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Drilling Process Design for Hybrid Structures of Polymer Composites over Titanium Alloy

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Abstract

This work aims at determination of optimum drilling process design for hybrid structures of polymer composites over titanium alloy in order to reach the needed quality and cost effectiveness for the aerospace industry. A set of experiments are designed to investigate the effects of process variables on the required torques and thrust forces and quality of the drilled holes. Surface response methodology is used to analyze the results. Process maps are introduced based on the experimental results and the optimum conditions for producing quality holes. Evaluation of the presented approach for process design is conducted using carbon fiber reinforced epoxy (IM7/977-3) composites over 6Al-4V titanium alloy (AB1) structure. The proposed study helps in approving the effectiveness of the new approach and in exploring the global optimum drilling parameters for damage free production of aerospace hybrid structures.

Keywords: Drilling process; Hybrid structure; Polymer composites over titanium alloy; Process maps, Response surface methodology

Introduction

New designs for modern aircraft require the use of hybrid structure, a combination of the ultra-light weight polymer composite skin with the high strength Titanium stiffeners. Such designs necessitate drilling of large number of holes in both materials during the assembly of aerospace hybrid structures as in the case of the newly developed Boeing 787. Several investigators have reported results earlier on the machining of single layer polymer composites. Emanuel and El-Gizawy have conducted extensive work in characterization of process behavior in drilling polymer-matrix composites [1-3]. Figure 1 summarizes their results on process-induced damage characterization during drilling of carbon fiber reinforced epoxy composites. It displays the effect of different rotational speed and feed of the drilling tool on generated damages (cracks and delamination of the reinforced fibers in addition to surface quality of the drilled holes [1]. Caprino and Taglieferi [4] showed that damage induced in the composite during drilling strongly depend on feed rate.

On the other hand, several studies have reported results on the drilling of single layer Titanium Alloys. Sharif and Rahim studied the effects of tool materials and machining parameters on the quality of drilled holes in Titanium Alloy-Ti-6Al-4V [5]. On a recent publication, Faqueh and El-Gizawy [6] concluded study on optimization of dimensional accuracy and surface finish in dry drilling of Ti-6Al-4V single plate. They presented their results on drilling process maps for Titanium Alloy that allow for selecting process conditions that satisfy both the required quality of produced holes and the productivity constraints.

Very few results are available on machinability particularly by drilling of hybrid aerospace structures. Redouane Zitoune et al. [7] carried out drilling trials in carbon-fiber reinforced plastics (CFRP)/ aluminum (Grade 2024) stack without coolant, with plain carbide (K20) drills of various diameters. Their qualitative results indicate that dimensional accuracy of the produced hales was diminished with increasing feed rate. On another publication by same authors [8], two types of tungsten carbide drills were used for drilling same materials stack as the one used in their earlier work, one with nano-coating and the other, without nano coating. They concluded that the shape and the size of the chips are strongly influenced by feed rate. The thrust force generated during drilling of the composite plate with coated drills was 10-15% lesser when compared to that generated during drilling with uncoated drills. According to the previous work by Ramulu et al. [9,10], some of the problems encountered with the quality characteristics of drilled composite-Ti stacks include severe tool wear, heat induced damage, hole size, roundness, shape, surface texture, and presence of titanium burrs. In their work, however, Ramulu et al. were interested in the effect of the different drilling parameters on thrust force, torque, and the presence of titanium burrs. The holes' dimensional accuracy under different drilling parameters was not evaluated. Moreover, the entire structure was drilled under the same speed and feed; a clear disadvantageous situation in industry since the composite requires a much higher speed and feed rate than titanium to avoid delamination, and titanium requires slower feed rates to avoid excessive tool wear and elevated temperatures.

Despite the extensive research in the field, existing results from single-layer machining simulations cannot be applied to multilayer machining cases, especially drilling. Vijayaraghavan et al. [11,12] discussed the challenges in modeling the machining of aerospace multilayered materials, which includes metal-composite stack ups. They showed that the modeling for multi-layered materials is different from that of single layered materials due to differences such as: multiple steady state assumptions, finite element (FE) models for single layered materials are inapplicable to burr morphology in multi-layered materials, and change of temperature properties across the work piece. The multilayer problem also brings about new machining parameters that do not exist in single layer machining operations such as clamping position and order of placement of materials for minimum burr formation. Choi [13] studied the effect of clamping position on gap formation during drilling of two sheets of SS 304L. He concluded that

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the clamping position only influences the elastic deformation while gap formation is due to plastic deformation that depends on the thrust force. The order of placement of the materials, on the other hand, is sometimes dictated by the nature of the manufacturing operation and cannot be changed. In this study, an approach combines surface response technique and optimization search method, is introduced for understanding the process behavior and selection of optimum parameters for drilling in aerospace multilayer structures.

