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Design, Efficiency and Finite Element Analysis of a Double Shear Punching Tool made of AISI A11 High Speed Steel

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Abstract: In this paper we modeled and designed a tool for a pneumatic punching machine along with its corresponding piston and piston rod. Our aim was to test the performance of the AISI A11 high speed steel as a potential punching tool. First, we lowered the force requirement by modeling the tool upon the double shear design. The tool design has been specifically made according to this material's mechanical capabilities. Then we ran a static analysis on the model using the two different software that is Catia V5R20 and Ansys 2019R1 to obtain the values of the equivalent stresses and the deformation occurring in the design upon the application of the necessary boundary conditions. At last we did the cost comparison of our model with the one which is already available in the market that is the flat tool design.

Keywords: Double Shear tool, Equivalent stress, Flat tool, AISI A11, pneumatic

Nomenclature:

f_c	**Cutting force, N**	a_3	**Effective area, m^2**
f_s	**Stripping force, N**	m_p	**Mass of piston, kg**
f_r	**Reduced force, N**	m_r	**Mass of rod, kg**
f_p	**Press force, N**	m_t	**Mass of tool, kg**
f_t	**Retraction force, N**	m'	**Total mass, kg**
l	**Length of cut, m**	s	**Stroke length, m**
t	**Thickness, m**	u	**Initial velocity, m/s**
τ	**Shear strength, N/m^2**	a_{c1}	**Extension acceleration, m/s^2**
k	**Percentage penetration**	a_{c2}	**Retraction acceleration, m/s^2**
i	**Shear length, m**	t_1	**Extension time, s**
P	**Working pressure, N/m^2**	t_2	**Retraction time, s**
r'	**Calculated bore radius, m**	t'	**Cycle time, s**
r_1	**Standard bore radius, m**	f_n	**Frequency, Hz**
r_2	**Rod radius, m**	h	**Height of piston, m**
a_1	**Piston area, m^2**	ρ	**Density of piston, Hz**
a_2	**Rod area, m^2**	r	**Rate per mass of material, /kg**

I. INTRODUCTION

Punching machine are operated upon various principles such as pneumatic, hydraulic, spring and rack and pinion. The majorly used mechanism are based on the hydraulic and the pneumatic. In hydraulic higher pressure can be used as compared to the pneumatic hence they are mostly suitable for large scale operation. The major advantages of pneumatic over the hydraulic are that the pneumatic system is much simpler and made up of simple materials and parts whereas hydraulic requires excessive amount of casing and safety due to their inert high pressure of operation and chance of rupture and damages sustained to these parts. Pneumatic are also much faster and leaner due to much lesser viscosity of gas mediums and lesser frictions and obstructions. When compared to the hydraulic here they can be utilized to rapid processing of the sheet metals. The cost of pneumatic system and of their maintenance is very much decreased due to these factors.

Pneumatically operated punching machine are great ideal for small scale industries which uses very much lesser energy consumption and smaller size of work jobs. P.C.Sharma in his textbook explained the "Methods of reducing Cutting Forces", which has shown a complete derivation of the force reduction formula for tools implemented with shears. The formula is governed by

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various variable which can help in significantly dropping the cutting force up to fifty percent of their present value as shown by P. Goyal et la. The paper showed the tabulated comparison of force requirement in flat tool and shear tool and the percentage force reduction being achieved in different amount of shear being given. In the study to blank a one millimeter of a thickness of sheet metal. The required force varied from fifteen thousand to twelve thousand on providing a one-millimeter shear to the tool. The ranges of sheet metal thickness have a huge variation, the minimum thickness successfully attempted was of less than 5×10^{-5} meters by Y. Qin et al. This can help our design to even be used on other thinner sheet metals if on practical usage there happens to be some errors.

