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# Analysis of Ultrasonic Machining for Surface Characteristics of Reinforced Glass Material

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***Index Terms: Ultra Sonic Machining, Glass Fiber Reinforced Polymer, Design of Experiments, Material Removal Rate***

## I. INTRODUCTION

Ultrasonic machining (USM) is the removal of material by the abrading action of grit-loaded liquid slurry circulating between the workpiece and a tool vibrating perpendicular to the workface at a frequency above the audible range. Ultrasonic machining, also known as ultrasonic impact grinding, is a machining operation in which abrasive slurry freely flows between the workpiece and a vibrating tool. It differs from most other machining operations because very little heat is produced. The tool never contacts the workpiece and as a result the grinding pressure is rarely more, which makes this operation perfect for machining extremely hard and brittle materials, such as glass, sapphire, ruby, diamond, and ceramics. The working process of an ultrasonic machine is performed when its tool interacts with the workpiece or the medium to be treated. The tool is subjected to vibration in a specific direction, frequency and intensity. The vibration is produced by a transducer and is transmitted to the tool using a vibration system, often with a change in direction and amplitude. The construction of the machine is dependent on the process being performed by its tool.

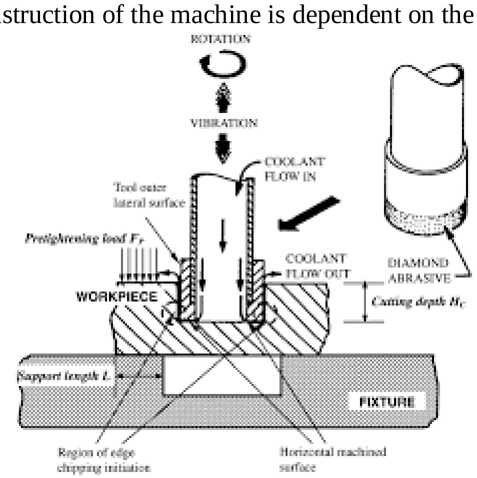


Figure.1 Ultrasonic machining Process

The tool material employed in USM should be tough and ductile. However, metals like aluminum, give very short life. Low-carbon steel and stainless steels give superior performance. The figure below shows a qualitative relationship between the material removal rate and lambda i.e. workpiece/tool hardness.

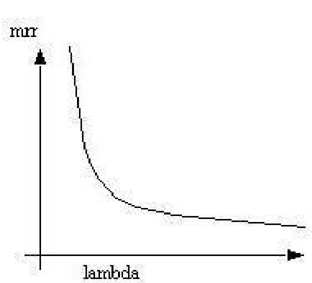


Figure.2 Length of Tool

 

The mass length of the tool is very important. Too great a mass absorbs much of the ultrasonic energy, reducing the efficiency of machining. Long tool causes overstressing of the tool. Most of the USM tools are less than 25 mm long. In practice the slenderness ratio of the tool should not exceed 20. The under sizing of the tool depends coupon the grain size of the abrasive. It is sufficient if the tool size is equal to the hole size minus twice the size of the abrasives.

Boron carbide is by far the fastest cutting abrasive and it is quite commonly used. Aluminium oxide and silicon carbide are also employed. Boron carbide is very costly and its about 29 times higher than that of aluminium oxide or silicon carbide. The abrasive is carried in slurry of water with 30-60% by volume of the abrasives. When using large-area tools, the concentration is held low to avoid circulation difficulties. The most important characteristic of the abrasive that highly influences the material removal rate and surface finish of the machining is the grit size or grain size of the abrasive. It has been experimentally determined that a maximum rate of machining is achieved when the grain size becomes comparable to the tool amplitude. Grit sizes of 200-400 are used for roughing operations and a grit size of 800-1000 for finishing.

As the tool vibrates with a specific frequency, abrasive slurry (usually a mixture of abrasive grains and water of definite proportion) is made to flow through the tool work interface. The impact force arising out of vibration of the tool end and the flow of slurry through the work tool interface actually causes thousands of microscopic abrasive grains to remove the work material by abrasion. Material removal from the hard and brittle materials will be the form of sinking, engraving or any other precision shape.

