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A Review on FSW of Aluminium and Aluminium Alloys - A Critical Approach

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***Abstract:** A process called as Friction Stir Welding (FSW) in which welding of materials takes place by plastic deformation in solid state and is highly applicable in joining of aluminium and copper alloys. The heat which is generated because of revolutions of the tool and work material in this process due to friction leads to joining of the said alloys cause of plastic deformation in solid state. An excessive usage of 7xxx is found in the field of transportation, marine and aviation sector. Fusion welding on the other hand causes welds defects like porosity and hot cracking when applied to aluminium alloys. Friction stir welding parameters like downward forces, tool material, traverse speed, rotational speed etc. has been studied and there effects on weld strength are determined. This review paper deals with latest trends and research focussed in field of FSWP of Al and its alloys and studies in brief impact of different factors on tensile strength of weld nugget, microstructural changes and eventually its impact on mechanical properties. This paper concludes unambiguously that use of these high strength Al alloys might take over for large usage in manufacturing sector in near future.*
***Keywords:** FSW, velocity of rotation of tool, tilt angle, microstructure, Tool geometry.*

I. INTRODUCTION

Although emerged at The Welding Institute in the year 1991 the FSW is today one of the premium methodologies especially designed to weld Al and aluminium alloys (also alloys of Cu and Mg). [1]. FSW process consists of a tool which rotates and is non exhaustible with a especially designed geometry of tool and shoulder. Pin of the tool is a protruding surface element which gets inserted into the adjoining border of sheet and is pass over across the border of the weld (Diagram 1). FSW finds its application largely in the aviation sector, marine industries, vehicle manufacture etc. Since aluminium alloy possesses high strength they are widely used in aviation industries. But having said that, riveting is also carried out which requires large workforce and is time consuming. This imparts to the heaviness to the airship. Instead of using these kinds of fasteners, friction stir welding can be advantageous in a way that reduction of weight can be achieved. Conventional welding approaches are not beneficial for welding of aluminium alloys because aluminium possesses high expansion and contraction coefficient. This leads to defects like hot cracking, porosity and lower mechanical properties. Earlier investigation of FSW applied to aluminium alloys implies that there is least deformation, better mechanical properties; improved strength of weld nugget is achieved.

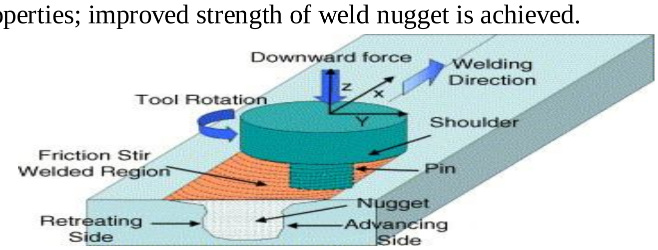

Diagram 1: A pictorial view of Friction Stir Welding [2]

A. *Following Section Deals with Various Basic Terminologies related to Friction stir Welding Process. [3]*
1) *Rate of Rotation:* The rate of rotation is the spin rate at which FSW tool rotates. Expressed in (rpm)
2) *Advancing Side:* This is the weld side wherein the direction tool rotation is alike to tool traverse direction
3) *Pull Back Side:* Pull back side is (also called as RS) weld side wherein the direction of tool rotation seems to be unlike in nature with tool traverse direction.
4) *Downforce (kN):* The force which the tools shoulders exerts on the upper layer of the workpiece in vertically downward direction.
5) *Travel velocity (mm/min):* Travel velocity is the velocity of the tool passing over along the weldment line relative to the workpiece.

Parameters like tool design, type of material and thickness of the plate decides the highest temperature that can be achieved in the process. The welding by FSW process occurs because of plasticised flow of material at adjoining area of workpiece to be welded. Following are some merits of friction stir welding:

a) Consumption of energy is lower compared to fusion welding.
b) Absence of filler material, shielding gas makes the process less harmful to the environment.
c) Repeatability and dimensional accuracy is better.
d) Welding defects like porosity, hot cracking etc are eliminated.
e) Good mechanical properties are achieved compared with conventional welding methods.