Experimental System Design

Experimental system configuration

Figure 2 displays schematic of the experimental setup. A computer numerical control (CNC) milling machine was used for the drilling experiments. CNC codes were written for drilling holes on the planned positions and with the required experiment conditions. An in-house designed and fabricated fixture was bolted onto the CNC Mill table in order to firmly secure the multilayer structure on the device (Figure 3). A Torque/Force sensor, ACCUTORQUE, was selected for the present investigation. The ACCUTORQUE sensor is a strain gauge based stator/rotor sensor capable of measuring the torque and thrust force generated in a variety of machining applications. It consists of three major components: a stator, rotor, and a gain amplifier. In addition to the Torque/force sensor, a data acquisition system is provided in order to collect and organize all data obtained from the sensory system. Calibration of the force/torque sensor was accomplished using an available calibration mechanism. The calibration results for both force and torque displayed linear relationship with the output voltage signals.

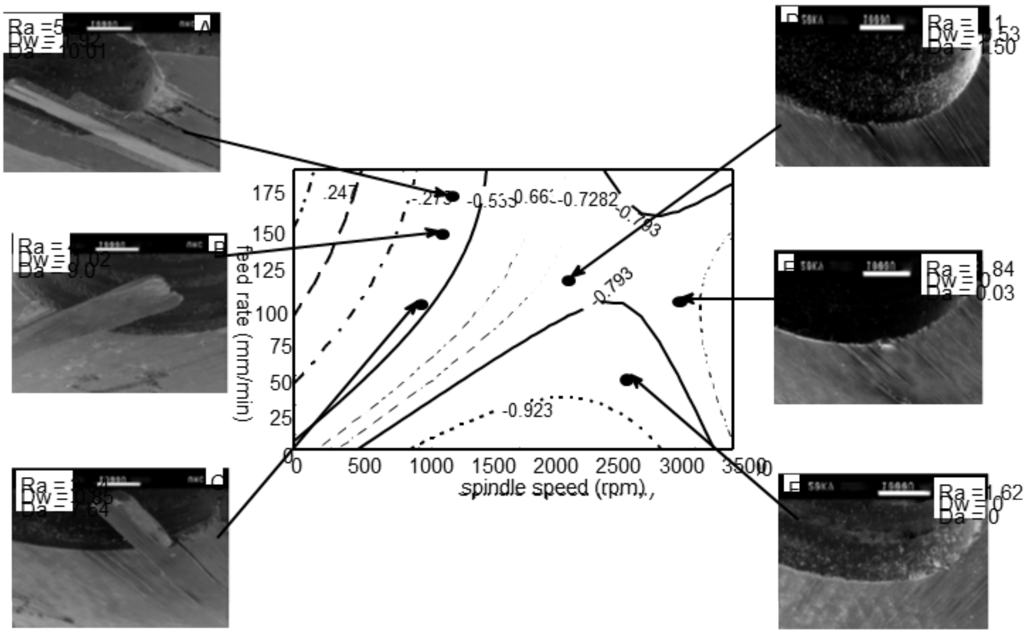

Figure 1: Effects of rotational speed and feed rate on process-induced damage in drilling carbon fiber reinforced epoxy composites [1].

