Scientific Journal of Impact Factor (SJIF): 4.14

e-ISSN : 2348-4470
p-ISSN : 2348-6406

International Journal of Advance Engineering and Research Development

Volume 3,Issue 5,May -2016

Optimization of Drilling Parameters for PMMA Acrylic

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Abstract: *PMMA is a very useful material in a biological surgery and for bone replacement. Also, it is highly used in research work, marine, aerospace, furniture because of its high mechanical properties and in corrosive properties. The RSM L20 array method of DOE is used to optimizing the drilling parameters for PMMA 8mm sheet and 8mm drill bit diameter. From this experiment it has been conclude that the 115 degree of point angle, 2000rpm spindle speed and 40 mm/rev feed is optimum for thrust force. 90 degree of point angle, 2500 rpm spindle speed, and 35 mm/min feed is optimum for the torque. 140 degree point angle, 1500rpm spindle speed and 35 mm/min feed is optimum for circularity.*

Keywords: *point angle, Drill tool dynamometer, Aerospace material, PMMA, circularity*

1.1. INTRODUCTION

Composite materials are used in industrial fields, such as aerospace, aircraft, automobile and sports, owing to their advantages in mechanical properties. However, it is difficult to machine composite materials with high efficiency to yield good-quality products. Conventional drilling with twist drill still remains one of the most economical and efficient machining processes for hole making as well as for riveting and fastening structural assemblies in the aerospace and automotive industries. During the past four decades, researchers have developed many types of drills, including multifaceted drill, saw drill, candlestick still, core drill, step drill and trepanning drill, all aimed at making better holes. With increasing demand for advanced composite materials, not only new concepts of tooling but also different realms of cutting conditions are needed. The step-core drill was developed for the same reason. Delamination is the most common defect during drilling due to the heterogeneity of both fibers and matrix. A few studies have proved that delamination is related to the thrust force in drilling composite material. The contribution of chisel edge to the thrust force for twist drill is often up to 40–60% of the total thrust force. The shorter the chisel edge, the smaller the thrust force will be. Pre-drilled, back-up plates and special drills can reduce delamination when drilling composite materials. Armarego and Wright found that the effects of feed rates, spindle speeds and the geometrical characteristics of the three drills on the resulting torque and thrust values are comparable regardless of the three different drill flank configurations used. DiPaolo et al. conducted an experiment to investigate the size of delamination region during drilling, which is confirmed to be related to the thrust force developed at the drill exit. Most of the published and manufacturers' literature correlates the drill material, drill geometry and feed rate to the delamination produced by twist drill. Hocheng and Tsao compared theoretical predictions of critical thrust force with experiment results at the onset of delamination for various drills, such as saw drill, candlestick drill, core drill and step drill. They found that among various drills, core drill allows for the largest drilling feed rate to avoid delamination. In general, the core drill is applied for drilling hard brittle materials, as in civil engineering structure, jewels and glass. However, the removal of chips poses problems when using the core drill. To resolve this, the step-core drill is designed to reduce chip removal in drilling. Although significant efforts have been devoted to understanding the drilling-induced delamination of twist drill, there have been few papers reporting the effect of step-core drill in drilling composite materials. Hence, this study aims to examine experimentally the drilling-induced thrust force of composite materials when using step-core drill.

PMMA (Polymethyl methacrylate) stands out from other plastics due to its high light transmission, it's extremely long service life, its specific properties such as high resistance to UV light and weathering and unlimited coloring options. Added to this, PMMA shows the greatest surface hardness of all thermoplastics. It can be fabricated by means of all thermoforming methods, and therefore offers huge creative scope. Another major benefit is that PMMA is 100% recyclable, which makes an essential contribution to saving natural resources.

Problem definition:

PMMA material is widely used for delicate furniture and in the different industries. PMMA material has nearer equivalent properties of bone and there is no any other material available near this value. PMMA is an alternative solution for bone when it is damaged or broken. So that's why it machining is important for surgery and also for delegating furniture and interior. For that optimizing is playing a measure role in the drilling operation of PMMA.

Objectives and Goal:

The main objective of this study is to improve the machining quality of PMMA. Study the significant effect of parameters on the machining quality and optimize the parameter using RSM Method of DOE.

