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Thermo-Mechanical Modeling of Friction Stir Welding of Copper Plate

Vipul Pranami[1]
[1]Assistant Professor of Mechanical Department, K.J. Institute of Engineering and Technology, Savli

Abstract*: Friction stir welding is a quite a new solid-state joining process. This joining method is energy efficient, environment friendly, and versatile. In specific, it can be used to link high strength aerospace aluminum alloys and other metallic alloys that are hard to weld by straight fusion welding. FSW is considered to be the most significant growth in metal joining in a era. In recent times, friction stir processing (FSP) was developed for microstructural modification of metallic materials. In this research paper, thermo-mechanical modeling of friction stir welding of copper plate is addressed. Specific emphasis has been given to: (i) mechanisms responsible for the formation of welds and microstructural refinement, and (ii) effects of friction stir welding parameters on resultant microstructure and concluding mechanical properties. The technology diffusion has ominously overtaken the fundamental accepting of microstructural evolution and microstructure– goods relationships.
Keywords: Friction stir welding, friction stir processing, thermo-mechanical modeling, diffusion,

I. INTRODUCTION

Friction stir welding is a solid-state welding process that acquired plentiful attention in research areas as well as manufacturing industry ever since its introduction in 1991. For nearly 20 years, FSW has been used in high technology applications such as aerospace to automotive till high meticulousness application such as micro welding. The foremost feature of a solid-state welding process is the non-melting of the work material which permits a lower temperature and a lower heat input welding process comparative to the melting point of materials being joined. This is expedient over the conventional fusion welding where excessive high heat input is required to melt the work material. Much less heat input required for FSW renders into economic benefits, harmless and less intricate welding dealings. The friction stir welding make it possible to join lightweight materials such as magnesium alloy, aluminum alloy, titanium and copper alloys which are very challenging to weld by conventional welding. These pure advantages have greatly increased the usage of these materials in structural solicitations. In addition, FSW also makes possible to produce thorough weldment in 5000 and 7000 series aluminum alloys that are not likely to be welded using conventional method. FSW does not produce flames or sparks. As a result, safety, environmental and lawmaking issues are not of major worry. FSW process provides confirmed good quality and strong weldment with cheap and lesser number of equipment, eradicates the use of filler metal and improved weldability. Due to these factors FSW has successfully been in a job in aerospace, automobile and ship building industries. The necessity to supplementary understand and improve FSW process continues to promulgate in many applications. Many researchers have looked into numerous methods including mathematical modelling of the process, targeting at understanding the physical-material interaction. Nevertheless, there is lack of recorded work in the literature on a system or method to quantitatively measure the welding parameter such as torque and force in FSW process.

II. FRICTION STIR WELDING PROCESS AND ITS STAGES

Friction stir welding set up consists of (1) cylindrical rotational tool, (2) two or more work materials of like or unlike material groupings (3) backing plate and (4) clamping or holding fixture as shown in figure 1. The rotating tool design consists of a combination of two cylinders of a definite radius ratio known as shoulder and smaller radius pin or probe, where the height of the pin or probe is generally more than half of the work material thickness and not equal to its overall thickness. The work materials to be joined may be arranged as orthodox welding method but the most common alignments used in FSW are abutted and lapped alignments. For any alignment, FSW has the competency to join thick plate without the need for special groundwork erstwhile to welding process. In the interim, the backing plate is to ensure the establishment of confine volume and it becomes a must when welding with a pin penetration imminent the bottom of the work materials. The most crucial part of the work materials set up is the holding or clamping fixture. Improper clamping may put at risk the mated surfaces to be welded and will engender gaps leading to the formation of worm hole or cavities in the weldment. FSW is the non-filler process; henceforward no ancillary material to fill in gaps created by the separation of the work materials is required.