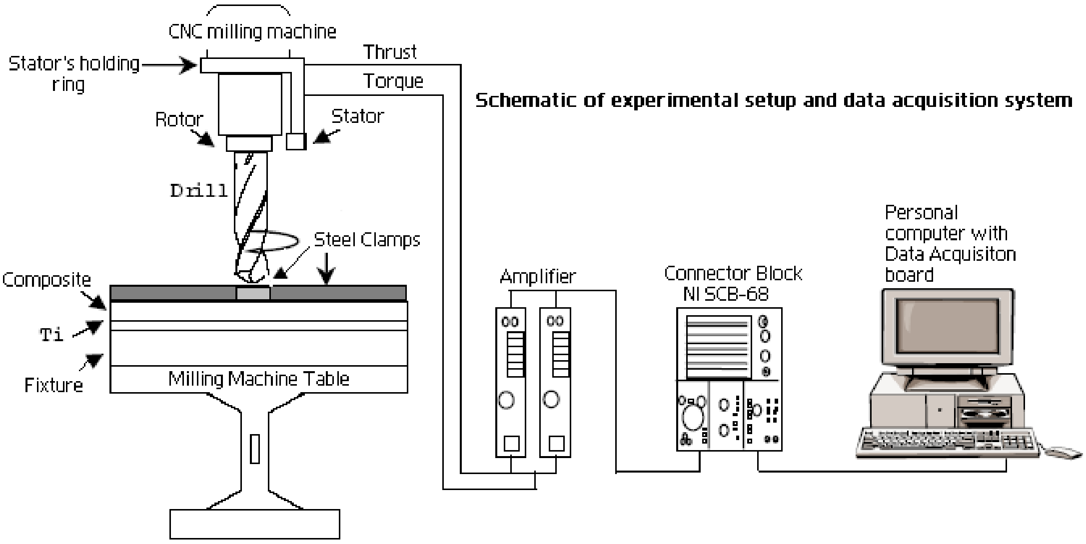

Figure 2: Schematic of the experimental setup.

Measurement techniques

Dimensional accuracy measurement: DP-4 touch probe by CENTROID (patent#6553682) was used to measure holes accuracy (Figure 4). Holes' accuracy was measured for both Composite and Titanium for each individual drill hole. The DP-4 probe was jogged over the center (roughly) of the hole, and then slowly the Z-axis was jogged down until the tip of the probe was inside the hole and not touching anything. The CNC controller was commanded to start the probing cycle. The stylus was jogged by the controller to each quadrant of the hole. It will then return to the center of the hole. A message box will appear on the screen that will display the measured diameter of the hole. The probe diameter and pre-travel distance were calculated by using a ring gauge with a 1.0000 inch (25.4 mm) Diameter before staring the experiment. The accurate compensation value was entered to the tool library in the CNC controller, so the value displayed for the diameter would represent the actual diameter value of the hole with the compensation already accounted for automatically.

Surface roughness measurement: Surface roughness of the drilled holes, were measured using a Mitutoyo Surftest 402 Profilometer which uses a ruby tip to contact the surface. Each hole was measured in four places approximately 90° apart. Table 1 displays the specifications of the used Profilometer.

Experimental Design and Procedures

Statistical design of the experiments

Two different techniques were used in the current investigation. Response surface with central composite design and Partial Factorial Design using Taguchi's Approach (Robust Process Design).

Response surface with central composite design

The response surface methodology (RSM) was used to design a set of experiments to capture the impact of the control parameters (feed and speed) on thrust force, torque, holes accuracy and surface roughness of the drilled holes. RSM methodology is useful for modelling and analysis in cases where the responses of interest are influenced by several factors and where the main objective is to optimize these responses. In this method a low order polynomial (Equation 1) is fitted between the response parameters of the process.

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_{12} X_1 X_2 + \beta_1 X_1^2 + \beta_2 X_2^2 \tag{1}$$

Where X_is are the input variables (speed, feed) that influence the response Y (holes tolerances, surface roughness, torque and thrust forces), β_0 and β_i are estimated regression coefficients. The method of least squares is then used to find the constants of the polynomials. In the present experiment, an RSM with central composite rotatable design with three center points are used. This design addresses the range of feeds and speeds for drilling titanium around the expected optimum values of the operation obtained during preliminary investigation of the same drilling process (Table 1). The cutting speed and feed for drilling the composite plates were kept constant for all tests, at their optimum values of 2300 RPM and 0.00784 IPR respectively. These conditions were established in an earlier comprehensive study by El-Gizawy et al. (Table 2) [1-3,6].

Partial factorial design using Taguchi's approach (Robust process design)

The goal of the Taguchi method is to identify the optimum settings for the different factors that affect the production process to yield a robust operation (minimum variability in performance). In this design the independent variables were the speed, feed and tool condition. The output or dependent variables were: surface roughness and holes' accuracy. Associated force and torque values for each experiment were also measured and recorded.