There are some certain limitations of FSW process such as:

- The functionality of the weld reduces due to the hole which forms as soon as tool is taken out from the workpiece.
- Uneven distribution of temperature when material thickness is more.
- High cost of the components.

II. LITERATURE REVIEW

Various process parameters associated with friction stir welding like tool geometry, downward force, tool rotational velocity, angle of the tool with the horizontal surface (or tilt angle) etc are influential in getting the optimum weld quality and weld strength.

A. The Velocity Of Rotation Of The Tool And Its Influence On Microstructural Properties

Numerical studies conducted for optimizing process parameter by making use of a model which thermally and mechanically suits to be certain about the material deformation and temperature variations in FSWP [4]. The thermal mechanical prototype helped investigate the impact of welding factors on the way material responded with increase in temperature. The results specified that peak temperatures in case of Friction stir welding process where achieved with rise in velocity of rotation. Also magnitude of welding speed increases the power input effectively increased for friction stir welding process. The defect called weld fash was observed due to accumulation of material near wake border formed at the retreating side. It was summarized that the weld quality will be more efficient when velocity of rotation of the tool will increase and their is a decrease of welding speed. With an increment of velocity of rotation of the tool as well as translational velocity formation of internal stresses was observed.

Mathematical and statistical model of optimizing process parameters of Friction stir welding when there is inter dependency of several independent variables with one dependent variable lead to surface response methodology [5]. Fabrication of butt joint configuration of the aluminium alloys AA6061-T6 was carried out for this investigation. Objective of the paper was to enhance the welding parameters with the aid of mathematical model to achieve higher amount mechanical properties like UTS, YS and percentage elongation. It inferred that the UTS and yieldstrength s of said alloy was increasing with a simultaneous rise in velocity of rotation the tool, welding velocity and downforce to a higher magnitude and then falls . ANOVA analysis indicated 95% confidence level.

In an experimental work [6] on FSW of AA6082 T6 and AA5083. The process parameters considered where tool geometry, welding velocity, and angle of tool with the surface and pin rotational velocity. Taguchi method was initiated to assure that velocity of rotation of the tool has maximum effect on TS as compared to weld velocity and a tilt of tool. Tensile strength is increase as geometry is changed from square to circular. To find the sequence in which the process parameters were interrelated weight method was utilized. Optimizations of two or more parameters were carried out by grey relational method. Main findings where that the share of velocity of rotation of the tool is much higher when distinguished with pin geometry and welding velocity. In this study tool tilt angle was significant.

In his experimental study conducted on FSW of Marine grade aluminium alloy AA5052 H32 aluminium plates. Process parameter used where angle of inclination of the tool [7] , velocity of rotation, geometry of the tool and velocity of weld. Use of surface response method and ANOVA for adequacy of the model along with scatter diagram was applied to show better coincidence with the predicted model. It inferred that robustness of weld nugget relys on velocity of rotation of the tool; velocity with which welding takes place has antonymous effect on robustness of the weld as compared to velocity of rotation of the tool. Regarding the tool profile it was concluded that circular pin geometry is optimum to get maximum tensile strength, share of velocity of rotation of tool is higher compared to tool profile.

Along with velocity of tools rotation, tool traverse velocity and tool profile also influences the weldability of the material. (Shalin Marathe, et al., 2018) analysed the impact of the above factors on weld strength of AA6061 aluminium alloy. For fabrication of the weld Vertical milling machine was employed. In this study velocity of rotation of tool and traverse speed are taken. Taguchi and ANOVA analysis along with surface response method is adopted. For effective weld strength tool traverse velocity of 15mm/min along with rpm of tool as 2750 revolution per minute along with taper pin profile was optimized.

B. Effect on Microstructure of Welded Specimen

Welding of different aluminium alloys is tedious to achieve by conventional welding because imperfections like porosity along with hot cracking. [8] Investigated that FSW will prove effective in welding of unlike alloys of Al i.e AA6061 **-** AA5086 for analysis of microstructural changes in various regions. Detection and analysis of microstructural changes were achieved with the help electron microscope. Comparison of microstructural changes along with tensile properties was estimated and it was revealed that hardness value 115 and effectiveness of joint was 56%.