II. PUNCH TOOL DESIGNS

The flat tools do not provide much shear force to the sheet metal hence they need higher degree of compressive force to perform the same operation. In double shear the stress distribution starts from the center point and gradually spreads out in the radial outward manner. The punch design we selected for the force reduction is the double shear due their symmetrical balance of the force and better stress distribution on its face. Whereas the single shear though having force reduction quality is bound to higher degree of bending on the overall components due to the unsymmetrical distribution of the force.

III. MATERIAL PREFERENCES

In our design we took the punching tool as high-speed steel (AISI A11) having yield strength of 9.5×10^{8} N/m^2 due to its high impact toughness than the other commonly used metals. This type of steel is manufactured using powder metallurgy and enriched with vanadium at 9.75% which provides it with better grain size and grain orientation.

The piston and rod are taken as cast iron (ASTM 45006) of yield strength 3.1×10^{8} N/m^2 due to its high availability and resistance to deformation, wear and oxidation. This is the most commonly used cast iron which has relatively high toughness and endurance and therefore is generally chosen as a staple material.

For model calculation and analysis, the sheet materials taken is aluminum (Al 6061) of shear strength 2×10^{8} N/m^2, due to their predominance in the industry. Aluminum is one of the most widely and intensively used sheet metal. Its high malleability and low shear strength have made them remarkable material in the sheet metal industry.

IV. CALCULATIONS

A. Terms

Cutting force (f_c) – The direct force acting on the sheet metal by the action of the tool during rapid actuation of the piston (in N/m^2).

Stripping force (f_s) – The recoil force by the sheet metal imparted due to the spring back effect of the material when being punched or blanked (in N/m^2).

Cutting force (f_c) = l x t x τ (in N/m^2)

Stripping force (f_s) = 10 **-** 20% of cutting force.

where, l = Length of periphery or the circumference of the sheet metal to be cut (in m).

t = Sheet thickness (in m)

τ = Shear strength of the sheet metal in (N/m^2)

Press force (f_p) = The total force needed to punch or blank a sheet metal regarding both the axial force and the spring back effect of the sheet metal (f_c + f_s) (in N/m^2).

B. Existing Force

Now, we calculate the existing force which is generally required to punch or blank a sheet with an unmodified flat tool.

The following are the parameters.

Total length of cut, l = 0.05 m

Sheet thickness, t = 0.002 m

The stripping force is been taken as the mean of the maximum and the minimum limits.

Stripping force, f_s = 15% of the cutting force

Maximum shear strength of aluminum, $\tau = 2\times10^{8}$ N/m^2

f_c = l x t x τ → 0.055 x 0.002 x 2e+8 = 20000 N

f_s = 3000 N

f_p = 20000 + 3000 = 23000 N

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Now, the cutting force is been obtained as 20000 N and the spring back effect of the aluminum sheet with 2 mm thickness was obtained as 3000 N. The press force which is the sum of the cutting force and the stripping force is obtained as 23000 N.

C. Force Reduction

Now, the force reduction is produced by providing the shear on the punch tool.
Force reduction is given by the standard formula,

$$f_r = \frac{f_p \times k \times t}{k \times t + i}$$

where, f_r = force needed after providing shear to the tool in N
The percentage penetration is given as the amount of tool shear which gets penetrated into the sheet metal upon impact.
k = percentage penetration (0.2 – 0.8)
The percentage reduction is calculated by observing the difference between the initial press force with the flat tool and the reduced press force after imparting shear on the tool.
Percentage reduction = $(f_p - f_r) \times 100 / f_r$
Taking k = 0.5 as the mean of the extreme values and i = 0.001 m as the amount of shear given.
$f_r = 23000 \times 0.5 \times 0.001 / (0.5 \times 0.002 + 0.001) = 11500$ N
The force reduction was obtained as 11500 N down from the initial 23000 N.
Percentage reduction = $\frac{(23000-11500)}{23000} \times 100 = 50\%$
By providing the shear we obtained 50% reduction in the press force by providing 1 mm shear to the tool.