The responses obtained from different experiments were analysed using response tables and graphical representation of the mean effects of each parameter on the machinability characteristics. The response analysis helps in identifying those process parameters that have the greatest impact on process variability and its level of performance. In determining this, the Signal-to-Noise (S/N) Ratio Analysis was used. It uses a transformation method to convert the measured response into an S/N ratio. Proposed by Taguchi [14], S/N ratios are performance measures that optimize a process. The S/N Ratio Analysis also provides a sensitivity measurement of the machinability characteristics of a process at various levels of both controllable and uncontrollable or noise factors. The optimum process design is achieved when the S/N

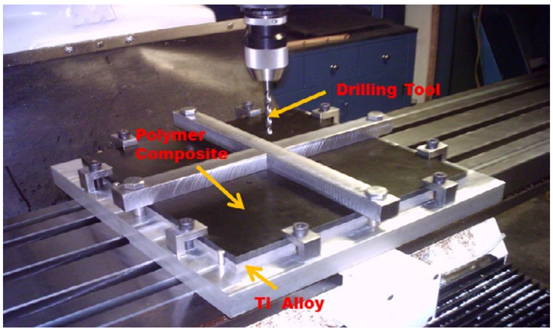

Figure 3: The experimental fixture for drilling process investigation of hybrid structure consisting of carbon fiber composite over Ti-6Al-4v alloy.

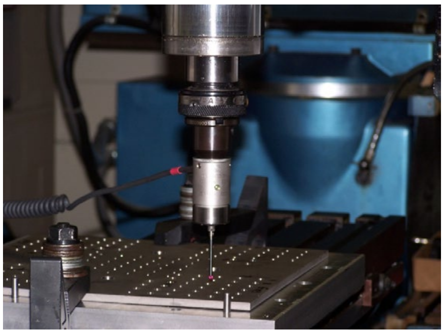

Figure 4: DP4-Probe used to measure holes dimensions.

Stroke	0.3 mm
Linearity	0.2 mm
Tip shape	Conical of 90°
Tip radius	5 μm
Force variance ratio	8 μm/1 μm
Curvature of radius of skid	30 mm(1.18")
Measuring force	4 mN or less

Table 1: Surface roughness measurements conditions.

Exp. #	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9(c)**	**10(c)**	**11(c)**	**12(c)**	**13(c)**
Speed (rpm)	500	500	600	600	480	621	550	550	550	550	550	550	550
Feed (ipr) $*10^{-3}$	1	1.44	1	1.44	1.2	1.2	0.89	1.51	1.2	1.2	1.2	1.2	1.2

Table 2: Experimental matrix using RSM.

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ratio is maximized. In other words, it is the process condition at which the variability, resulting from the uncontrollable factors, is minimized. In this phase of investigation, three levels were used for both: speed and feed. The expected optimum value was obtained from the first phase using RSM experiments, and the other lower and upper levels were obtained by decreasing and increasing the optimum value by 20%, respectively. Two levels were used for the tool condition either new or half-life tool. A half-life tool was used previously to drill 26 holes. A third level for tool condition (new tool) was also introduced in the experimental design in order to maintain balance of levels of all variables (orthogonal design). Tables 3 and 4 display the coded experiment matrix and the experimental log, respectively.

Investigation procedures

Investigated materials and tools: Composite Plates, made out of carbon fibers reinforced resin (IM7/977-3) were used. These composite plates were designed, fabricated and provided by The Boeing Company, St. Louis, Missouri after they were cut to dimension by water jet (12" x 12"x 0.379").

Titanium Plates, AMS-9046 plates were used. These are made out of 6Al-4V titanium alloy, also known as AB1. The yield strength is 120 ksi, while the ultimate strength is 130 ksi and elongation is 10%. These plates were also supplied by The Boeing Company, after being cut to dimension by water jet (12"x 12"x 0.279").

The Drill Bits, used are GUH051-00732006.350 manufactured by Guhring from Albstadt, Germany. It is a solid carbide ¼" drill with 118 degree point angle.

Experimental methods: The investigated hybrid structures of polymer composites over titanium alloy were first clamped together and secured inside the drilling fixture. Testing was then conducted by drilling the composite first at the recommended optimum conditions. No lubricant was used (dry drilling), and a vacuum was used for cooling and composite dust collection. Each experiment was replicated two times. Torque and force signals were recorded for all the holes in order to have more understanding of the process behavior. After the holes were drilled in the composite, Titanium was drilled with the holes having the same conditions drilled one after the other to minimize the error among replications due to tool wear. The lubricant supplied by Boeing was always used when drilling Titanium.