With decrease in the spindle speed the robustness of the welded joint also reduces. [O V Flores, et al., 1998] investigated the tensile strength related characteristic of weld nugget. Welding in case of FSW process takes place due to plastic deformation of the material to be joined. (J.Q Su, T.W Nelson, et al., 2002) investigated and compared the parent metal which was not affected with the TMAZ and HAZ. The aluminium alloy used was AA7050 T651 of 6.35mm thick. The study revealed that the microstructure of parent metal was completely changed and was converted to equiaxed grain structure. Continuous Dynamic Recrystallization was the vital mechanism used.

Fusion welding of high strength AA7039 alloy is not feasible by conventional fusion welding technique since it leads to solidification defect like cracking and porosity. [R.K.R Singh, Chaitanya Sharma et al., 2010] analysed the grain size behaviour and robustness of high strength aluminium alloy AA7039 in after welding heat treated condition were studied. Butt welds were fabricated of size 150mmx50mmx6mm of AA7039 with cylindrical pin profile .The paper concluded that TMAZ has coarser grain structure compared to nugget zone which has fine and equiaxed grains. Peak temperatures attained during FSW strongly influences the microstructural changes of the material to be joined. [11] performed the FSSW of aluminium and Mg alloy. Experiments revealed that for similar alloys like Al2024, Al6111 and AZ91 the peak temperatures attained where near to solidus temperatures of parent metal. Whereas in case of dissimilar materials Al6111/AZ91 peak temperature attained corresponded to alpha Magnesium plus the eutectic temperature of 437°C Although for FSP, there is no filler material used but to enhanced robustness of dissimilar welded joints [12] used Nickel foil as filler material. Experiment was conducted for hybrid laser FSW among AA6061 T6 and AZ31 Magnesium alloy. When comparison was made among the FSW and Hybrid welding(laser) of above dissimilar plates defect free weld were observed in laser hybrid welding. In case of no filler material for FSW process, the tensile strength was gone up to 66% of base material of Magnesium for hybrid welding merely because of Nickel foil used.

It was researched by [13] wherein influence of factors on tensile strength, crack initiation along with fatigue propagation of dissimilar aluminium alloys was described. Factors influencing the friction stir welding were defined through a optimizing software known as mode FRONTIER. UTS and YS increase as force of welding was increased. For alloys which are precipitation hardenable welding parameters along with tool geometry were critical. Tool geometry and tool thickness influenced the TMAZ and HAZ respectively. While FSW was performed the change in microstructure of welded joint was consequential with the internal stresses developed within the weld. In case of FSW, highest temperature achieved in the process and the quenching of welded component attributes to the quality of weld. [14] carried out experiment to analyse the mechanical properties in relation to quenching rates. A 6.35mm thick plate of AA7050 T7451 was used in this investigation. Output variables like microstructure of welded specimen , robustness of weld and hardness were found out with variable process parameters along with the limiting conditions. Submerged friction stir welding resulted in reduced size of grain structure of the welded specimen, torque and energy consumption was also more compared to normal FSW. Transversal tensile strength was having powerful relation with heat affected zone.

It was [15] studied the FSW of four mm thick plate of AA5083 along with influencing factors like velocity of rotation of tool keeping the speed of welding constant (40mm/min). Tool profile used was having taper shape. Experiment was conducted at 900, 1120, 1400 and 1800 revolution per minute. Study revealed that better tensile strength was achieved at 1120(rpm).

AA1100 aluminium alloy is one of the alloys having high corrosion resistance majorly used for sheet metal application with moderate strength. Experiment was performed (P Raja et al., 2018) to study the UTS of the welded joint by varying rpm of the tool and speed of welding. FSW process was performed on CNC machine by variable process parameters. Ultimate tensile strength of 98.08 Mpa was evaluated and it was 19.12% less than the base material. YS of the base metal were found as 66.76Mpa with 0.2 per cent on stress-strain curve.