Survey of Literature

To study the effect of various drilling parameters on the hole quality is reviewed by following research study:

Irfan Khan et al. working on "Selection of optimum Drilling Parameter in Drilling of commercial Acrylic sheet to achieve minimum Hole Expansion by using Taguchi Approach". They observed that accuracy of the hole depends upon the various factors such as cutting speed, feed, tool geometry, work material and thickness of the work piece to be drilled. During the drilling operation heat is generated at tool work interface, which tends to decrease the accuracy of the hole. They use Taguchi method to achieve the minimum hole size expansion in drilling of **acrylic sheet**. They measure effect of cutting parameters, such as cutting speed and feed rate, and point angle on hole size(without considering the thermal effect). A plan of experiments, based on L9 Taguchi design method was made and drilling was done with the selected cutting parameters. All tests were run at cutting speeds of 660, 1115 and 1750 r.p.m. and feed 0.04, 0.08, and 0.15 mm/rev and point angle of 90°, 118°, and 140°. The optimum level for spindle speed, feed rate and tool angle are observed at v =1750 rpm, f =0.15, θ =118° .

Rana M. Taha et al. worked on "hole drilling in polymethyl methacrylate (**PMMA**) using co2 laser". The hole depth, width and penetration velocity of evaporation depend on different constraints such as power, material, exposure time, distance between drilling tool and the material, the drilling tool, etc. They used laser beam as drilling tool. 16W CO_2 laser (10.6μm) and transparent Perspex (PMMA) work piece with 8mm thickness were used. The distance between laser beam and the material was 5cm. Different powers for CO_2 laser were used for different exposure time. The most suitable power for drilling a hole in a PMMA workpiece with 8mm thickness using a CO_2 laser working in CW mode was 2W, where in this value of power, a maximum value of the aspect ratio was achieved by them in this study.

Rupeshkumarpandey et al. worked on "Modelling and optimization of temperature in orthopaedic drilling: An in vitro study". They use the Taguchi and response surface methodology (RSM) for modelling and optimization of the temperature produced during bone drilling. The drilling of bone is a common procedure in orthopaedic surgery to produce hole for screw insertion to fixate the fracture devices and implants. They found major problem which encountered during such a procedure is the increase in temperature of the bone due to the plastic deformation of chips and the friction between the bone and the drill. The increase in temperature can result in thermal osteonecrosis which may delay medicinal or reduce the stability and strength of the fixation. They conducted drilling experiments on poly-methyl-meth-acrylate (PMMA) (as a substitute for bone) using Taguchi's L27 experimental design technique. The cutting parameters used are drill diameter, feed rate and cutting speed. They established a second-order model between the drilling parameters and temperature using RSM. The experimental results show that the drill diameter is the most significant drilling parameter affecting the temperature during drilling followed by cutting speed and feed, respectively. The values predicted and the values obtained from experiment are fairly close, which indicates that the developed RSM model can be effectively used to predict the temperature in orthopaedic drilling. Optimal cutting condition for minimum temperature is drill of diameter 6 mm, feed rate of 35 mm/min and spindle speed of 1500 rpm.

Rupeshkumar Pandey et al. worked on "Predicting Temperature in Orthopaedic Drilling using Back Propagation Neural Network". This work deals with the prediction of temperature in orthopaedic drilling using back propagation neural network. Drilling of bone is common to prepare an implant site during orthopaedic surgery. The increase in temperature during such a procedure increases the chances of thermal invasion of bone which can cause thermal osteonecrosis. Drilling operations have been performed in PMMA (as a substitute for bone) work-piece by high- speed steel (HSS) drill bits over a wide range of cutting conditions. Drill diameter, feed rate and spindle speed are used as input for the back propagation neural network whereas temperature is taken as output. The performance of the trained neural network has been tested with the experimental results. Good agreement is observed between the predictive model values and experimental values. Network with 5 neurons in the hidden layer is found to be optimal. Increasing the neurons beyond it increases the complexity of the system as indicated with increase in MSE.