Following the drilling of all the holes, the diameters of the drill holes were measured, the readings of each pair of replications were averaged then the result was subtracted from the nominal diameter value of ¼" to get the diameter deviation from the nominal value. The surface roughness, R_a, of the drilled holes in the composite was measured for each hole using a Profilometer. Two readings 90° apart were taken then averaged for each hole after outliers were ignored. A significant variation in surface roughness was noticed in some cases among replications, so the average value of readings among each pair of replications was used in the analysis. After the data was collected, the results were interpreted using expert statistical software. The surface equations were obtained and differentiated to obtain the optimum condition of each of the independent variables, (speed and feed), corresponding to each of the dependent variables, (force, torque, hole accuracy and surface finish). The drilling procedure for Taguchi's approach followed the same procedure used for RSM.

Results and Discussions

Characterization of process behavior and optimization

Process maps for drilling hybrid structures of polymer composites over titanium alloy: Figure 5 displays a typical three dimensional surface relating the effect of the independent variables (speed and feed) on one of the quality characteristics of the process. In this plot, the maximum force value measured during drilling of titanium was selected as the major response. The process contour map for thrust force extracted from the surface plot is shown in Figure 6. Similar surface plots for the torque, the deviation of the diameter from the nominal value and surface roughness, were also generated from the results. The corresponding process contour maps were also constructed in the same fashion as the thrust force map displayed in Figure 7. Figure 8 represents a contour map for the generated torque during drilling of the composite plate. Figure 9 displays process contour maps of deviation of diameter of the machined holes (inch), from the nominal value in the composite plate. Figure 10 displays process contour maps of the surface roughness R_a, (μ-in) of hales in the composite. Figures 9 and 10 reveal the significance of the selected machining parameters for titanium in controlling dimensional accuracy and surface finish of the holes drilled in the composite plates. The results indicate that machining condition for titanium that lead to longer continuous chips will be detrimental to dimensional accuracy and surface finish of holes machined in the composite plate. Titanium chips smear and alter the interior surface of the composite holes.

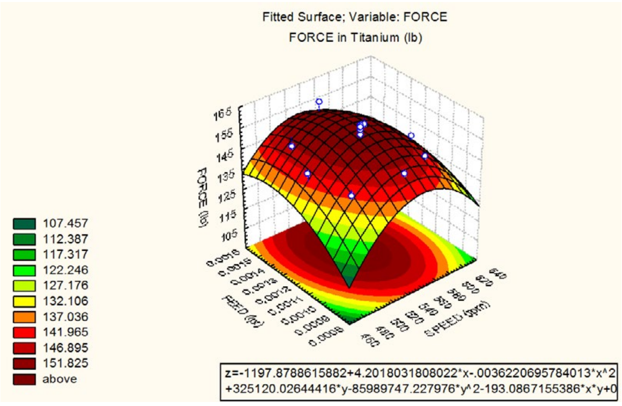

Figure 5: Fitted 3-D surface and equation of the force, (lbs), in titanium.

Exp. #	Speed (rpm)	Feed (ipr)	Tool
1	1	1	1
2	1	2	2
3	1	3	1'
4	2	1	2
5	2	2	1'
6	2	3	1
7	3	1	1'
8	3	2	1
9	3	3	2

Table 3: Coded experimental matrix.

Exp. #	Speed (rpm)	Feed (ipr)	Feed (ipm)	Tool
1	496.56	0.000832	0.413138	T_{new}
2	496.56	0.00104	0.516422	$T_{1/2}$
3	496.56	0.001248	0.619707	$T_{new(d)}$
4	620.7	0.000832	0.516422	$T_{1/2}$
5	620.7	0.00104	0.645528	$T_{new(d)}$
6	620.7	0.001248	0.774634	T_{new}
7	744.84	0.000832	0.619707	$T_{new(d)}$
8	744.84	0.00104	0.774634	T_{new}
9	744.84	0.001248	0.92956	$T_{1/2}$

Table 4: Experimental Log with actual values.

Desirability contours: A typical problem in process development is to find the set of levels of the controlled or independent parameters that yield the most desirable characteristic of the product. The procedure used to tackle this problem involves two steps [6]:

1. Predicting responses on the dependent parameters by fitting the observed response using an equation based on the levels of the independent variables.
2. Finding the levels of the input variables that simultaneously produce the most desirable predicted response on the output variables.