## II. MACHINING UNIT

The above figure schematically depicts the major components of a typical ultrasonic machining setup. The vibration exciter, a magnetostrictive transducer 1, is fixed to the body 2 of the acoustic head using the shoulder 3 and the thin walled cup 4. The winding of the transducer is supplied with an alternating current, at ultrasonic frequency, by the generator 5. The alternating magnetic field induced by the current in the core of the transducer, which is made from magnetostrictive material, is transformed into mechanical vibration in the core. Its main elements are an electromagnet and a stack of nickel plates. The high frequency power supply activates the stack of magnetostrictive material which produces the vibratory motion of the tool. The tool amplitude of this vibration is usually inadequate for cutting purposes, and hence the tool is connected to the transducer by means of a concentrator which is simply a convergent wave guide to produce the desired amplitude at the tool end. The waveguide or concentrator 6 transmits this vibration to the tool 7. The concentrator takes the form of a bar with a variable cross section. It is specially designed to transmit vibration from the transducer, to the tool, with an increase in the amplitude. The selection of frequency and amplitude is governed by practical considerations. The workpiece 10 is placed under the tool, on a plate 8, in a tray 9, within abrasive slurry. The body of the acoustic head is adjusted to the base's guides 11 and is subjected to a static force P which drives the tool in the direction necessary to machine the workpiece. The magnetostrictive material is brazed to a connecting body of monel metal. A removable tool holder is fastened to the connecting body and is made of monel metal or stainless steel. All these parts, including the tool, act as one elastic body, transmitting the vibrations to the tip of the tool. The abrasive slurry is circulated by pumping, and it requires cooling to remove the generated heat to prevent it from boiling in the gap and causing the undesirable cavitation effect caused by high temperature.

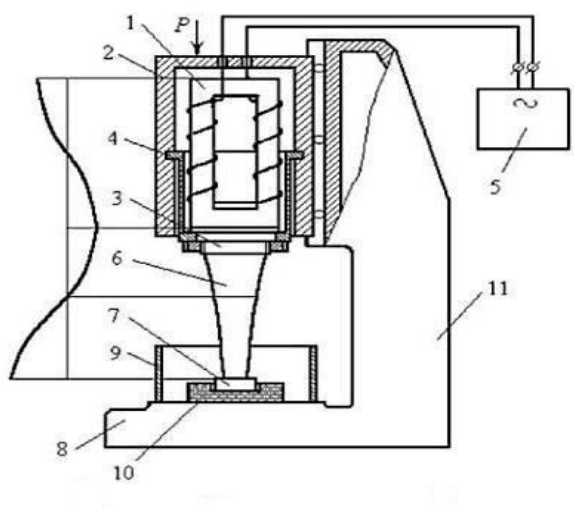


Figure 3 Ultrasonic Machining

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The ultrasonic vibration machining method is an efficient cutting technique for difficult-to-machine materials. It is found that the USM mechanism is influenced by these important parameters.

- Amplitude of tool oscillation (a0)
- Frequency of tool oscillation (f)
- Tool material
- Type of abrasive
- Grain size or grit size of the abrasives
- Feed force - F
- Contact area of the tool – A
- Volume concentration of abrasive in water slurry – C
- Ratio of workpiece hardness to tool hardness; $\lambda=\sigma_w/\sigma_t$
  $\lambda$=tool size, $\sigma$=hardness

## III. METHODOLOGY

The objective of the present work is to find out main effect of cutting speed, feed rate, drill diameters, work piece material, drill material and interaction effect between drill material and cutting speed on MRR, Surface roughness, Hole diameter error, and burr height. The determination of factors which needs to be investigated depends on the responses of interest. The factors that affect the responses were identified using several methods such as brainstorming, cause and effect analysis and flowcharting. The lists of factors studied with their levels are given in the Table 3.1 the minimum DOF required in the experiment are the sum of all the degrees of freedom of factors and their interaction. In the present experiment setup, there are 4 three level factors and one is 2-level factor i.e tool