D. Model Specifications

We took pressure as the mean of the standard pneumatic pressure utilized in industries for pneumatic operations and the press force of 11500 is been rounded off to the nearest thousand.
Pressure utilization (P) = 1×10^6 N/m^2 and the force needed 11500 N being rounded off to 12000 N for safety purposes.

1) *Bore Radius:* The bore radius is calculated by the relation of pressure and force, we know that the force is 12000 N and the pressure is 1×10^6 N/m^2.

P = force/bore area
$P = \frac{fr}{(\pi \times r'2)} \rightarrow 1\times10^6 = \frac{12000}{(\pi \times r2)} \rightarrow r' = 0.0618$ m
The bore radius is thus obtained and as per the standards, bore radius is been taken as r_1= 0.0625m.
From the standard bore radius and rod radius relation we get take the rod radius as r_2 = 0.016 m.

2) *Actuation Time Period and Stroke Length:* Now, we find the time taken by the parts in retraction and extension. We will also calculate the necessary stroke length to be kept regarding the actuation time of the piston. First, the respective area of the cross section of the piston and the rod is calculated from their radii.

Area of piston $a_1 = \pi \times (0.0625)^2 = 12.2718\times10^{-3}$ m^2
Area of rod $a_2 = \pi \times (0.016)^2 = 80.4247\times10^{-5}$ m^2
During the extension the pressure would be supplied only at the top portion of the piston, while during retraction the same pressure would be applied on the retraction with the area being the difference of the piston and the rod.
$a_3 = a_1 - a_2 \rightarrow 12.2718\times10^{-3} - 80.4247\times10^{-5} = 11.4675\times10^{-3}$ m^2
The mass of the piston, the piston rod and the tool are obtained by the product of the volume and the density of each part.
m_p = 5.541 kg, m_r = 2.373 kg, m_t = 0.063 kg
The total mass is obtained by the summation of the mass of each part.
$m' = m_p + m_r + m_t \rightarrow 5.541 + 2.373 + 0.063 = 7.977$ kg
The force is known as 12000 N and the mass is calculated above and the corresponding acceleration is calculated by the below relation.
$f_r = m' \times a_{c1} \rightarrow 12000 = 7.977 \times a_1 \rightarrow a_1 = 1504.3249$ m/s^2
By equation of motion we can calculate the stroke length when keeping the time period as 0.01 s which is also the extension time taken by the piston. $s = ut_1 + \frac{1}{2} a_{c1} t_1^2$
$s = 0.5 \times 1504.3249 \times 0.01^2 \rightarrow s = 0.0751$ m

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Therefore, we obtained the stroke length as 0.0751 m.
Now for calculating the retraction, we already know the area involved during the retraction as 11.4675×10^{3} m^2, the pressure is constant of 1×10^6 N/m^2, so the force is calculated.
$f_t = P \times a_3 \rightarrow 1\times10^6 \times 11.4675\times10^{-3} = 11467.553$ N
Similarly, for this force the acceleration is calculated keeping the total mass same.
$f_t = m' \times a_{c2} \rightarrow 11467.553 = 7.977 \times a_{c2} \rightarrow a_{c2} = 1437.5771$ m/s^2
From the equation of motion, $s = ut_2 + \frac{1}{2} a_{c2} t_2^2$
we know the stroke length and the acceleration the time of retraction is calculated.
$0.0751 = 0.5 \times 1437.5771 \times t_2^2 \rightarrow t_2 = 0.0102$ s
The time period for the one complete cycle is the sum of the time taken for extension and the retraction.
Time for one cycle $t' = t_1 + t_2 = 0.0202$ s
Frequency, $f_n = \frac{1}{t'} = 49.50$ Hz

V. PARTS AND MATERIAL PROPERTIES

Table 1 Piston property

Material	Cast iron (ASTM 45006)
Young's modulus (N/m^2)	1.2×10^{11}
Poisson's ratio	0.291
Density (kg/m^3)	7870
Mass (kg)	5.541
Coefficient of thermal expansion (/Kdeg)	1.21×10^5
Yield Strength (N/m^2)	3.1×10^8