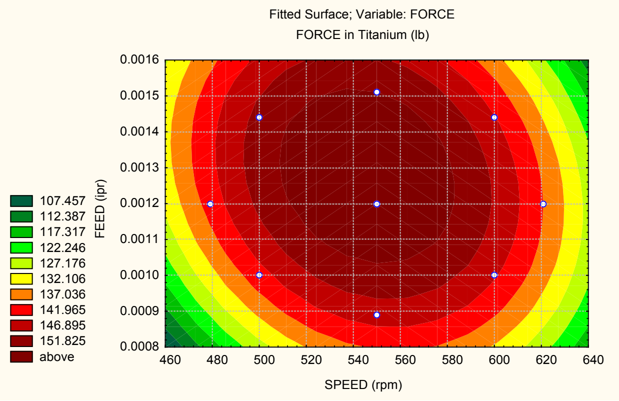

Figure 6: Process contour maps of thrust force (lb.), during drilling titanium.

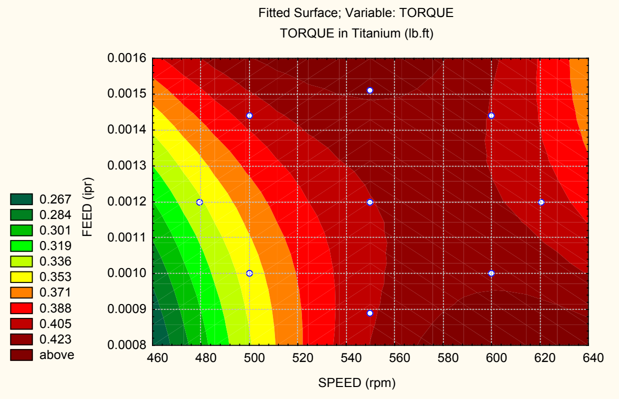

Figure 7: Process contour maps of torque, (lb.ft), during drilling titanium.

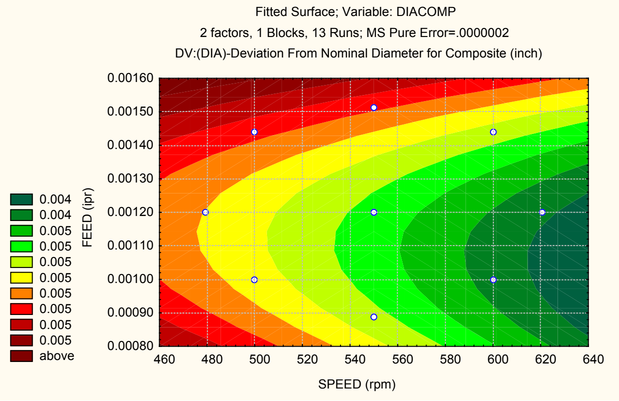

Figure 8: Process contour maps of deviation of diameter, (inch), from the nominal value in the composite.

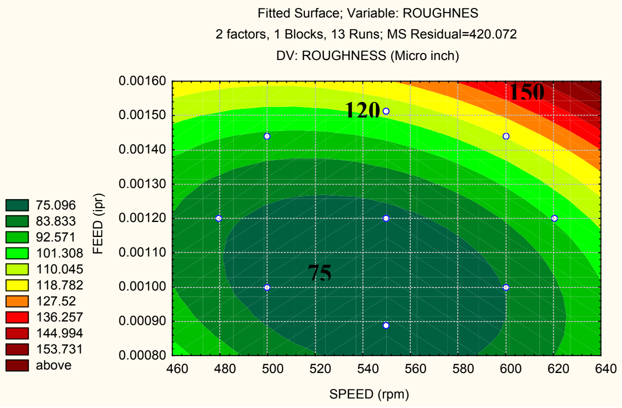

Figure 9: Process contour maps of the surface roughness R_a, (μ.in), of holes in the composite.

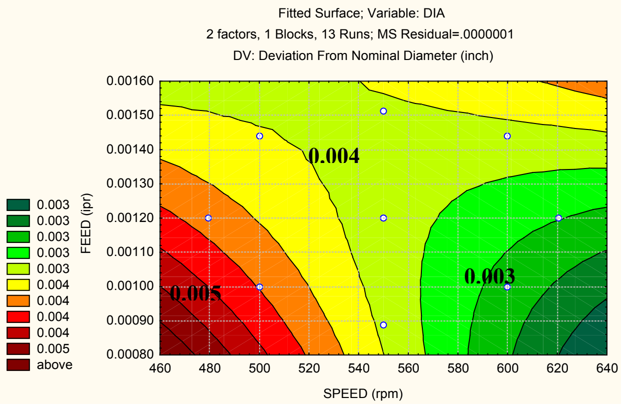

Figure 10: Process contour maps of deviation of diameter, (inch), from the nominal value in titanium.