M.M. Hanon et al. Worked on "Comparison between Practical and Theoretical Investigations of Laser Drilling". This paper presents a comparison between the behavior of two different laser drilling processes, The first is a practical drilling application of the alumina ceramic with thickness of 2.2 mm using Nd:YAG laser, whereas the other is a simulation of the transient heat transfer using COMSOL Multiphysics 3.5a for drilling PMMA substrate of thicknesses of 2.5 mm. For Experimental work, Effects of the laser peak power, pulse duration and repetition rate, have been determined using optical images taken from the inlet and outlet of the samples. Different laser beam parameters have been used for the laser drilling process of alumina ceramic. Concerning the simulation, the beam parameters used for this study are selected to simulate drilling process. Effects of laser output power and exposure time have been carried out via the studying of the temperature distribution on the cross section of the substrate to determine the optimum conditions obtained from the combination of parameters that improves hole quality. It has been indicated that the results behaviour of the practical and simulation of this work are in good agreement when compared to each other. Concerning to the simulation, craters have remained a blind hole when the laser output power and the exposure time used 0.96 W and 2 s respectively, while full holes have been investigated when the laser beam reached up to 1.82 W output power and 3 s exposure time.

Rupesh Kumar Pandey &S.S.Panda at al. Worked on "Optimization of Orthopaedic Drilling: A Taguchi Approach". It is important to minimize the thermal invasion of bone during drilling. They applied Taguchi method to investigate the optimal combination of drill diameter, feed rate and spindle speed in dry drilling of PMMA for minimizing the temperature produced. They found that the diameter has the highest influence on temperature produced during drilling PMMA, followed by the spindle speed and feed rate respectively. The optimal combination of the control factors is A1B2C1 for minimum temperature generation, i.e. drill of diameter 6 mm, feed rate of 35 mm/min and spindle speed of 1500 rpm.

Irfan Khan el al. Worked on "Optimization of burr height in drilling of commercial Acrylic sheet using Taguchi method." They worked to investigate the influence of cutting parameters, such as cutting speed and feed rate, and point angle on burr height produced when drilling acrylic sheet by Taguchi experiment. A plan of experiments, based on L9 Taguchi design method, was made and drilling was done with the selected cutting parameters. All tests were run at cutting speeds of 660, 1115 and 1750 r.p.m. and feed 0.04, 0.08, and 0.15 mm/rev and point angle of 90°, 118°, and 140°. The orthogonal array, signal-to-noise ratio, and analysis of variance (ANOVA) were employed to investigate the optimal drilling parameters. It was found that higher cutting speeds and higher feed rate produces better results with higher tool angle 140˚.

Design of Experiments

Design of experiments (DOE) is a systematic, rigorous approach to engineering problemsolving that applies principles and techniques at the data collection stage so as to ensure the generation of valid, defensible, and supportable engineering conclusions. In addition, all of this is carried out under the constraint of a minimal expenditure of engineering runs, time, and money.DOE is one of the most important techniques for systematic planning, execution and structural evaluation of the experiments.

There are four general engineering problem areas in which DOE may be applied

1. Comparative
2. Screening/Characterizing
3. Modeling
4. Optimizing

In the Comparative, the engineer is interested in assessing whether a change in a single factor has in fact resulted in a change/improvement to the process as a whole.

In the Screening Characterization, the engineer is interested in "understanding" the process as a whole in the sense that he/she wishes (after design and analysis) to have in hand a ranked list of important through unimportant factors (most important to least important) that affect the process. In the Modeling, the engineer is interested in functionally modeling the process with the output being a good-fitting (high predictive power) mathematical function, and to have well (maximum accuracy) estimates of the coefficients in that function.

In the Optimizing, the engineer is interested in determining optimal settings of the process factors; that is, to determine for each factor the level of the factor that optimizes the process response.