Table 2 Rod property

Material	Cast iron (ASTM 45006)
Young's modulus (N/m^2)	1.2×10^{11}
Poisson's ratio	0.291
Density (kg/m^3)	7870
Mass (kg)	2.373
Coefficient of thermal expansion (/Kdeg)	1.21×10^5
Yield Strength (N/m^2)	3.1×10^8

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Table 3 Tool property

Material	High speed steel (AISI A11)
Young's modulus (N/m^2)	2×10^{11}
Poisson's ratio	0.27
Density (kg/m^3)	7418
Mass (kg)	0.063
Coefficient of thermal expansion (/Kdeg)	1.07×10^{5}
Yield Strength (N/m^2)	9.5×10^{8}

VI. STATIC ANALYSIS

A. *Boundary Conditions*

1) Clamped at -Z axis on the piston
2) Force applied on the tool
a) 12000 N at +Z axis
b) 0 N at +X, +Y, -X, -Y and –Z axis

B. *Meshing*

1) Type: Parabolic
2) Element Sizes:
a) Piston 0.01 m
b) Rod 0.01 m
c) Tool 0.0019 m

C. *Deformation*

The deformation solution has been amplified 400x times in both the software to achieve distinguishable results. The maximum displacement of nodes was at the tool face and minimum was at the piston head. The displacement is seen to be decreasing with the increase in the z coordinate. The maximum displacement of the tool is found to be 6.55×10^{-5} m. The maximum displacement of the piston rod is found to be 4.58×10^{-5} m. The displacement is seen to linearly decrease with the increase in z coordinate. The minimum displacement on the piston rod is 6.55×10^{-6} m. Similarly, the piston is the least affected with the displacement with absolutely being zero across its every nodal coordinate. Similarly, pattern is observed in the deformation analysis done in Ansys. With the maximum displacement of 6.25×10^{-5} m. The maximum displacement of the piston rod is at the junction of the tool and the rod of about 4.86×10^{-5} m. The displacement similarly decreases linearly with the value at the rod head being 6.94×10^{-6} m. The piston rod is virtually under zero nodal displacement in this analysis too.