FSW process encompasses four phases which are (1) plunging phase, (2) dwelling phase, (3) welding phase, and (4) retract or exit phase. Temporarily, the process starts with rotating tool pin or probe propelling onto the aligned work materials under a constant axial load to generate friction heat. This process will uninterruptedly increase the temperature at the immediate contacting surface of the rotating tool and work material. The process continue until the temperature at the immediate contact of the rotating tool and the work material increased to a temperature which bases the work material to soften, plasticized and ominously lose its strength. Subsequently, these conditions allow the rotating tool to penetrate to a certain depth generally just about to the thickness of work material. The plasticized material is subjected to dislodgment by the rotating tool pin plunge, efficiently being flied out with a portion of the generated heat, thus introducing new abrupt lower temperature and harder surface of work material. This event elucidates the transient heat generated through pure mechanical friction work at the tool and work material interface. The end of the plunging phase is connoted by the sound contact of the rotating tool shoulder with the immediate work material surface. At this instant, the process enter the dwelling phase where the rotating tool is permitted to dwell for a period of time, initiating the temperature to increase further, up to its hot working temperature. The heat engendered from frictional work is greatly dependent on the qualified increase of contact surface area as well as the comparative speed. The heat generated causes the affected area under the shoulder to expand sizably. Remarkably, the heat causes the work material close to the immediate contact to lose its strength and becoming plastic. As soon as this condition is reached, thin soft material layers is produced and would stick to the dynamic rotating tool surfaces, pin and shoulder and being forced to be evacuated along. Suddenly the mechanical friction heat generation is moderately turned into plastic dissipation heat generation. It is explained by the energy debauched from the internal shearing of diverse velocity between the displaced soften work material layers to static more solid surface. In an ideal world, intermittent heat generation mechanisms due to friction work and plastic dissipation take place because of the transient heat transfer consequence and the material ability to regain its strength as heat is lost to the atmosphere. In tallying, the other role of these frictional work and plastic deformation mechanisms are to tempt soft material displacement and causes the stirring action or unembellished material deformation which later produce the amalgamated joint.

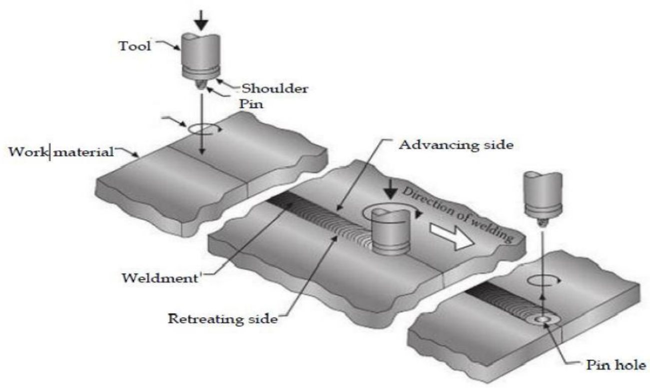

Fig. 1 *Friction stir welding process phases of a butted work material configuration*

The dwelling phase is tailed by welding phase. Once the local temperature of work material under the rotating tool reaches its hot working temperature and is ample soft to be stirred and expatriate, the rotating tool is moved crossways along the welding line. This traverse motion caused the plasticized soft material at the prominent edge of the rotating tool being cuddled and sheared through a small gash formed by the displaced soft material at the side or adjacent of the tool, if possible in the tool rotation direction. The displaced soft material is then dumped to the gap at the trailing edge left by rotating tool pin or probe. The soft plasticized material is displaced forcedly by the rotating tool along its rotating direction under a closed encapsulation of stiffer solid work material wall and gyrating tool shoulder. The soft material is forged to the trailing edge in layers, founding weld nugget. Next to each traverse increment of the rotating tool motion, the shifting of soft plasticized work material to the trailing edge will bring together new solid, lower temperature work material at the leading edge. Thus it reinstates friction work heat generation mechanism aforementioned to plastic deformation mechanism and unceasingly repeating the heat generation process all over yet again at each traverse displacement of the tool. This produces cyclical transient heat generation. This cyclic process takes part during the course of the welding phase and strongly exaggerated by the combination of the rotating tool's traverse and rotational speed. Recapitulation, during the welding phase the plasticized material is exposed to displacement, extrusion and shearing mechanisms eased by the tool rotation, thrust and transverse movement under cyclic heat generation along welding line and as a final point merging welding nugget in the trailing side. At the end or exit phase of FSW process, the rotating tool is withdrawn from the work material leaving a cylindrical hole mark that once occupied by the tool pin. For beautifying reason, the cylindrical hole may be jam-packed with filler material at the end of the welding process but the most conjoint method used is by bringing together dummy material prior the exit phase. Dummy material is of the same material used for the work material to be weld and placed at the end of welding line where the rotating tool is permitted to traverse to and exit inside it. The dummy material is far along to be cut away leaving good surface finish. Though, this highlighting issue would remain in the application of innovated friction stir spot welding. These procedure phases in FSW are reliant on to one another to produce a good incorporated weldment and are strongly affected by the welding constraints. The promise of good weldment is determined by proper control of erratic measureable welding parameters such as rotational speed, torque and axial plunge force, traverse speed, tool geometry and coordination in the form of heat energy. Analogous to other conventional welding methods, heat energy remarkably determines the quality of the joint.