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Use of [16] Zinc Aluminium alloy in his experimental work to examine the microstructure and micro hardness of heat treated AA7020-O produced by FSW process. It implied that residual stresses were reduced with increase homogeneity of grain structure due to heat treatment. Optimization of process parameters was found and and sound welding was produced at minimum weld speed. Fine grain microstructure structure was observed by maximizing the rate of welding.

To have a clear study of the factors affecting the robustness and microstructural changes by conducting heat treatment after welding was done, [M.W. Mahoney, et al., 1998] carried out a study. Wherein alloy selected was a AA7075 T651 and the thickness of plate was 6.35(mm). Post weld aging process was carried out and it revealed that the deteriorated tensile strengths of the welded nugget was improved. But this was accomplished at the loss of ductility and UTS. It also concluded that brittleness could be significant if long term natural aging was to be performed. Tear ridges were observed after conduction of fractography when a comparative study was made between as weld and post weld situations. Micro cracks were observed in after weld situation were larger compare to micro cracks in as weld situation. Fracture occurs along the flow lines in both the cases, but in case of post weld it occurred at a very close distance from the weld nugget (2mm). Yield strength was unaffected in post weld aging phenomenon.

Impact of internal stress and grain size variations in FSW of aluminium alloy AA2050 [17] were studied. In this research work to find the internal stresses developed a method called cut compliance method was used. Also in this study crack propagation in the FSW weld was studied. It was observed in the experiment that fatigue crack initiation was significantly formed due to internal stress developed during FSW process. Two approaches were used to determine the fatigue crack initiation viz. cut compliance method and stress intensity factor.

On the same lines, but using different approach [18] analysed the microstructure grain size of AA2195 (Aluminium-Copper-Lithium-Magnesium) aluminium alloy. A approach wherein author used a method known as “stop action method” by freezing the FSW process. Sudden halting of the FSW process and at once quenching resulted in visible sectioning of the grain structure.

The peak temperature reached during FSWP causes a considerable change in the microstructure in the thermal mechanical heat affect area or (TMAZ) along with (HAZ). To study the grain size distribution occurring along these areas [10] performed the investigation in AA2519. FSW resulted into coarser grain structure in this alloy which were accountable for the strength of this alloy got converted into equilibrium stage in both the zones. Peak temperature attained during FSW give rise to fine scale metallurgical phenomenon along with age hardening.

C. Effect of tool Geometry

Over the years, researchers have recognised that pin profile of tool is important factor which influences the grain size distribution and various other attributes of the weldment. Primarily the FSW tool serves two purposes viz. the flow of material and localised heating. It also influences the higher temperatures attained during FSW process, energy required etc. In this regard [19] carried out research for AA7075 T6 simply to find the optimum shoulder diameter of the tool. It was inferred that with increase of shoulder diameter the highest temperatures attained during FSW process also increases. Perfect diameter of the tool shoulder was evaluated for different rpm. For 355 rpm corresponding tool shoulder diameter was 30mm, for 560rpm corresponding tool shoulder diameter was 25mm and for 710rpm corresponding tool diameter was 20mm respectively. Energy required for above combinations was also high. Peak temperatures attained were well under limits for conventional FSW.