| Experiment No | Tool material | Frequency(KHz) | Amplitude (micro-meter) | Conc. (%) |
|---|---|---|---|---|
| 1 | Ti | 19 | 15 | 30 |
| 2 | Ti | 19 | 30 | 35 |
| 3 | Ti | 19 | 50 | 40 |
| 4 | Ti | 22 | 15 | 30 |
| 5 | Ti | 22 | 30 | 35 |
| 6 | Ti | 22 | 50 | 40 |
| 7 | Ti | 25 | 15 | 30 |
| 8 | Ti | 25 | 30 | 35 |
| 9 | Ti | 25 | 50 | 40 |
| 10 | Ca | 19 | 15 | 30 |
| 11 | Ca | 19 | 30 | 35 |
| 12 | Ca | 19 | 50 | 40 |
| 13 | Ca | 22 | 15 | 30 |
| 14 | Ca | 22 | 30 | 35 |
| 15 | Ca | 22 | 50 | 40 |
| 16 | Ca | 25 | 15 | 30 |
| 17 | Ca | 25 | 30 | 35 |
| 18 | Ca | 25 | 50 | 40 |

Table3.1 Input Parameters

material The number of DOF for factors A,B, C are two and for factor D is one. The total DOF for the experiment explained in Table 3.2. As the DOF required for the experiment is nine the orthogonal array (OA) to be used should have more than nine dof. The most suitable orthogonal array which can be used for this experiment is L18, which has 17 DOF assigned to its various columns.

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The additional four DOF used to measure the random error. Taguchi orthogonal arrays are experimental designs that usually require only a fraction of the full factorial combinations. The columns of arrays are balanced and orthogonal. This means that in each pair of columns, all factor combinations occur same number of times. Orthogonal designs allow estimating the effect of each factor on the response independently of all other factors. Once the degrees of freedom are known, the next step is to select the orthogonal array (OA). The number of treatment conditions is equal to the number of rows in the orthogonal array

| Factors | Factors designation | Level 1 | Level 2 | Level 3 |
|---|---|---|---|---|
| Tool material | A | titanium | Carbide | |
| Frequency | B | 19 | 22 | 25 |
| Amplitude | C | 15 | 30 | 50 |
| Conc. | D | 30 | 35 | 40 |

Table 3.2 Factors and their levels of interest

and it must be equal to or greater than the total degrees of freedom and experimental design of L18 is shown in Table 3.1
Response factor has to be calculated and the response characteristics given in the Table 3.3

| Response name | Response type | Units |
|---|---|---|
| Material Removal Rate (MRR) | Higher the better | $mm^3/min$ |
| Surface Roughness | Lower the better | Microns |
| Tool wear rate | Lower the better | mm3/hr |

Table3.3 Response Characteristics

Figure 4 Experimental Setup

## IV. RESULTS AND ANALYSIS

The effects of parameters i.e. tool material, frequency, amplitude, concentration of slurry and interaction between tool material and frequency were evaluated using ANOVA and factorial design analysis. A confidence interval of 95% has been used for the analysis. One repetition for each of 18 trails was completed to measure the Signal to Noise ratio(S/N Ratio).

### *A. Results for MRR*

The results for MRR for each of the 18 treatment conditions with repetition and MRR of each sample is calculated from weight difference of work piece before and after the performance trial. The results for MRR were analyzed using ANOVA for identifying the significant factors affecting the performance measures. The Analysis of Variance (ANOVA) for the mean MRR at 95% confidence interval is given in Table 4.1. The variance data for each factor and their interactions were P value to find significance of each. From Table 4.1 tool material (A), amplitude (C) and concentration (D) have the P value less the 0.05 that means these factors are significant. Interaction between tool material and frequency has the P value more than the 0.05 that means this factor is insignificant. Frequency has value of P more than 0.05 that means it is insignificant.

