Prediction of Delamination in End Milling of GFRP Using ANSYS

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Abstract

The use of Glass Fiber Reinforced Plastics (GFRP) has increased manifold over the last few years. Generally developed for aerospace and other high-end applications, composites are now making inroads into the automotive and general engineering markets. Thus good quality and cost-effective manufacturing of GFRP composites becomes imperative. One of the machining process milling is the most practical operation available for producing an accurate shape and high quality surface. Delamination is recognized as one of the most critical defects that can result from the machining of composites. Delamination due to milling has been a major research for many years and a considerable amount of work has been done to reduce it by statistical means. A lot of experimental work has to be done in order to know the optimal cutting conditions with respect to factors on delamination, which is cumbersome. These necessities a need for developing suitable prediction model in order to reduce the number of experiments being conducted to determine the optimal values for various applications. In this study a suitable prediction model for milling of GFRP has been developed using Ansys 11 Software. In order to understand the effects of process parameters on the delamination milling experiments using K10 end mill on three different types of GFRP with different speed, feed and depth of cut has been performed and analyzed using FEM model. Using FEM model the desired cutting parameters for minimized appearance of delamination in different GFRP has been developed and its value has been compared with the experimental values. It has been found out that the discussed FEA model results are close to be experimental results.

***Keywords**: Milling, GFRP, Delamination, FEM model of GFRP, Failure Criteria.*

1 Introduction

Glass fibers with polymeric matrices have been widely used in various commercial products such as piping, tanks, boats and sporting goods. Glass is by far the most widely used fiber, because of the combination of low cost, corrosion resistance, and in many cases efficient manufacturing potential. It has relatively low stiffness, high elongation, and moderate strength and weight, and generally lower cost relative to other composites. It has been used extensively where corrosion resistance is important, such as in piping for the chemical industry and in marine applications. It is used as a continuous fiber in textile forms such as cloth and as a chopped fiber in less critical applications [1].

Glass fibers are strong as any of the newer inorganic fibers but they lack rigidity of on account of their molecular structure. The properties of glasses can be modified to limited extent by changing the chemical composition of the glass, but the only glass used to any great extent in composite materials is ordinary borosilicate glass, known as E-glass [2].

Among several industrial machining processes, milling is a fundamental machining operation. End milling is the most common metal removal operation encountered. It is widely used in a variety of manufacturing industries including the aerospace and automotive sectors, where quality is an important factor in the production of slots and dies. The quality of the surface plays a very important role in the performance of milling as a good-quality milled surface significantly improves fatigue strength, corrosion resistance, and creep life [3].

Milling composite material is significantly affected by the tendency of these materials to delaminate under the action of cutting force, feed force and depth force respectively. For these reasons there has been a lot of research and development with the objectives of optimizing cutting conditions to obtain a determined delamination [4-6].

Tsao studied prediction and evaluation of delamination factor in use of twist drill, candle stick drill and saw drill. The approach is based on Taguchi's method and the analysis of variance (ANOVA). An ultrasonic C-Scan to examine the delamination of carbon fiber-reinforced plastic (CFRP) laminate was used. The experiments were conducted to study the delamination factor under various cutting conditions. The experimental results indicate that the feed rate and the drill diameter are recognized to make the most significant contribution to the overall performance. The objective was to establish a correlation between feed rate, spindle speed and drill diameter with the induced delamination in a CFRP laminate. The correlation was obtained by multi-variable linear regression and compared with the experimental results [7].

Wen-Chou studied the concept of delamination factor Fd (i.e. the ratio of the maximum diameter D_{max} in the damage zone to the hole diameter D) proposed to analyze and compare easily the delamination degree in the drilling of carbon fiber-reinforced plastic (CFRP) composite laminates. Experiments were performed to investigate the variations of cutting forces with or without onset of delamination during the drilling operations. The effects of tool geometry and drilling parameters on cutting force variations in CFRP composite materials drilling were also experimentally examined. The experimental results showed that delamination-free drilling processes may be obtained by the proper selections of tool geometry and drilling parameters. The effects of drilling parameters and tool wear on delamination factor were also presented and discussed [8].