III.LITERATURE REVIEW

Considering the heat generation and the temperature history during the friction stir welding process is the prime step towards accepting the thermomechanical interaction taking place during the welding process. The initial modeling maneuvers focused on probable estimation of heat generated during the FSW process.

Song and Kovacevic [2002] projected a united heat transfer model of both the tool and the workpiece for FSW to embrace the tool penetration and pulling out phase. A poignant coordinate was adopted to reduce the strain of modeling the heat generation due to the movement of the tool pin. The finite difference method was used for unraveling the control equations and the results acquired were in good agreement with the experimental outcomes. Chen and Kovacevic [2003] proposed a 3-D finite element analysis model to study the thermal past and thermomechanical process in butt welding of aluminum alloy 6061-T6. The model assimilated the mechanical reaction of the tool and thermomechanical processes of the welded material. The friction between the material, the probe and the shoulder was involved in the heat source. X-ray diffraction technique was used to quantify the residual stresses developed in the plate and the measured outcomes were used to authenticate the effectiveness of the proposed model. From the study, it was reported that fixturing relief to the welded plates affected the stress distribution of the weld. Soundararajan *et al.* [2005] urbanized a finite element thermomechanical model with mechanical tool loading bearing in mind a uniform value for contact conductance and used for envisaging the stress at workpiece and backing plate interface. The non-uniform contact conductance were defined from pressure distribution silhouettes and used in predicting the temperatures in the thermal model. The thermomechanical model was then used in forecasting the developed stresses. X.K.Zhu and Y.J.Chao [2003] carried out 3-D non-linear thermal and thermo-mechanical numerical simulations for the FSW of 304L stainless steel. They developed FEA code WELDSIM. They scrutinized two welding cases with tool rotation speed of 300 rpm and 500rpm.The main motto was to study the variation of transient temperature and residual stress in a friction stir welded plate of 304L stainless steel. They determined transient temperature field and calculated residual stresses in the welded plate using a 3-D elastic-plastic thermomechanical simulation.

Y.F. Sun *et al.* [2010] investigated of the welding parameter dependent microstructure and mechanical properties of friction stir welded pure copper. The process included a welding speed ranged from 200 to 800 mm/min, a rotation speed ranged from 400 to 1200 rpm and an applied load ranged from 1000 to 1500 kg. In the stir zone, a remarkably refined microstructure with average grain size of 3.8 m can be obtained by increasing the applied load to 1500 kg Zhang Wen *et al.* [2012] studied microstructure and mechanical properties of dissimilar pure copper/1350 aluminum alloy butt joints by friction stir welding. The dissimilar friction stir welding of pure copper/1350 aluminum alloy sheet with a thickness of 3 mm was investigated. Complicated microstructure was formed in the nugget, in which vortex-like pattern and lamella structure could be found. No intermetallic compounds were found in the nugget. The hardness distribution indicates that the hardness at the copper side of the nugget is higher than that at the aluminum alloy side, and the hardness at the bottom of the nugget is generally higher than that in other regions. The ultimate tensile strength and elongation of the dissimilar welds are 152 MPa and 6.3%, respectively. Rodrigues *et al.* [2013] studied the influence of the shoulder geometry on FSW of 1mm thick copper-DHP plates. The welds were produced using three different shoulder geometries, flat, conical and scrolled, and varying the rotation and traverse speeds of the tool. The flat shoulder tool proved to be inadequate for performing welds, because many defects were produced for all welding conditions. In turn, the scrolled shoulder tool is more effective than the conical one in the production of defect free welds. X.Y. Chen *et al.* [2013] studied microstructural evolution and mechanical properties of dissimilar Al–Cu joints produced by FSW. A defect-free joint was obtained when the traverse speed was lowered from 40 mm/min to 20 mm/min. A good mixing of Al and Cu was observed in the weld nugget zone (WNZ). A large amount of fine Cu particles were dispersed in the upper part of the WNZ producing a composite-like structure. In the lower part, nano-scaled intercalations were observed and identified by transmission electron microscopy (TEM). A distinct rise in hardness was noticed at the Al/Cu interface.