| Source | SS | v | V | F | P | SS' | % contribution | Status |
|---|---|---|---|---|---|---|---|---|
| Tool material (A) | 4.292 | 1 | 4.292 | 4.25 | 0.043 | 3.002 | 2.90 | Significant |
| frequency (B) | 4.716 | 2 | 2.358 | 2.34 | 0.159 | | | Insignificant |
| amplitude (C) | 72.165 | 2 | 36.083 | 35.75 | 0.000 | 69.585 | 67.27 | Significant |
| conc (D) | 11.487 | 2 | 5.744 | 5.69 | 0.029 | 8.907 | 8.610 | Significant |
| Tool material × frequency (E) | 2.713 | 2 | 1.357 | 1.34 | 0.314 | | | Insignificant |
| Residual error | 8.074 | 8 | 1.009 | | | | | |
| Total | 103.448 | 17 | | | | | | |
| E-pooled | 15.503 | 12 | 1.29 | | | | | |

Table 4.1 ANNOVA for MRR

Fig.1 and Fig.2 shows the main effect plot of MRR for Means and interaction plot for MRR. Fig.3 shows the main effect plot for MRR of S/N ratio

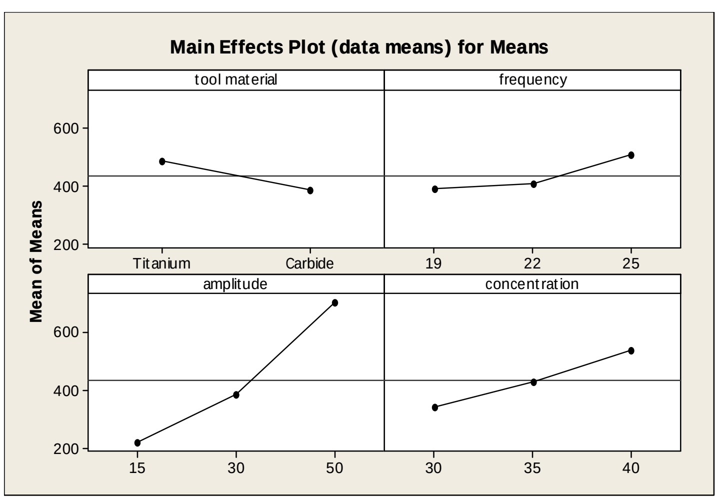


Figure 4.1: Main effect plot of MRR for Means

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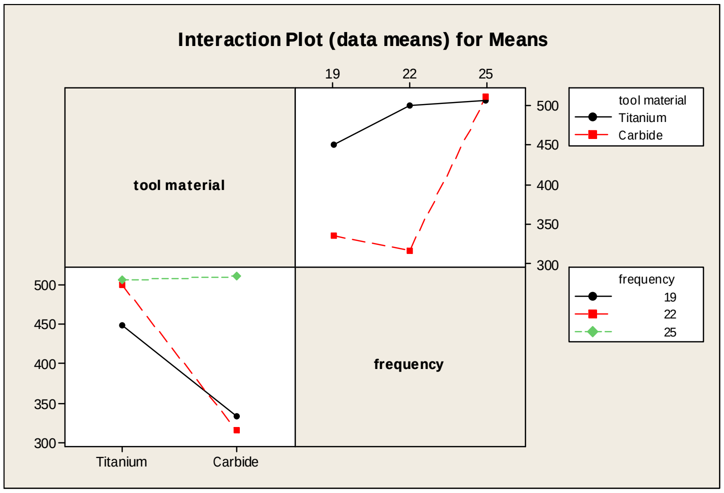