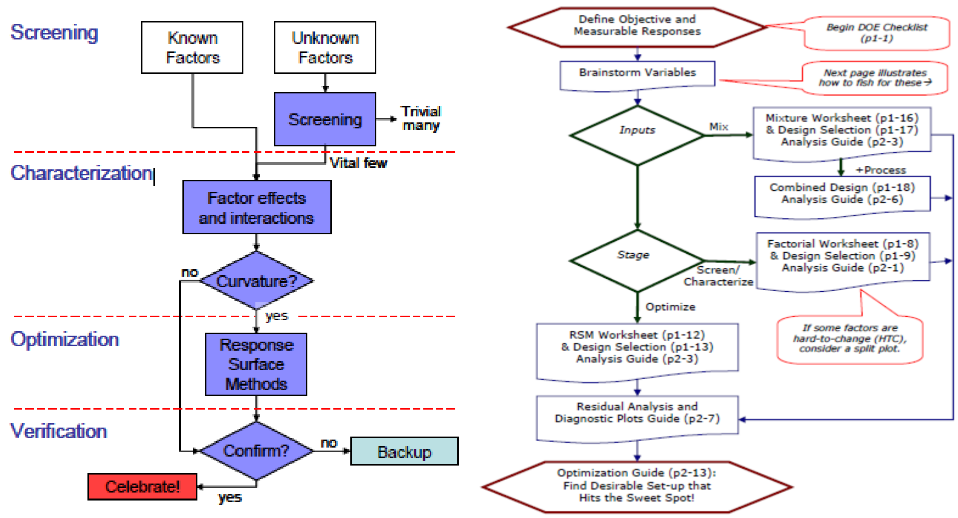

Figure 1 Schematic flow charts of DOE

Research Methodology

This research study has been divided in three steps:

In the first step define the area for the research study and our main focus is to improve the machinability and optimization of parameter. From the wide area of machining operation this study has been focused on drilling machine parameter optimization for PMMA(Poly methyl methacrylate)material which is known as Plexiglas. To find out the research gap certain literatures has been reviewed. Design of Experiment method is used for this optimization. There are three parameters and three level array has been designed for RSM method. Machining parameters selected for this study is focused to drilling parameters for 8mm PMMA such as speed, feed, and point angle of drill as input. The torque, surface roughness and circularity for drilling of hole will be measured with help of dynamometer, surface roughness tester and universalMeasuring Microscope.

RSM Method has been used for the minimizing the hole expansion in the drilling of PMMA sheet Taguchi recommends analysing the mean response for each run in the inner array, and he also suggests analysing variation using an appropriately chosen signal-to-noise ratio (S/N). These S/N ratios are derived from the quadratic loss function, and three of them are considered to be standard and widely applicable. These are:

(1) Lower is best, (2) Higher is best, (3) Average is best Our target is to achieve minimum hole expansion so we have used lower is best which is

$$\frac{S}{N} = -10\log\left\{\frac{1}{N}\sum_{I=0}^{N} y^2\right\}$$

(2) There lower S/N ratio corresponds to a better performance. So, the optimal level of the process parameters is the level with the lowest S/N value.

Three machining parameters were selected as control factors, and each parameter was designed to have three levels, denoted by 1, 2, and 3. The experimental design was based on L27 (3*3*3) orthogonal array for RSM method. There three level designed for different factors for PMMA sheet[10] spindle speed 660-1115–1750 rpm, feed rate 0.04–0.08–0.15 mm/rev and point angle of 90-118 - 135forPMMAsheetof 6mm thickness. Circularity, surface roughness and thrust force have been observed as an output. This study will be carried out for the influence of the cutting tool geometry, material thickness, feed and speed on the thrust force and delamination produced when drilling a PMMA. Sample of data will be obtained from the dynamometer for HSS tools are compared and computed.Each sheet of PMMA (300 x 600 x 4 / 6 / 8 mm) will have drilling operation carried out on Radial drilling Machine.

Experimental setup

The experimental work has been carried out to optimizing the affecting parameters on the PMMA drilling. PMMA is the highly recommended material for dental surgery, orthopedic surgery, interior furniture, aero space material and many more. PMMA have Mechanical properties nearer to the bone properties and no any other material is nearest to the PMMA. So it is widely used to replacing the bone. This study is focused on the optimization of drilling parameters of the PMMA with the used of RSM Design of Experiment Method. The parameters at designed for three level optimization at point angle 90˚,115˚, 140˚; feed at 35, 40,45 mm/min; and speed at 1500rpm, 2000rpm, 2500rpm. the experiment has been carried out on the vertical CNC milling machine JYOTI PX-10 at CSPIT college - Changa, The response for this optimization taken by drill tool dynamometer for thrust force and torque, and circularity has been measured by electron microscope. The workpiece of PMMA is having a dimension of 40 x 75 x 8 mm and marked by experimental Runs from R1, R2,……R20 for batter convenience. Three different point angle tools have been purchased from the manufacturer 90˚, 115˚, and 140˚. The RSM array L20 has been designed for performing the experiment.