Drilling of holes is an important machining operation to ascertain the assembly operations in intricate composite parts. The research endeavors in the field of drilling of composite materials have focused on optimization of the operating variables, tool geometry and theoretical modeling of the critical thrust force. The result of analysis of variance (ANOVA) was used to make assumptions for developing a Finite Element model for predicting drilling induced damage. The FE results were found in good agreement with the experimental results. Few specific topics, other, more advanced studies, have been conducted to understand the complex physical behavior underlying the specific machining process [9].

A study at ERC/NSM on the investigation of high speed milling processes for machining dies and molds. A special flat end milling operation, using a single insert index able tool with a straight cutting edge (i.e. zero helix angle), was selected to investigate chip formation in milling. Dry milling of P-20 mold steel using a plain tungsten carbide (WC) cutter was simulated for selected cutting conditions (cutter diameter: 15.88 mm, cutting speeds: 50, 100 and 200 m/min, feeds: 0.1 and 0.155mm/tooth, axial depth of cut: 1 mm, and radial depth of cut: 15.88mm). Chip formation, cutting temperatures, tool stresses and cutting forces were predicted from Finite Element Method (FEM) simulations. This study demonstrated the effectiveness of FEM simulations in predicting process variables in a simple flat end milling operation [10].

Finite Element Analysis (FEA) is known since 1960-1970 and has been used to analyze forming Processes and designing tools. Finite Element Method (FEM) permits the prediction of cutting Forces, stresses, tool wear and temperatures of the cutting process so that the cutting tool can be designed. With this method the best cutting parameters were determined [11, 12].

An inverse method of identification for the determination of material parameters that are used for the FEM simulation of milling processes was proposed. First of all, a special device has been instrumented and calibrated to perform force and torque measures, directly during milling experiments in using a piezoelectric dynamometer and a high frequency charge amplifier. The experimental results were saved and filtered to obtain reliable and accurate data. Then FEM simulations of milling were performed using explicit ALE based FEM code. The material behavior is firstly described from a Johnson-Cook constitutive law and different characterization tests have been lead in a wide range of conditions to be used to identify a new behavior law adapted to the process. A fracture model was also added to consider chip formation and separation. Finally, identification procedures are proposed for the determination of material law parameters. These procedures are based on an objective function to minimize, firstly defined by the experimental and numerical results obtained in the turning process and secondly by the experimental and analytical results obtained in milling process. The identification approach is mainly based on the Surfaces Response Method in the material parameters space, coupled to a sensitivity analysis. A Moving Least Square Approximation method was used to accelerate the identification process [13].

Milling of glass fiber reinforced plastic and prediction of delamination was done using RSM and ANN Method. It showed the influence of various cutting parameter on delamination [14].

All above work were limited to statistical method or prediction using FEM by inverse method. In this work prediction of delamination of various GFRP for different cutting condition has been made using FEM technique.

2 Experimental Procedure

2.1 *Material, equipment and tool*

A composite material is an anisotropic, heterogeneous medium, made by combining two or more materials with differing properties. Properties of the composite are different from those of the constituent materials. The components of the composite do not merge completely in to each other and can be physically identified along with the interface between them. The properties of the interface also contribute to the properties of the composite. Many common materials could be classed as composites, but in this is concerned with various Glass Fibre Reinforced Polymer (GFRP) composites.

2.2 *Compositions of Various Glass Fiber Reinforced Polymers (GFRP)*

Specimen – 1

Glass Fiber Reinforced Polymer (GFRP) composite materials used in the tests are made of epoxy matrix (Araldite LY556) reinforced with 55% of chopped fiber glass using Hardener (HY951) was produced by WRM procedure with 6.5mm thickness (8 lay-up).

Table 1: Chemicals and Reinforcement used in GFRP Specimen-1

Matrix	Epoxy, Araldite LY556
Hardener	HY 951
Reinforcement	WRM (Woven Roving Mat)
WRM	8 layers
Manufacturing Process	Hand-layup

Specimen – 2

The GFRP composite material is prepared with 50% EP-306 and 50% Ep-86 FL. The fibers are reinforced in the form of Woven row mat with DGEBA as resin.

Table 2: Chemicals and Reinforcement used in GFRP Specimen-2

EP-306	45 g
EH-758	5 g
EP-286 FL	47 g
WRM	142 g (12 layers)
Weight fraction	0.47 (DGEBA)
Curing time/Pot life	10 min
Manufacturing Process	Hand-layup

Specimen – 3

The GFRP composite material is prepared with 75% EP-306 and 25% EP 286 FL. The fibers are reinforced in the form of Woven row mat with DGEBA as resin.