Figure 2: A taper cylindrical tool profile

In case of dissimilar alloy also tool profile be it taper, cylindrical or concave shaped inverted tool have impact on the grain structure. Study of impact of profile of the tool in FSW of AA6061-AZ61 was carried out [20]. Analysis from ANSYS inferred that heat flux was more in case of internal taper tool profile whereas in case of threaded geometry of tool uneven distribution of heat flux was observed. The higher temperatures attained in case of FSWP is primarily due to heat generated because of friction at the weld area. Amount of heat generated differs for various tool pin profiles. Experiment conducted for AA1100 [21] revealed that SS310 tool accord largely to heat generation. Since the effect of pin diameter was not significant it was kept minimum. Favourable conditions for FSW of AA1100 were achieved with concave shoulder along with conical shape of the toolpin. Tool geometry like the inclination of the tool with the surface plays a significant role in analysis of force and torque accompanied in friction stir welding process. An experimental investigation was conducted [22] to study the force and torque generated and its influence on microstructure on welded joint for AA6061 T6. The study showed a considerable increase in the force, both welding force and downward force, with rise in tool inclination with the horizontal. A comparative study was made among taper tool and taper threaded tool which inferred that generation of torque and downward force was less in tool which was taper and contrarily welding force was high in the same. It concludes in case of tool which was taper thread that changes incurred in force of weld decrease with rise in magnitude of tilt of the tool. A [23] relative analyses between tool profile viz. straight and tapercylindrical tool profile was performed in FSW of AA2014 aluminium alloy. For the above alloy having application in aircraft structures, use of tool profile which was taper and cylindrical contributed to defectfree welds. The mechanical properties were also enhanced with the usage of taper cylindrical tool profile. It was [24] investigated that the influence of velocity of rotation of the tool and geometry of tool on aluminium alloy AA6061 which has good corrosion resistant properties. Various tool geometries like square, taper, straight, threaded etc. were considered for fabrication of joints in the range of 800 rpm to 1600rpm. It was inferred that the tensile and mechanical properties were enhanced by the use of square pin profile of the tool at 1200rpm. Along with mechanical properties, significant improvement was observed in microstructure. The welding in case of FSW process takes place due to plastic deformation of the weldments. The effect geometry of tool on the fluidity of the material was [S. D. Ji, et al., 2012] studied. In this investigation aluminium alloy AA2014 was used and a finite column model of FSW was created. In the welded area the velocity of flow of material was observed to be high when the cone angle was decreased. It was concluded that the better flow behaviour was achieved by concentric shoulder of tool. In a experimental study conducted [25], FEM (Finite Element Method) was used to predict the material flow characteristics along with microstructural changes. The FSW process was carried to weld AA6061 and AA7075 respectively. In this study tool geometries having conical and cylindrical pin profiles were used along with changes in the advancing side speeds. It was inferred in the research that the flow of material along the RS was in the same direction of the rotating tool whereas in case of material flow along AS was unlike that of the direction in which tool was rotating. The effect of inclination or tilt angle of tool with the surface on quality of weld of FSW of Al alloy AA5052 -H32 were conducted [Shamsudeen , et al., 2018] and weld quality was measured in terms of UTS. It was inferred by the author that a square tool pin profile attributed to better weld joint. A rise in the magnitude of angle of inclination of the tool lead to good coalition of material below the tool shoulder and was one of the influencing parameter for good weldability. In a experiment conducted on FSW on milling machine of AA1100 [27] consequences of pin profile of the tool on the microstructure and allied attributes were studied. The heat generated in the FSWP is governed by the tool profile which is adopted to perform the said welding. The comparative studies were presented for flat shoulder and centred circles and spirals. The research concluded that broad weldstir region was more significant in centred circles and spirals shoulder profile than the flat shoulder along with large grain size. The tool geometry also significantly contributed to different material flow regions and amount of frictional heat generated.

Practical studies were performed by [28] on AA5754 H111 aluminium alloy wherein the shoulder geometry and the coating of the tool were considered to examine the quality of weld nugget. The hardness and the grain size obtained in were largely attributed to the size of shoulder of the tool. There was certainty in the welds obtained with carbide coated tool shoulder. Also it was inferred that even quality welds were obtained with the use of cone tool.

III. CONCLUSION

In this review paper the process parameters involved in FSW process are discussed and their impact on mechanical properties, microstructure and tensile strength are elaborated. Many authors are applying FSW/P both for similar aluminium as well as for dissimilar aluminium alloys. Strong inferences regarding the UTS of welded specimen were obtained which in the former case was less in comparison to that of base material also implied good robustness compared to other welding process. Apart from this some researchers are utilizing some simulation methods to validate their analyses in relation to material flow characteristics at and around the TMAZ and HAZ respectively.