Figure 2 CNC Vertical Milling machine used in Experiment for drilling

Table 1 Designed L20 array of RSM for PMMA drilling

SR	Point Angle	Feed mm/min	Speed rpm	Point Angle	Feed mm/min	Speed rpm
1	0	0	-1	115	40	1500
2	-1	-1	-1	90	45	1500
3	1	-1	1	140	45	2500
4	0	0	0	115	40	2000
5	0	0	0	115	40	2000
6	-1	1	1	90	35	2500
7	1	1	1	140	35	2500
8	0	0	0	115	40	2000
9	1	-1	-1	140	45	1500
10	-1	0	0	90	40	2000
11	-1	-1	1	90	45	2500
12	0	0	0	115	40	2000
13	-1	1	-1	90	35	1500

14	1	0	0	140	40	2000
15	0	0	0	115	40	2000
16	0	0	0	115	40	2000
17	0	-1	0	115	45	2000
18	0	1	0	115	35	2000
19	1	1	-1	140	35	1500
20	0	0	1	115	40	2500

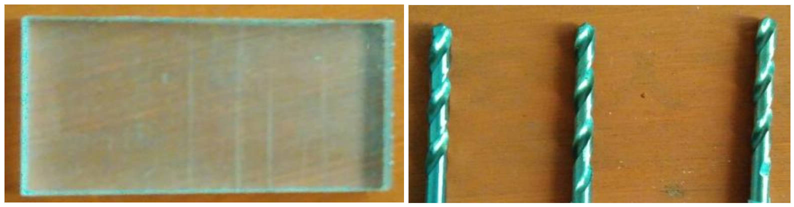

Figure 3 Work piece for experiment &Drill bits for Experiment

Figure 3 shows the cutting size of PMMA sheet of 40 x 75 x 8 mm for experiment and different point angle of 8mm diameter HSS drill bits used in this experiment. The point angle used for this experiment is 90 degree, 115 degree and 140 degree.

Figure 4Experimental setup

It is desired to reduce the size of sheet to fix it onto the dynamometer. Dynamometer is used from CSPIT_college, changa, Gujarat which is supplied by Muttutoyo Company. The capacity of drill tool dynamometer is 200KgF Thrust force, 10Kgm Torque, fixture size is 3". It is used to measure thrust force, torque in the experiment during drill the hole. For the experimental work drill tool dynamometer is fixed onto the CNC vertical Milling machine bed by given flange. Desired drill bit is inserted into the drill chuck of the VMC Machine. From R1,R2,…..R20 number of cutting PMMA sheet insert onto the dynamometer one by one as per designed run and fix it by given fixture. Then start the program for drilling the hole. Change the drill bit after completing its operation for different speed and feed.

5.1. Results and Discussion:

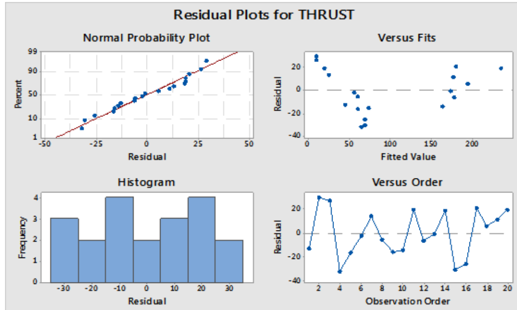

Figure 5 Residual plots for Thrust

Figure 5shows the residual plots for thrust force. It has been observed that all the resultant points are nearer to the regration line and for that our design model is acceptable for thrust force.

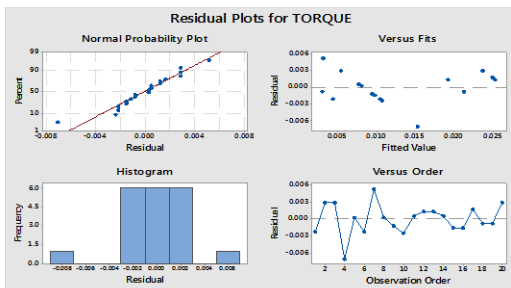

Figure 6 Residual Plots for Torque

Figure 6 shows the residual plots for torque. It has been observed that all the resultant points are nearer to the regration line and for that our design model is acceptable for torque.