Table 3: Chemicals and Reinforcement used in GFRP Specimen-3

EP-306	67 g
EH-758	8 g
EP-286 FL	23 g
WRM	142 g (12 layers)
Curing time/Pot life	15 min
Manufacturing Process	Hand-layup

2.3 *Machine Selection*

To conduct the experiment, it was necessary to use a Vertical Machining Center (VMC). For Specimen I a Vertical machining centre with 10kw spindle power and a maximum spindle speed of 8000 rpm was used to perform the experiment. For specimen 2 and 3 a Universal Milling machine with a spindle speed of 45-1400m/min, longitudinal feed of 18 mm/min and cross feed range of 16-800 mm/min. The machine has a Vertical feed of 6.3-315 m/min and a clamping area of 300 X 1000 mm. The fixation of the composite material was made in such a way so as to eliminate the vibration and displacement.

2.3.1 Tool Selection

The Tools that were chosen for milling were K10 end mill Solid carbide tool coated with Titanium nitride having four flutes each with Square Ends. The tools used for the study is SGS Carbide make.

2.4 *Cutting conditions*

For each specimen different factors and levels were set as shown below

Table 4: Cutting parameters for specimen-1

FACTORS	LEVELS		
Cutting Speed (m/min)	100	700	1300
Feed(mm/min)	5	350	650
Depth of cut (mm)	0.5	1	1.5
Tool material	Ttitanium Nitride coated soild carbide tool		

Table 5: Cutting parameters for specimen-2 specimen-3

FACTORS	LEVELS	
Cutting Speed (m/min)	700	1300
Feed(mm/min)	350	650
Depth of cut(mm)	1	1.5
Tool material	Ttitanium Nitride coated soild carbide tool	

2.5 *Measurements of delamination*

For specimen I measurement of delamination using pulsed Thermography was done. The computation of the delamination was done by the measurement of the Maximum width of damage (Wmax) suffered by the material, the damage normally assigned by delamination factor (F_d) was determined. This factor is defined as the quotient between the maximum width of damage (Wmax) and the width of cut (W). The value of delamination factor (F_d) can be obtained by the following equation:

$$\mathbf{F_d = W_{max} / W} \tag{1}$$

W_{max} being the maximum width of damage in mm and W the width of cut in mm. The maximum width of damage in µm was obtained by the images from the Altair software.

For specimen 2 and 3 a profile projector with a resolution of 0.001mm and a magnification of 100X was used to measure delamination. The experimental setup is shown in figure 1.

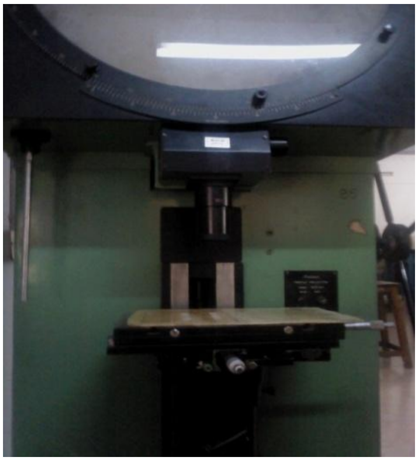

Figure 1: Profile Projector experimental setup for specimen-2 and specimen-3

3 Finite element analysis

3.1 *Finite Element modeling of end milling*

The finite element method has been a fundamental analysis technique and has widespread use in engineering Community. FEM is a computer-based numerical for calculating the strength and behavior of engineering structures. It can be used to calculate deflection, stress, forces, vibration, buckling behavior and many other phenomena. It can be used to analyze either small or large-scale deflection under loading or applied displacement. It can analyze elastic deformation or permanently bent out of shape plastic deformation. In the finite element method, a structure is broken down into many small simple blocks or elements. The behavior of an individual element can be described with a relatively simple set of equations. Planning the analysis is arguably the most important part of any analysis, as it helps to ensure the success of simulation. Oddly enough, it is usually the one analysts leave out. The purpose of an FE analysis is to model the behavior of structure under a system of loads. In order to do so, all influencing factors must be considered and determined whether their effects are considerable or negligible on the final result. This finite modeling of end milling involved a great deal of complexity as the mill being a very complex tool and so is the process and chip geometry. So the preprocessing phase was done considering various parameters from element selection, boundary conditions, material properties and right selection of pre-processor and solver tool. Using Pro/engineer, the simple end milling of different materials has been made with end milling diameter of 10 mm then it was converted into IGES (inter graphic exchange system) format which is very common format to exchange data between different software's. The modeling of end milling are shown in Figure 2, some of the resulting important delamination, a finite-element analysis (FEA) was carried out. Although most of this delamination can be obtained through experimentation, the elastic-plastic transition behavior in plastics is not easily to study under experimental conditions. Hence, need for FEA modeling.