IV. THERMOMECHANICAL MODELING

The prime liability of thermal model is to reckon the transient temperature fields developed in the workpiece during friction stir welding. A numerous assumptions have been made in developing the finite element thermal model, which include (i) work piece material is isotropic and homogeneous (ii) no melting occurs during the welding process. (iii) thermal boundary conditions are symmetrical across the weld centerline. (iv) Heat transfer from the workpiece to the clamp is neglected.

When the geometry part is concerned in the numerical model since the weld line is the symmetric line, only half of the welded plate is modeled. Also symmetric condition is used to reduce the simulation time. The dimensions of the copper plate s use was 60 mm × 20 mm × 3.1 mm. The length of the pin is 2.8 mm. Diameter of the shoulder is 12 mm and that of the pin is 3 mm. It is shown in figure 2. In the present thermal analysis, the workpiece is meshed using a brick element called SOLID226. The element has 20 nodes with up to 5 degrees of freedom per node. Three dimensional SOLID226 elements were used to mesh the sheets. A hexahedral mesh with dropped midside nodes is used.

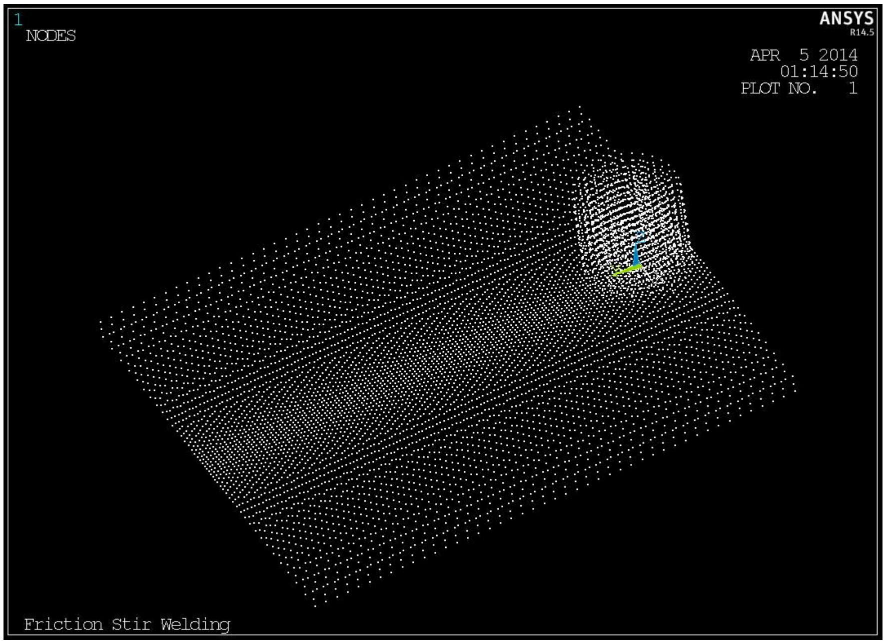

Fig. 2 *Geometry of the workpiece and tool*

Thermal properties of the material such as specific heat, thermal conductivity and density are temperature dependent. In FSW process an accurate estimation of temperatures is critical because the stresses and strains developed in the weld are temperature dependent.