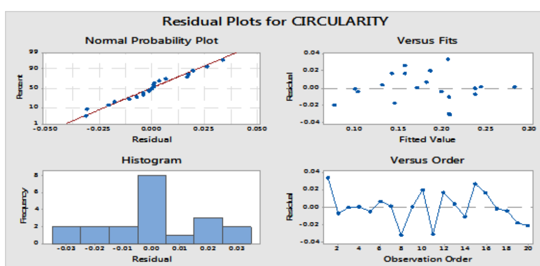

Figure 7 Residual Plots for Circularity

Figure 7 shows the residual plots for circularity. It has been observed that all the resultant points are nearer to the regration line and for that our design model is acceptable for circularity.

Circularity

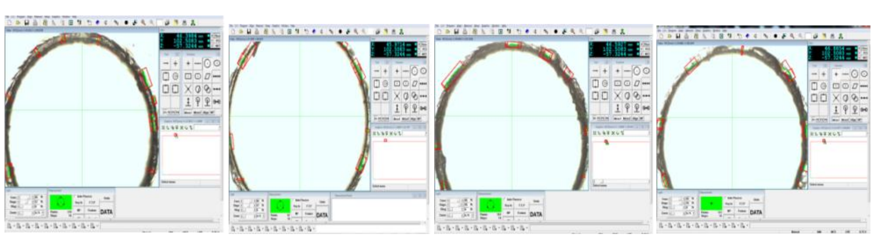

Figure 8 Photographic view of circularity measurement in 3D microscope(R10, R13, R15 and R17)

Figure 8 shows the photographic view of different circularity (delamination) results for the experiment R10, R13, R15 and R17. From the all observation it has been noticed that higher cutting angle gives the better results in circularity.

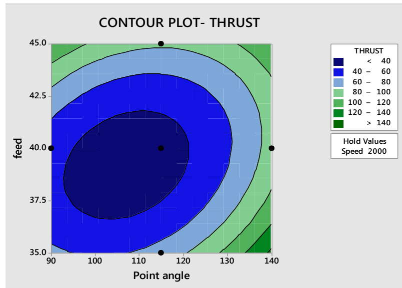

Figure 9 Contour plot for Thrust VS feed and Point angle

Figure 9 shows the contour plot for thrust VS feed and point angle. It shows that the optimum value of thrust force is gain in 90 to 105 point angle and 35 to 40 mm/min feed. It has been observed that the increase in point angle and feed from optimum value the thrust force is increased.

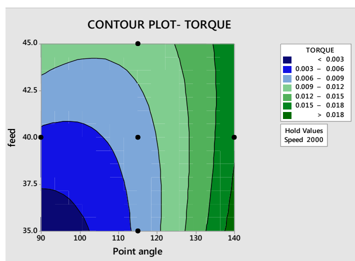

Figure 10 Contour plot for Torque VS feed and Point angle

Figure 10 shows the contour plot of torque vs feed and point angle. It has been observed that the optimum value of the torque gain in 90 to 100 degree point angle and 35 to 37.5 mm/rev feed. From this figure it has been observed that the increase in point angle and feed torque value is increasing.

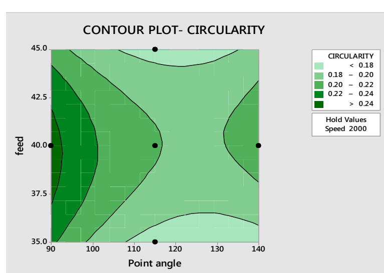

Figure 11 Contour plot for Circularity VS feed and Point angle

Figure 11 shows the contour plot for circularity vs feed and point angle. It has been observed that the point angle 110 to 140 gives the optimum circularity and minimum feed 35 to 36 gives the optimum circularity. From this figure it has been observed that the increasing the point angle and lowest feed gives optimum circularity.

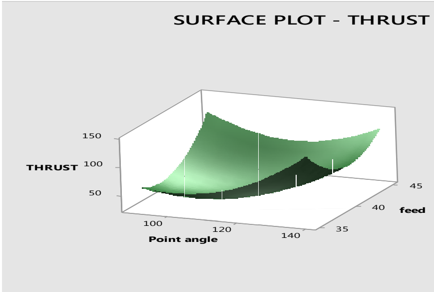

Figure 12 Surface Plot for Thrust Vs feed and point angle

Figure 12 shows the surface plot for thrust force vs point angle vs feed. Form this figure it has been observed that the optimum value of thrust force gain low point angle and medium feed. It has been conclude that the increase the point angle the thrust force is increased and at the medium feed thrust force is optimum.