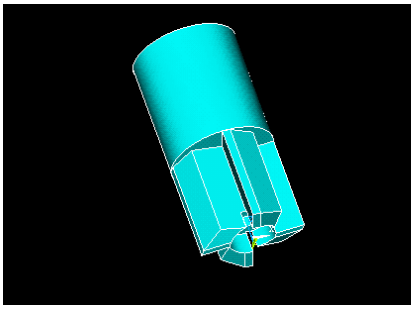

Figure 2: Modeling of end milling

In addition to validating experimental findings, the FEA prediction of this delamination can shorten the cycle time for determining optimum filler quantities that will maximize the resulting composite properties. A finite element model of the experimentally molded specimens was created using ANSYS 11.0 software. Preliminary results from delamination tests indicated that the composite material was very brittle but exhibited linear deformation in its elastic state. Thus the model was developed using a SOLID layer 46 element, using an elastic material, with mechanical characteristics. Because we are considering a thermosetting plastic with granular additives, behavior is fairly uncertain. SOLID layer 46 elements permit irregular shapes, and its layer 46 allow for any spatial orientation. The Material property used for modeling GFRP are given below in the table 6.

Table 6: Material Properties of GFRP Specimen 1, 2 and 3

SPECIMEN	1	2	3
Modulus of elasticity	(X-direction) 48 GPa	(X-direction) 50 GPa	(X-direction) 75 GPa
Modulus of elasticity	(Y-direction) 12 GPa	(Y-direction) 8 GPa	(Y-direction) 15 GPa
Bulk modulus	6.0 GPa	5 GPa	9 GPa
Poisson's ratio	0.25	0.25	0.25
Allowable tensile stress	(X-direction) 550 MPa	(X-direction) 159.24MPa	(X-direction) 226.09 MPa
Allowable tensile stress	(Y-direction) 34 MPa	(Y-direction) 15 MPa	(Y-direction) 25 MPa

3.2 *Layers of GFRP*

The work piece has different layers (8, 12, and 12) of glass fiber so appropriate model was constructed for modeling of different layer to make composite lamina. Different properties were given for layup process like orientation, different properties of different layers. Orientation of different layers can be done by fiber orientation depending on the loading condition. The layers of GFRP are shown in Figure 3, 4 and 5.

3.3 *Meshing of GFRP*

Initially constructing the finite element work piece model the solid elements of layer 46 were used to mesh the work piece with uniform mesh density all over the work piece.