A prediction profile for a dependent variable consists of a series of graphs, one for each independent variable, of the predicted values for the dependent variable at different levels of one independent variable, holding the levels of the other independent variables constant at specified values, called current values. Inspecting the prediction profile can show which levels of the predictor variables produce the most desirable predicted response on the dependent variable. The number of levels at which to compute predicted values for each independent variable was set to twenty grid points.

It can be seen in Figure 11 that the desired minimum value of force corresponds to a feed of 0.00151 ipr, and a speed of 620.71 rpm. However, from the convergence plot at the bottom of the graph, it can be seen that the force is very close to convergence at rather a much lower feed of 0.00089 ipr. Same thing is noticed about the convergence for the optimum speed. It is very close to converging at a lower speed of about 479.29 rpm. This delay in convergence is attributed to experimental errors. Having more repetitions should lead to better convergence behavior.

As for the torque, Figure 12 shows that the optimum conditions to obtain minimum torque are 0.00089 ipr feed, and 578.28 rpm speed. At higher rpm the desirability function stays almost the same indicating that after reaching the optimum speed any increase in speed won't reduce the torque value any further.

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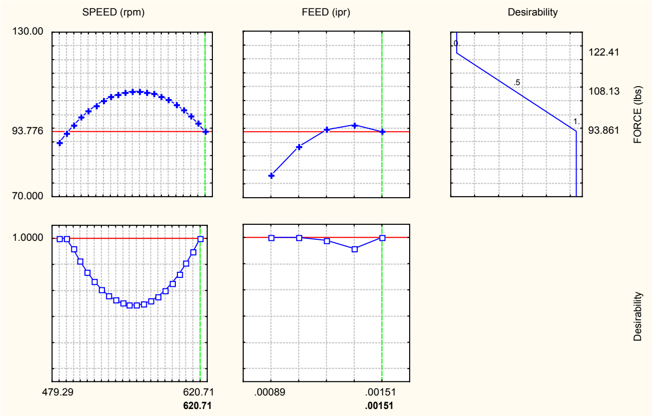

Figure 11: Desirability contours for minimizing force in titanium.

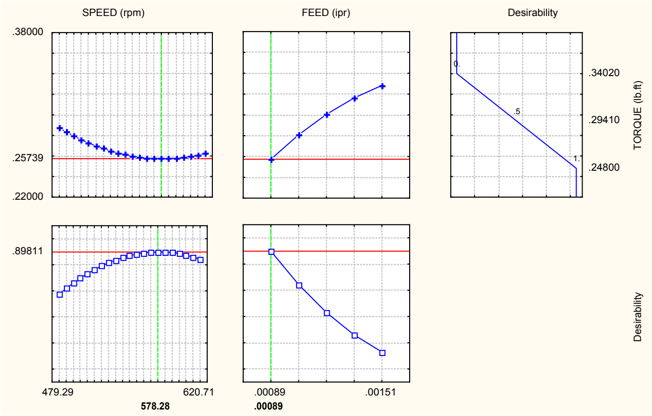

Figure 12: Desirability contours for minimizing torque in titanium.

Robust process design: The S/N ratio was calculated for each output observation using the following equation:

$$\eta_i = -10\log_{10} y_i^2$$

Where η_i is the ith transformed output, y_i is the ith untransformed output. After all the data was transformed using the above expression, the effects of each factor were calculated and tabulated. The effect of each factor was calculated using the expression:

$$A_i = \left(\sum_{j=1}^{n} A_{ij} \right) / n$$

Where A_i is the effect of factor A at level i. and n is the number of observations where level i of factor A occur. A_{ij} represent transformed outputs of factor A at level i. Table 5 and Figure 13 display main effects of different control parameters and their investigated levels calculated using the above equations with the diameter data in the composite. The analysis indicates that a speed of 496.56 rpm, a feed of 0.001248 and a sharp tool yield a process that will produce robust hole tolerances in the composite.

Holes surface roughness in composite is the other quality characteristic considered in this analysis. The results are plotted in Figure 14. The general conclusion is that low speed, intermediate feed and new (sharp) tool would give robust performance with very low variability in surface roughness in machined holes of the composite side. Specifically, a speed of 496.56 rpm, a feed of 0.00104 inch/rev., and a sharp tool in drilling Titanium will yield robust surface finish in the composite.