TABLE I
THERMAL MATERIAL PROPERTIES OF COPPER

Temperature (°C)	0	200	400	600	800	1000
Thermal conductivity (W/m°C)	401	401	393	379	366	352
Specific heat (J/kg°C)	390	395	398.44	417	432	451
Density (Kg/m^3)	8940	8927	8903	8880	8867	8860

The solver consists of two load step i.e. load step 1 and load step 2 it lasts for 6.5 seconds. The load step 1 includes tool thrusting towards the workpiece material. It lasts for 0-1 seconds with the 10 sub steps of 0.1 seconds. In load step 2 tool starts rotating, generates heat due to friction and plunges into the workpiece. It lasts for time interval 1 to 6.5 seconds i.e. 5.5 seconds.

V. RESULTS

In this section temperature as well as stress responses are being shown in the form of plots for copper. The maximum temperature i.e. 800 °C is obtained at 6.5 seconds. The temperature's value varies in between 0.003227 °C to 519.233 °C from 0-2.5 sec. Maximum temperature is 519.233 °C beneath the tool. In the figure 4 the temperature range is in between 685.289 °C to 792.682 °C and the time duration is 5.0-6.5 sec.

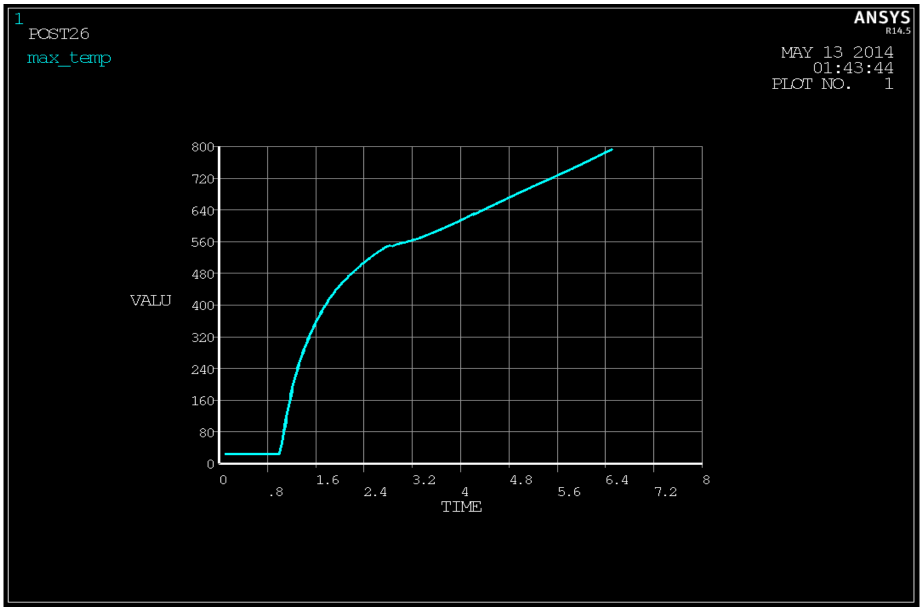