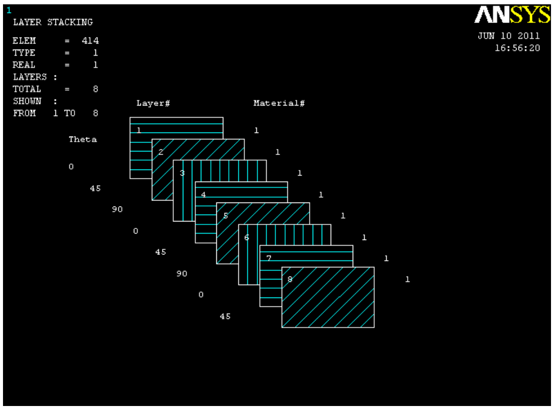

Figure 3: Layers of GFRP specimen-1

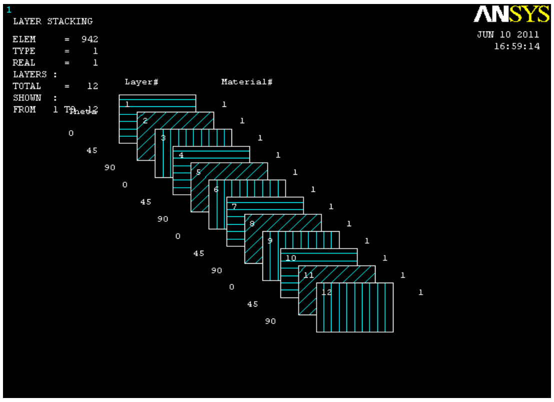

Figure 4: Layers of GFRP specimen-2

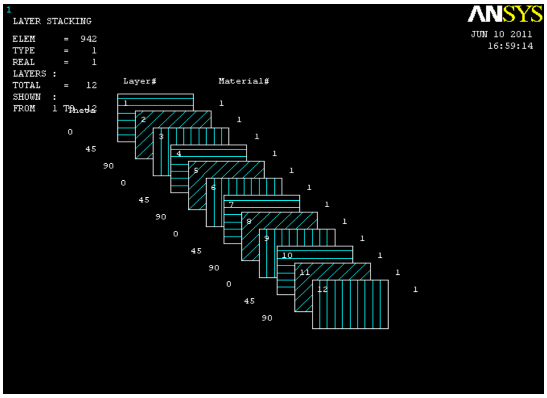

Figure 5: Layers of GFRP specimen-3

3.4 *Failure criteria*

To determine whether a laminate will fail due to applied loading, the program first calculates stresses across the different plies. It next applies a failure criterion based on these stress levels using a failure theory. A laminate is considered to fail when a first ply or a first group of plies fails. Failure of composites occurs in multiple steps. When stress in the first ply or a first group of plies is high enough, it fails. This point of failure is the first ply failure (FPF) beyond which a laminate can still carry the load. For a safe design, laminates should not experience stress high enough to cause FPF. The point where the total failure occurs is termed the ultimate laminate failure (ULF). Failure of composites occurs on a micromechanical scale due to fiber damage, matrix cracking, or interface or interphase failure. These local failure modes cannot predict global laminate failure satisfactorily. The theories available for laminate failure criteria are Tsai-Hill Failure Criterion,• Tsai-Wu Failure Criterion and Maximum Stress Criterion. In this work, Tsai-Wu Failure Criterion is applied for analysis of end mill damaged slot.

3.4.1 Tsai-Wu failure criterion

The Tsai-Wu criterion is applied to composite shells. The Tsai-Wu failure criterion is a Phenomenological failure theory which is widely used for anisotropic composite materials which have different strengths in tension and compression. This failure criterion is a specialization of the general quadratic failure criterion proposed by Gol'denblat and Kopnov and can be expressed in the form.

$$F=F_1xs_{xx}+F_2xs_{yy}+F_3xs_{zz}+F_{11}xs_{xx}^2+F_{22}xs_{yy}^2+F_{33}xs_{zz}^2+F_{12}xs_{xx}xs_{yy}+F_{13}xs_{xx}xs_{zz}+F_{23}xs_{yy}xs_{zz}+F_{44}xs_{yz}^2+F_{55}xs_{xz}^2+F_{66}xs_{xy}^2 \qquad (2)$$

Where

$F_1= (1/F_{X+}) - (1/F_{XC})$, $F_2= (1/F_{X+})-(1/F_{XC})$

$F_3= (1/F_{Z+}) - (1/F_{ZC})$, $F_{11}= (1/F_{XC+})\ X\ F_{Xt}$

$F_{22=}\ (1/F_{Yt+})\ X\ F_{YC,}\ \ F_{33=}\ (1/F_{Z+})\ X\ F_{ZC}$

$F_{44}= (1/F_{SYZ})^2$, $F_{55}= (1/F_{SXZ})^2$

$F_{66}= (1/F_{SXY})^{2}$

Here SXX, SYY, SZZ are the stress components in X, Y, Z directions. SXY, SYZ, SXZ are the interlaminar shear stresses. FX_t, FX_C are the X-direction tensile and compressive failure stress, respectively. FY_t, FY_C are the Y-direction tensile and compressive failure stress, respectively. FZ_t, FZ_C are the Z-direction tensile and compressive failure stress, respectively. FSXZ, FSYZ, FSXY are the shear failure stresses. F_{12}, F_{23}, F_{13} are determined by biaxial tests. When the value of the function reaches unity, failure of the composite material under combined loading is predicted. This criterion considers the total strain energy (both distortion energy and dilatation energy) for predicting failure. It is more general than the Tsai-Hill failure criterion because it distinguishes between compressive and tensile failure strengths. For a 2D state of plane stress (s3 =0, t13 =0, t23 =0) that is assumed for the composite shells, the failure index is computed. The program reports the factor of safety (FOS) as 1 / (F.I.). The FOS should be greater than 1 for laminates to be safe. The maximum stress and the maximum strain failure criterion represent the material failure in the principal direction only. The Tsai Wu Failure criteria take into account the interaction of the stress components in all directions. In this work, this criterion has been applied for finding the damage around the slot. Therefore, it is a more realistic approach to predict failure than the maximum stress and strain theories.