Conclusions

An experimental approach for development of damage-free drilling of hybrid structures of polymer composites over titanium alloy was established and verified. The present approach involves statistical design of experiments to develop the process knowledge base and multi-objective optimization techniques in order to account for the contribution of the major process quality responses (dimensional accuracy, surface finish and process-induced defects) and to allow for an effective trade-off among all competing machinability characteristics. Evaluation of the present approach was conducted using carbon fiber reinforced epoxy (IM7/977-3) composites over 6Al-4V titanium alloy (AB1) structure. The study proved the effectiveness of the new approach in selecting the global optimum drilling parameters for damage free production of hybrid structures of polymer composites over titanium alloy.

The results generated from the present approach were used for constructing process maps for the machinability of hybrid structures of polymer composites over titanium alloy. These maps are effective tools that can be used by industry as road maps in selecting process designs that satisfy both quality requirements and productivity constraints. Optimum drilling process design for hybrid structures of polymer composites over titanium alloy has been explored. The present study reveals the followings**:**

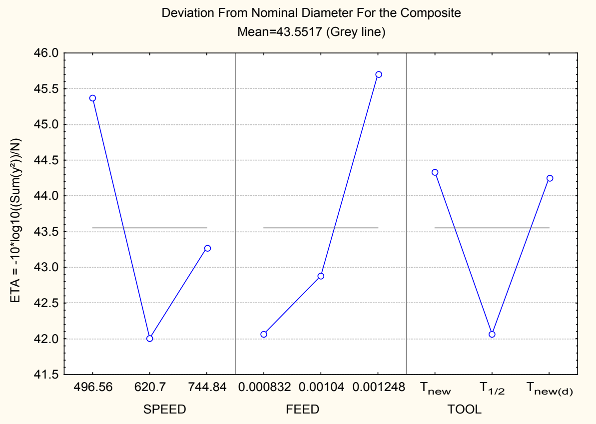

Figure 13: Plot of S/N (ETA) main effects on holes tolerances of composite.

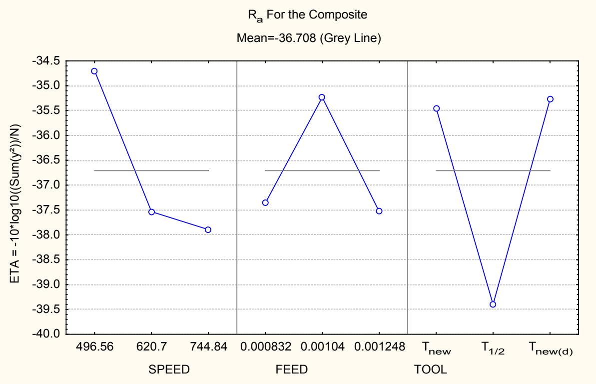

Figure 14: Plot of S/N (ETA) main effects on holes surface roughness of composite.

Composite Exp. #	Speed(rpm)	Feed(ipr)	Feed(ipm)	Tool	Untransformed Dev From Nom.(y_i)	Transformed Dev. From Nom. (η_i)
1	496.56	0.000832	0.413138	T_{new}	0.00580	44.731440
2	496.56	0.00104	0.516422	$T_{1/2}$	0.00805	41.884082
3	496.56	0.001248	0.619707	$T_{new(d)}$	0.00335	49.499104
4	620.7	0.000832	0.516422	$T_{1/2}$	0.00965	40.309454
5	620.7	0.00104	0.645528	$T_{new(d)}$	0.00785	42.102607
6	620.7	0.001248	0.774634	T_{new}	0.00660	43.609121
7	744.84	0.000832	0.619707	$T_{new(d)}$	0.00875	41.159839
8	744.84	0.00104	0.774634	T_{new}	0.00585	44.656883
9	744.84	0.001248	0.92956	$T_{1/2}$	0.00630	44.013189

Table 5: Experimental data for holes tolerances of composite.

a. In general high speed of 2300 rpm and low drilling feed of 0.00784 inch per revolution are recommended for the production of delamination-free and good surface finish holes with the required dimensional accuracy, in the epoxy composites.

b. An optimum drilling speed of 600 rpm and feed of 0.0012 inch per revolution are recommended for production of quality holes in the titanium layer while maintaining the quality of the holes initially generated in the composite layer.

c. Drilling the titanium layer with a lower speed of 500 rpm and a feed of 0.0010 inch per revolution while maintaining sharp tools during the process would lead to a robust process performance with minimum variability.

Acknowledgements

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