/2}) \sqrt{\frac{16E\, V_f \sigma_S^m X_C^2}{3dR^4(1-\nu^2)}} \quad (12)$$

Equation (12) represents the second part of the analysis where the critical fiber length X_C could be obtained. If 'l' is greater than $2X_C$, the fibre will not be pulled out and it will be subjected to fracture instead.

The two proposed models in this work firstly for assessment of the critical water jet pressure which could be the main parameter affecting the delamination process in the cut sample of the composite material and secondly the model for estimation of the critical fibre length of the composite material will be discussed in the following section.

2. Results and Discussion

The relation between the critical delamination pressure, uncut thickness, water jet radius and fiber volume fraction could be plotted using equation (9) of the analysis above. Figure (2) exhinits the critical delamination pressure 'P_C' versus the uncut thickness 'h' at different water jet radii. It can be seen that the critical delamination pressure increases with the increase of the uncut thickness. It can also be noticed from fig. (2) that the effect of the water jet radius R on the critical delamination pressure is very small at low 'h' and increases with the increase of the uncut thickness.

Figure (3) exhibits the effect of varying the critical delamination pressure on the water jet radius at various uncut thicknesses. It can be seen from fig. (3) that the critical delamination pressure decreases rapidly with the increase of water jet radius.

Figure (4) shows the relationship between the critical delamination pressure and the fibre volume fraction of the composite material at different values of the uncut thickness. It can be seen from fig. (4) that the critical delamination pressure seems to be slightly sensitive to the variation of fiber volume fraction.

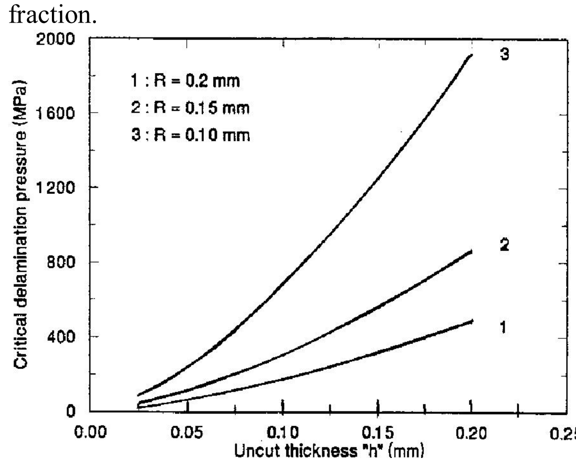

Figure (2): Critical delamination pressure versus uncut thickness at different values of water jet radii.

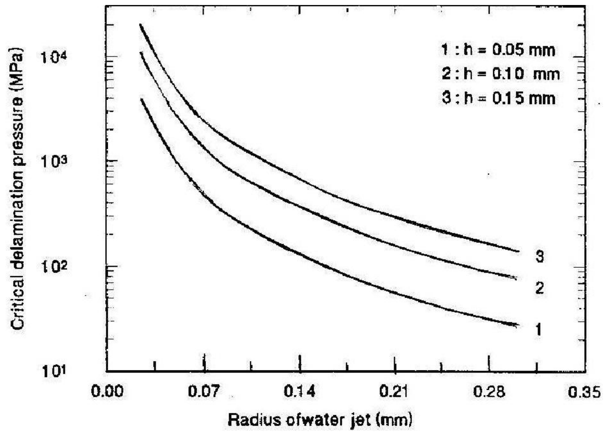

Figure (3): Critical delamination pressure versus radius of water jet at different values of uncut thickness.

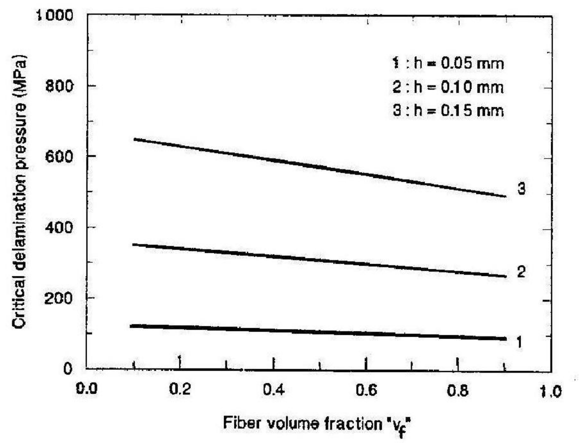

Figure (4) Critical delamination pressure versus fiber volume fraction at different values of uncut thickness.

To examine the validity of the proposed model in the current work, experimental results should be compared with the analytical predictions. Hashish [12] has published a rather complete set of experimental data of water jet machining of composites including linear cutting, turning, milling and drilling. In the hole piercing section, Hashish presented the clear consequence of the use of high pressure and low pressure respectively. Delamination damage of a 6.3 mm thick graphite epoxy composite is generated at pressure of 345 MPa while the exit showed a clean cut at pressure of 241 MPa. This is the first quantitative report of the effect of water pressure on material delamination.

For high strength graphite/epoxy with fiber volume fraction of 0.6 and ply thickness of 0.1 mm, E is equal to 124 GPa, the fracture toughness of both the fiber and matrix are o.1 and 0.2 kJ/m^2 respectively and the water jet diameter was taken to be 0.3 mm [12]. By applying the above data to the proposed model in this work above, the critical water jet pressure at the onset of delamination upon exit could be calculated and it is equal to 316.66 MPa.

Table (1) shows the comparison between the theoretical prediction and the experimental results. As can be seen from the table, the prediction lies between the values of the experimentally justified range. Once the critical fracture pressure is obtained, the critical fibre length could be calculated from equation (12) which is required to assess the mechanism of fibre failure, either by pulling out or by fibre fracture. These remarks are the logic deduction from the current analysis which clearly foresees the roles of the level of load and the resistance to plate pending in causing delamination.

Table (1): Comparison between the predicted theoretical results from the current model and the experimental values.

Predicted critical delamination fracture pressure obtained from the current model	316.66 MPa
Experimental results from reference [12]	241 MPa (no delamination) 345 MPa (delamination occurs)

Conclusion

In this work, a theoretical model is developed for predicting the critical delamination pressure during water jet machining of composite laminates using 'LEFM' and circular plate bending theory.

The model incorporates the material parameters such as the strength of the fibre and matrix, the fibre volume fraction and young's modulus of the composite material.

The machining parameters were also included in the model such as the uncut thickness (lamina thickness) and the diameter of the jet.

The predicted theoretical analysis was compared with the experimental results of other independent workers and good agreement was found to be hold between both of them.

The model includes an equation to assess the critical fibre length below which the fibres tend to be pulled out of the matrix rather than to be fractured.

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