4 Results and discussion

The result obtained from experimental testing and FEA analysis are discussed.

4.1 *Simulation results*

The Simulations results for specimen 1, 2 and 3 obtained using Tsai-wu failure criteria are shown in figure 6, 7 and 8.

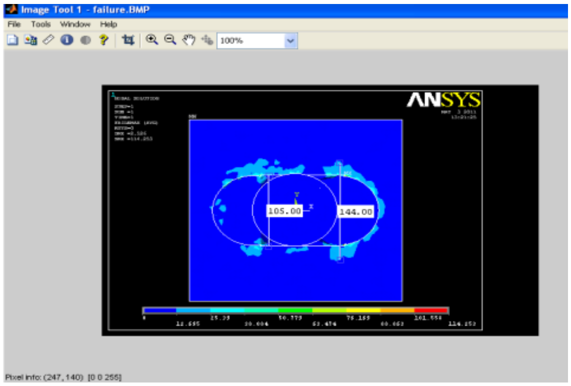

Figure 6: Delamination of GFRP specimen-1

CACULATION OF DELAMINATION

Delamination = D_{max}/D_{actual}

D_{max} =144mm , D_{actual} =105mm

Delamination =1.37mm

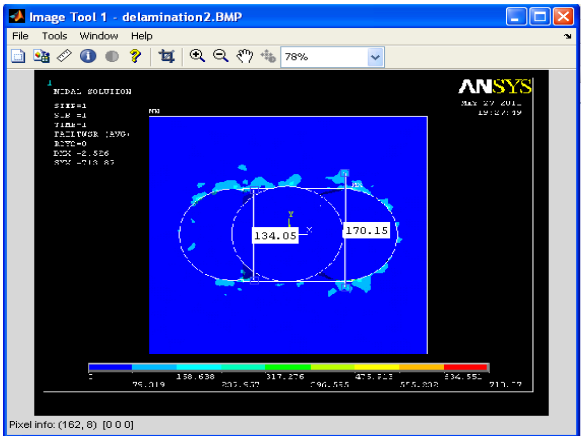

Figure 7: Delamination of GFRP specimen-2

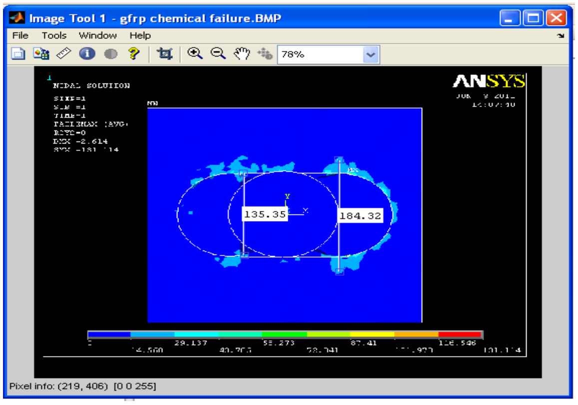

Figure 8: Delamination of GFRP specimen-3

4.2 *Comparisons of experimental and simulation results*

The results obtained from the experimental testing and simulations have been compared are shown in the table 7. It has been found out that the discussed FEA model results are close to be experimental results.

Table 7: Comparisons of experimental and simulation results

Specimen	Delamination in experimental results (mm)	Delamination in FEA results (mm)
I	1.48	1.37
II	1.50	1.26
III	1.45	1.36

5 Conclusions

The delamination that occurs during milling severely influences the mechanical characteristics of the material. In order to avoid these problems it is necessary to determine the delamination occurring due to machining operation. In order to understand the effects of process parameters on the delamination a large number of machining experiments has to be performed. Using FEM model the desired cutting and material parameters for minimized appearance of delamination can been developed using the above procedure. It has been found out that the discussed FEA model results are close to experimental results. Further 3D FEM models applied to milling can also be developed and after simulations is adaptable to industry.

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