Since aluminium and its alloys are having high strength to weight ratio will find large scale application in manufacturing sector in near future. Having said that, dissimilar aluminium alloys will more researched and studied for numerous commercial applications.

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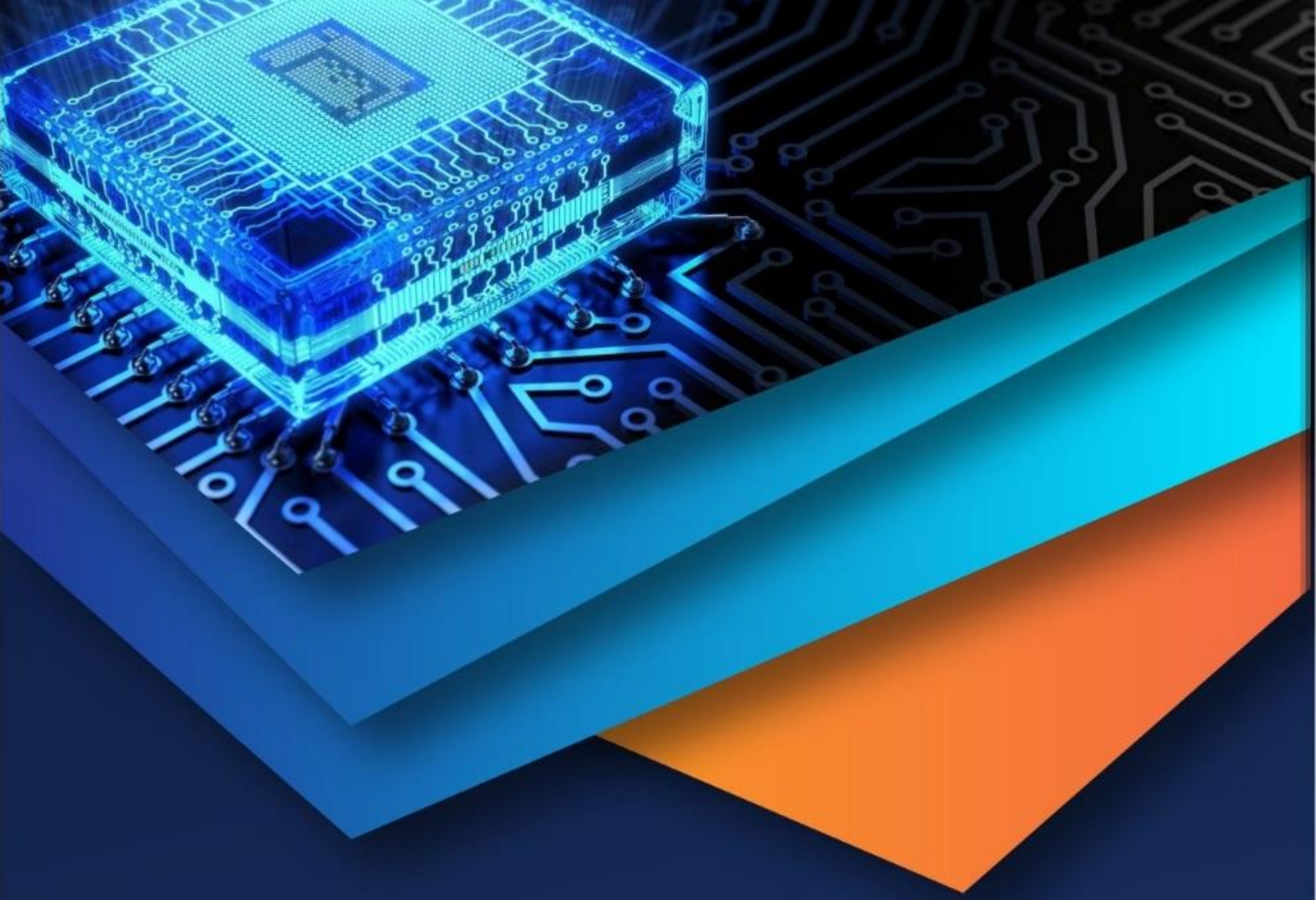

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