Fig. 3 *Plot of maximum temperature against time*

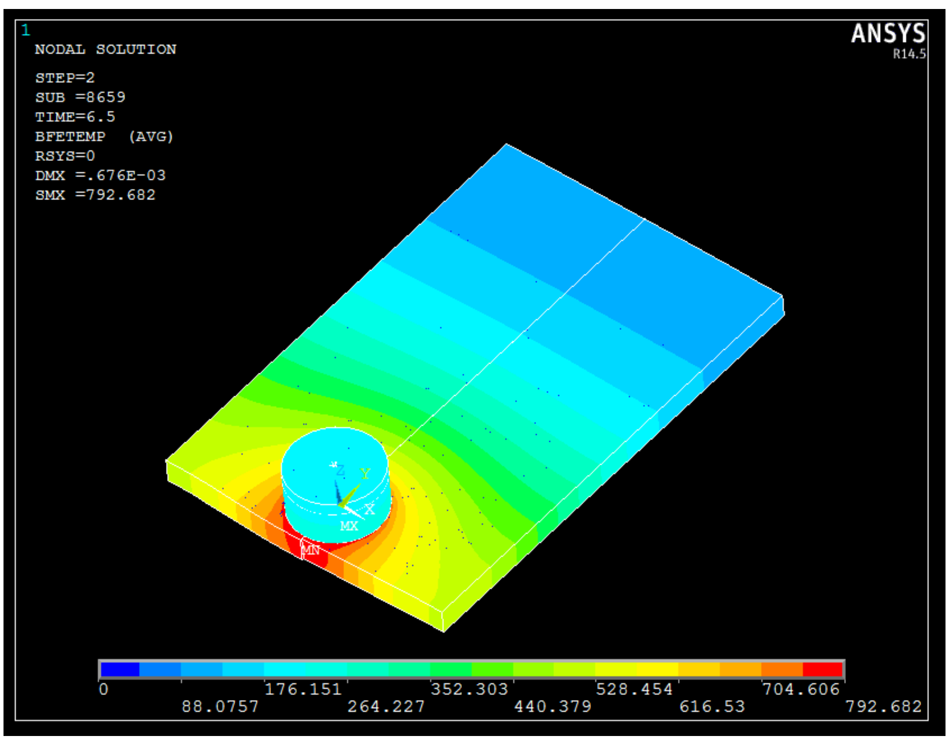

Fig. 4 *Plot of maximum temperature against time 6.5 seconds*

The equivalent stress varies from N/m^2 (SMN) to 0.99465 N/m^2 (SMX) as shown in figure 5 for the time duration of 6.5 sec.

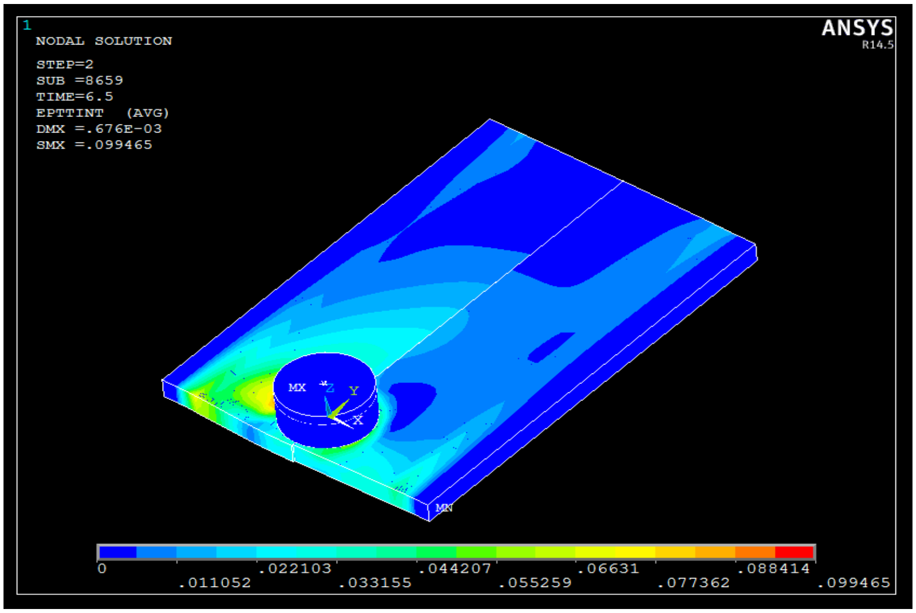

Fig. 4 *Plot of maximum stress against time 6.5 seconds*

VI. CONCLUSION

This simulation is carried out on copper plate having dimension 60mm × 20mm × 3.1mm. The diameter of tool shoulder is 12 mm and that of pin is 3 mm. Length of the pin is 2.8 mm. Tool is rotating at the 400-1200 rpm. Maximum temperature i.e. 792.682 ºC is obtained at 6.5 seconds. The temperature against time shows that the generation of heat due to friction begins in second load step. Figure 3 and Figure 4 clearly show that friction is responsible for generating most of the heat needed, while the contribution of heat due to plastic deformation is less significant. Because the tool-penetration is shallow and the tool pin is ignored, the plastic heat is small compared to frictional heat.