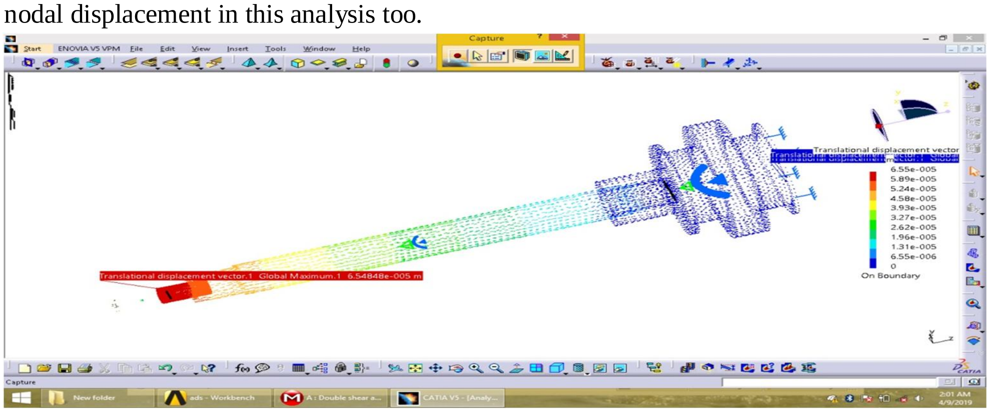

Fig 1 Deformation in Catia

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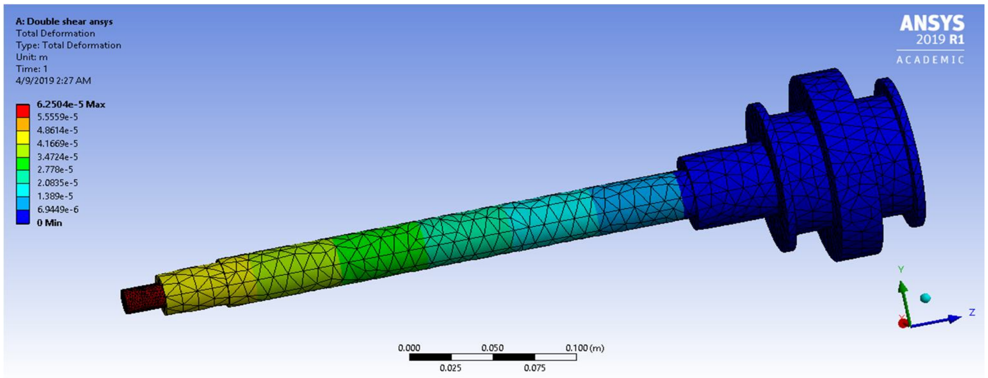

Fig 2 Deformation in Ansys

D. Equivalent Stress

Equivalent stress or von mises stress analysis is being done to validate that the stress concentration is not higher than the materials' yield strengths, which could potentially tell if the parts are under the safe limits. The maximum nodal stress was obtained at the periphery of the tool face. The overall nodal stresses were lower the yield strength in every case. The maximum yield stress in case of the analysis in Catia is found at tool face outer radius about 2.67×10^8 N/m^2. The minimum was found to be at the piston head at about 4.36×10^4 N/m^2. The stress at every node was lower than the concerned materials' ultimate yield strength. The analysis result pattern with the Ansys model was found to be the same. With the maximum at the punch tool face at 2.65×10^8 N/m^2. The stress was mostly concentrated in the tool. The least stress is at the piston. The material chosen as such is ideal for the taking the stress of the impact force. The lowest is found at the piston head with 5.3×10^4 N/m^2.