Figure 4.2: Interaction plot for MRR

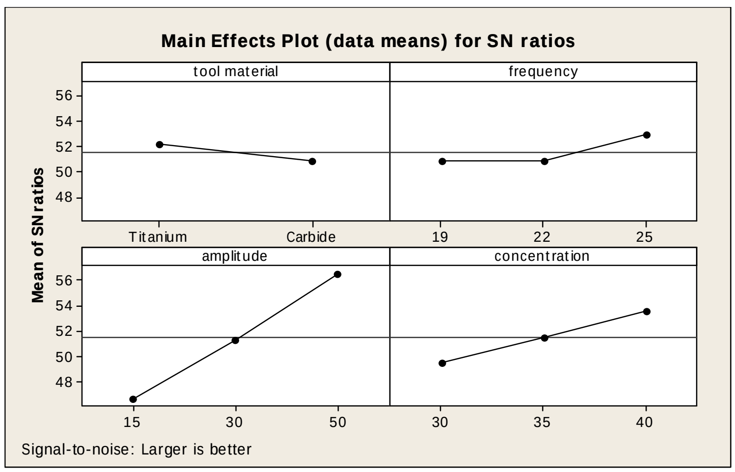


Figure 4.3 Main effect plot for MRR of S/N ratio

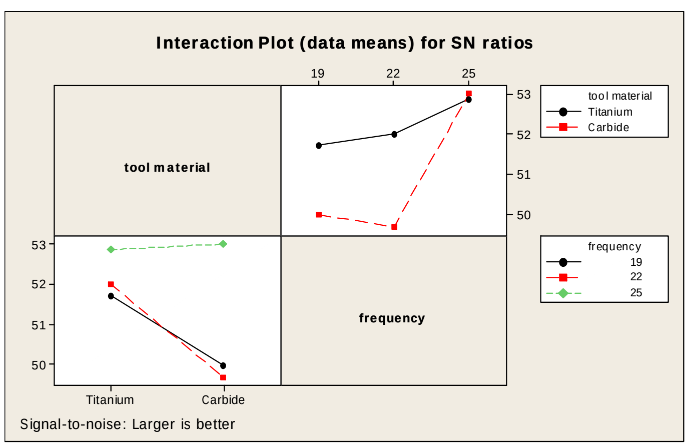


Figure 4.4 Interaction plot for MRR of S/N ratio

## *B. Optimal Design*

The same level of all the significant factors provide a higher mean value and reduced variability so nothing has to be compromised. The level of factors which improves average and uniformity may conflict, so a compromise may have to be reached. Also a compromise has to occur when multiple responses are considered and the same factor level may cause one response to improve and other to reduce.

In this experimental analysis, the main effect plot in Figure 4.1 is used to estimate the mean MRR with optimal design conditions. In Table 4.2 it is concluded that highest MRR was achieve at amplitude of 50 micro-meters with 40% of slurry concentration and with titanium tool. In S/N ratio highest MRR was found at 25 KHz frequency, 50 micro-meter of amplitude and 40% of slurry concentration. MRR is a “Higher the better” type response. In this experiment analysis, different experimental trials have been chosen to obtain satisfactory results. After conducting the experiments, the optimum treatment condition within the experiments determined based on prescribed combination of factor levels is determined to one of those in the experiment.

Table 4.2 Significant factors and interactions for MRR

| Factor | Affecting mean | | Affecting variation | |
|---|---|---|---|---|
| | contribution | Best level | contribution | Best level |
| Tool material (A) | significant | level 1(Ti) | insignificant | |
| Frequency (B) | insignificant | | significant | Level 3(25) |
| amplitude (C) | significant | Level 3(50) | significant | Level 3(50) |
| Conc. (D) | significant | Level 3(40) | significant | Level 3(40) |
| Tool material*frequency (E) | insignificant | | insignificant | |

## V. RESULTS AND CONCLUSION

The effect of parameters i.e. tool material, frequency, amplitude and concentration were evaluated using ANOVA design analysis and Regression analysis. The purpose of the ANOVA was to identify the important parameters in prediction of MRR. Some results consolidated from ANOVA and plots are given below

The effect of parameters i.e. tool material, frequency, amplitude and conc. were evaluated using ANOVA and factorial design analysis. A confidence interval of 95% has been used for the analysis. Two repetitions for each 18 trails were completed to measure the Signal to Noise ratio (S/N Ratio).

ANOVA table shows that tool material with F value 4.25, amplitude with F value 36.08 and concentration 5.74 are the factors that significantly affect the MRR, with % contribution of 2.9%, 67.27 % and 8.61% to MRR

The other factor frequency was found to be insignificant. For S/N ratio frequency, amplitude and concentration are significant to reduce the variation of MRR.