In future experimental investigations can be carried out to verify the numerical simulations observed over here.

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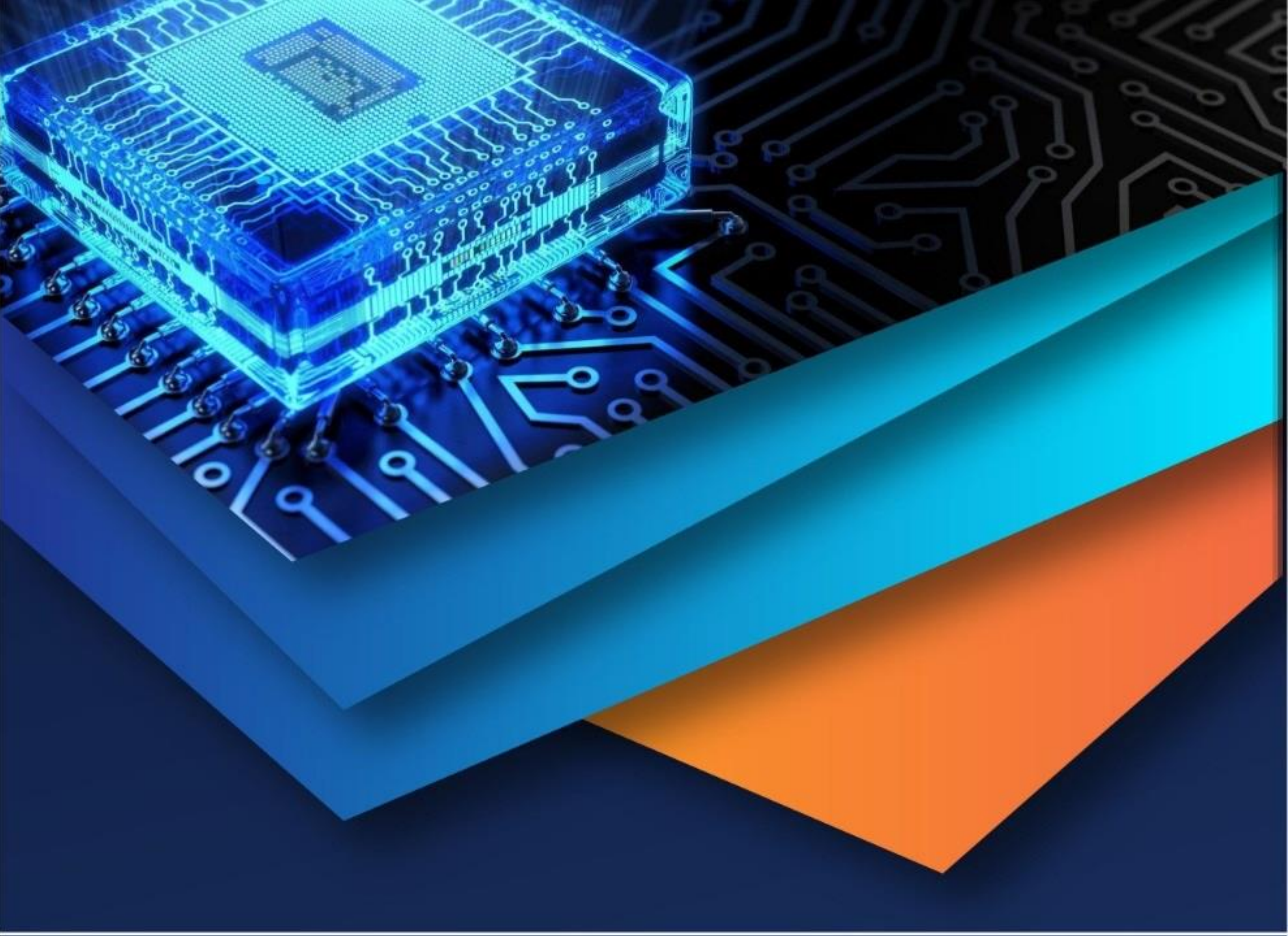

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