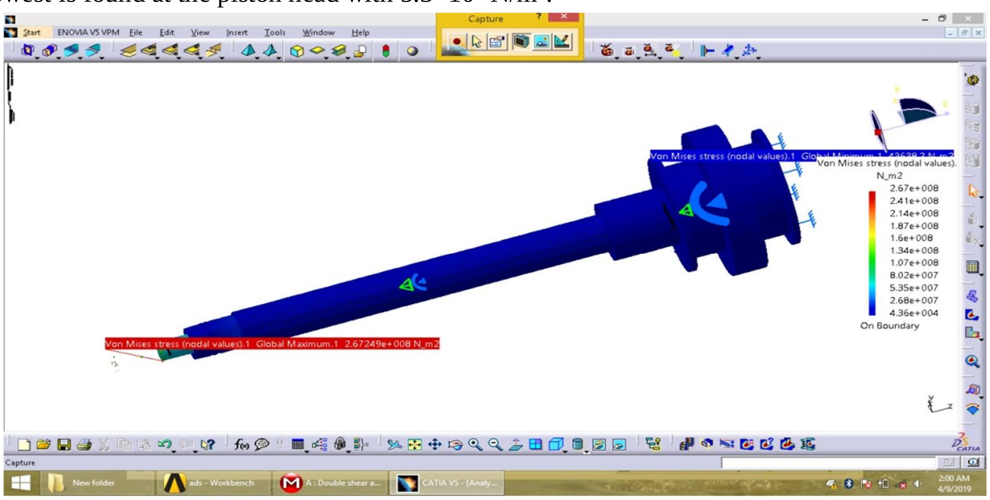

Fig 3 Equivalent stress in Catia

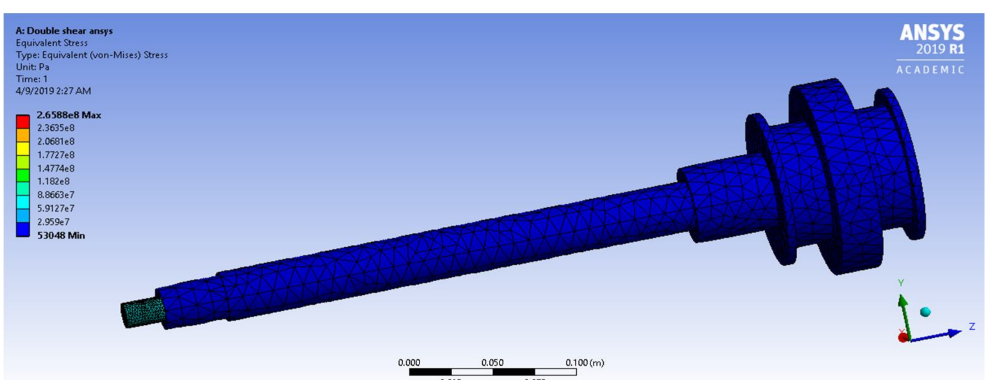

Fig 4 Equivalent stress in Ansys

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VII. COST COMPARISON

Comparing the Double shear design with the more traditional Flat tool they both requires a force of 12000 N and 23000 N respectively to punch a same material of same thickness as we calculated before. Now to achieve these forces we need to provide various design modification in both the types of tools. Here, we calculated and applied these modifications on the flat tool based on three criteria so as to achieve 23000 N force output. We kept the parameters of the Double shear tool constant for making the comparisons.

Table 4 Cost estimation by pressure alteration

	Double Shear	Flat tool
Pressure applied (N/m^2)	1×10^6	
Force required (N)	12000	23000
Area of piston (m^2)	0.012	0.023
Height of piston (m)	h	
Volume (m^3)	$0.012h$	$0.023h$
Density (kg/m^3)	ρ	
Mass (kg)	$0.012h\rho$	$0.023h\rho$
Rate of material(/kg)	r	
Cost (₹)	$0.012h\rho r$	$0.023h\rho r$
Cost variance	47.82% cheaper	

Table 5 Cost estimation by actuation time alteration

	Double Shear	Flat tool
Pressure applied (N/m^2)	1×10^6	1916666.66
Force required (N)	12000	23000
Area of piston (m^2)	0.012	
Height of piston (m)	h	
Volume (m^3)	$0.012h$	
Density (kg/m^3)	ρ	
Mass (kg)	$0.012h\rho$	
Acceleration (m/s^2)	$1 \times 10^6/h\rho$	$1916666.66/h\rho$
Stroke (m)	s	
Actuation time (s)	$2 \times 10^{-6}h\rho$	$1.04 \times 10^{-6}h\rho$
Frequency variance	42% faster	

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Table 6 Cost estimation by piston cross section area alteration

	Double Shear	Flat tool
Pressure applied (N/m^2)	1×10^6	1916666.66
Force required (N)	12000	23000
Area of piston (m^2)	0.012	
Height of piston (m)	h	
Volume (m^3)	$0.012h$	
Density (kg/m^3)	ρ	
Mass (kg)	$0.012h\rho$	
Acceleration (m/s^2)	$1\times 10^6/h\rho$	$1916666.66/h\rho$
Actuation time (s)	0.01	
Stroke length (m)	$50h\rho$	$95h\rho$
Energy utilized (Nm)	$6\times10^5 h\rho$	$21.85\times10^5 h\rho$
Energy variance	27.46% more efficient	

VIII. CONCLUSION

The resultant deformation and the equivalent stresses result in both the software were within the 1% variance. The equivalent stress was much lower than the yield strength. There were no fatal deformations in the geometry of the model on running the deformation test. As per the various results we can conclude that the AISI A11 High Speed Steel is an ideal choice for the application as a punching/blanking tool material and can provide superior efficiency when utilized in a double shear tools as compared to the flat tools.