So the confidence interval around the MRR is given by 8.52 ± 1.43 $mm^3$/min.

The present study was carried out to study the effect of input parameters on the MRR and surface roughness and tool wear rate. The following conclusions have been drawn from the study:

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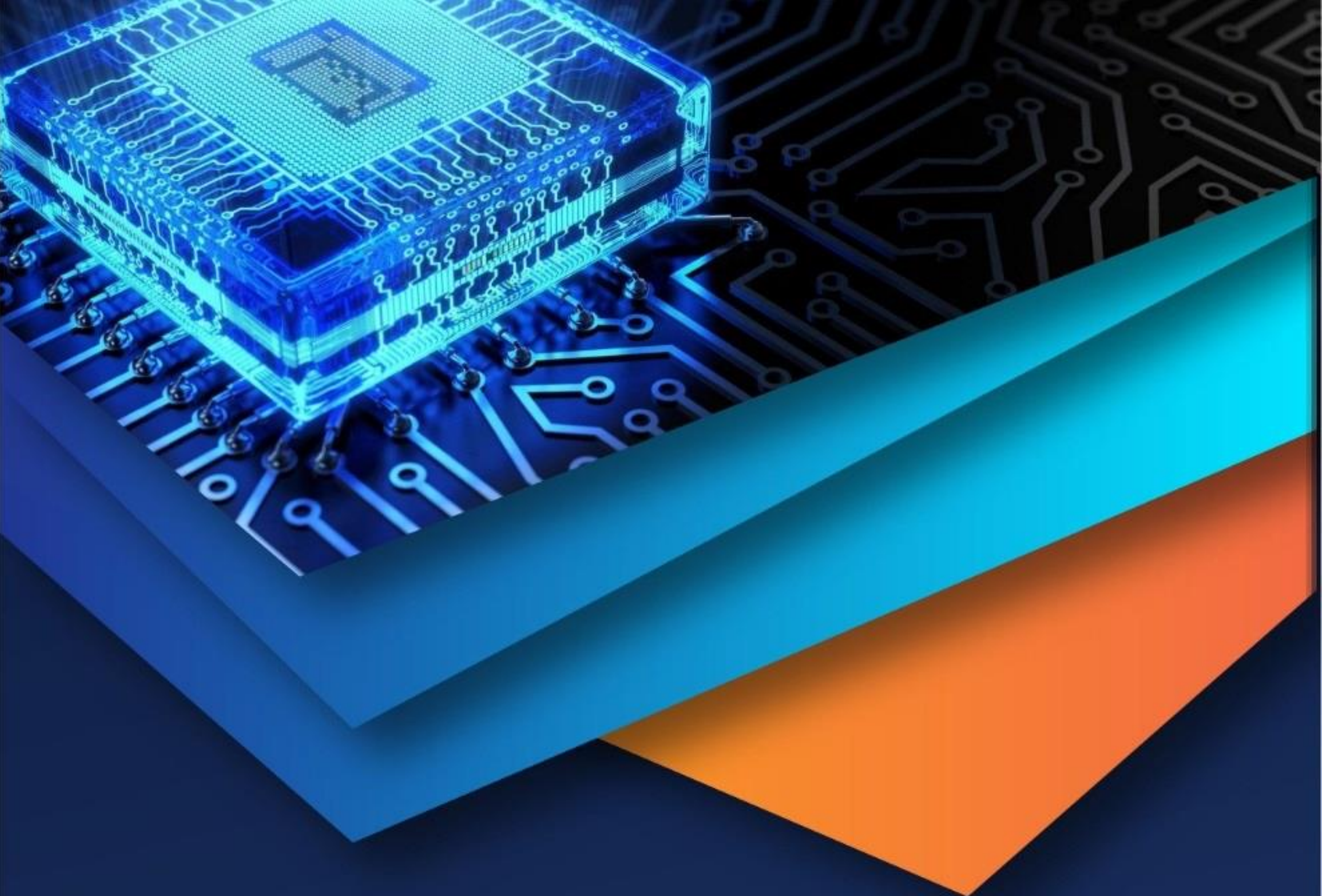

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