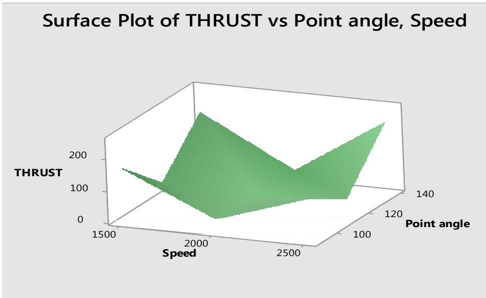

Figure 13 Surface plot for thrust force Vs speed and point angle

Figure 13 shows the surface plot for thrust force vs speed and point angle. It has been observed that the thrust force is optimum at medium speed and medium point angle. It has been conclude that the thrust force is higher at low and high point angle, and it is higher at low and high spindle speed.

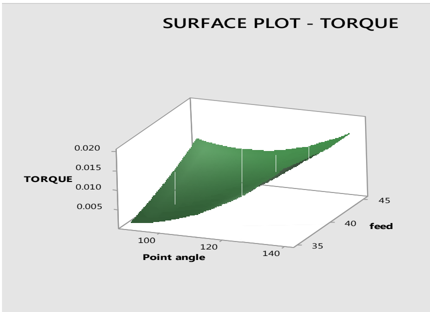

Figure 14 Surface Plot for Torque Vs feed and point angle

Figure 14 shows the surface plot for torque Vs feed and point angle. From this figure it has been observed that the minimum value of torque gain at minimum point angle and minimum feed. From this figure it has been conclude that increasing the feed and point angle gives the higher torque force.

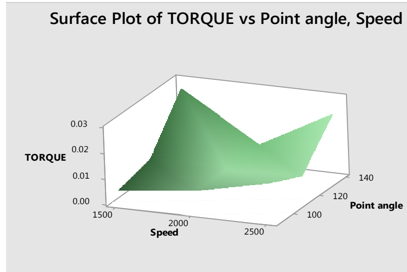

Figure 15 Torque Vs Speed and Point angle

Figure 15shows surface plot for torque Vs speed and point angle. From the above figure it has been observed that the low speed and low point angle results the low torque required. From the above figure it has been conclude that increasing the speed and point angle torque is increased.

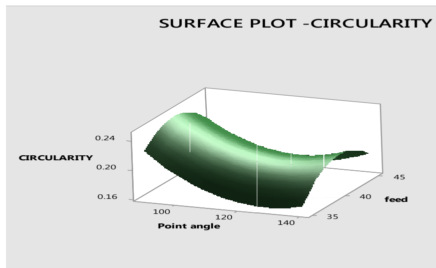

Figure 16 Surface Plot for Circularity Vs feed and point angle

Figure 16 shows the surface plot for circularity vs pint angle and feed. From this figure it has been observed that minimum circularity gain at the higher point angle and low feed. It has been conclude that the increasing the feed and decreasing the point angle the circularity is reduced.

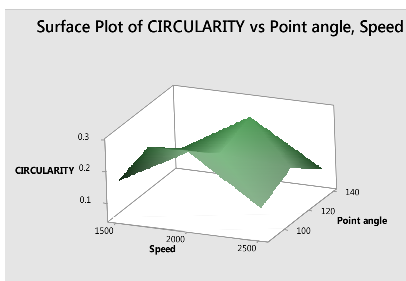

Figure 17 Surface plot for circularity Vs Speed and point angle

Figure 17 shows the surface plot for circularity Vs speed and point angle. From the above figure it has been observed that the high speed low point angle gives the low circularity. It has been conclude that the increasing the speed and point angle decreasing the point angle results increasing the circularity.

Conclusion

PMMA is a very useful material in a biological surgery and for bone replacement. Also, it is highly used in research work, marine, aerospace, furniture because of its high mechanical properties and in corrosive properties.

From this experiment it has been conclude that the 115 degree of point angle, 2000rpm spindle speed and 40 mm/rev feed is optimum for thrust force. 90 degree of point angle, 2500 rpm spindle speed, and 35 mm/min feed is optimum for the torque. 140 degree point angle, 1500rpm spindle speed and 35 mm/min feed is optimum for circularity.

Scope of Future work

More responses with larger number of resultant array give more accuracy in optimization in RSM method.

Different drill diameter, different thickness of PMMA, effect of different types of drill bit will be required to measure with different DOE techniques.

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