A. 27.46% more energy efficient
B. 42% faster in punching a similar material with similar thickness
C. 47.82% cheaper by the potential market rate

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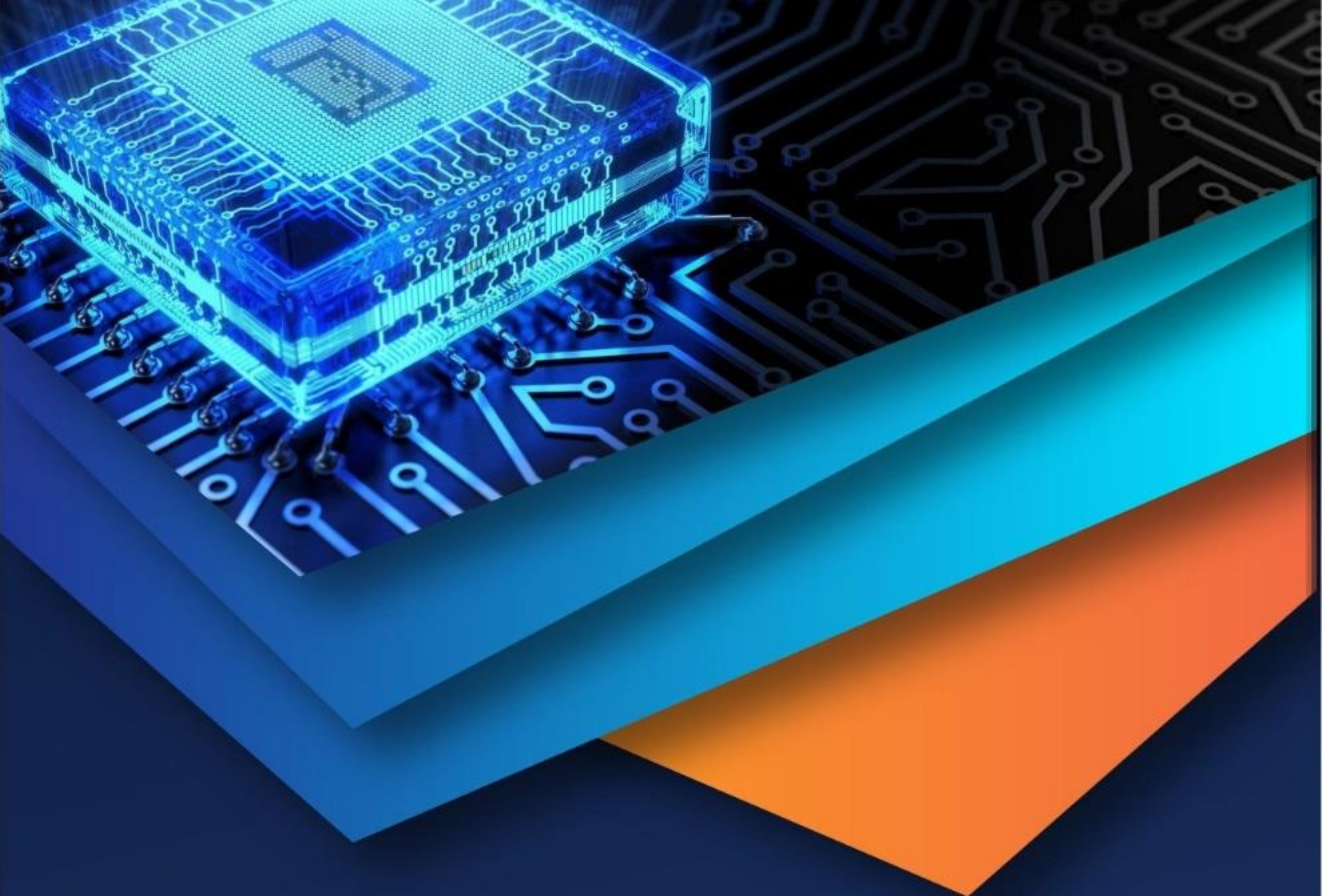

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