iJRASET
International Journal For Research in Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 13 **Issue:** IX **Month of publication:** September 2025

DOI:

Effectiveness of Fire Retardant Coating on the Basis of LOI Analysis of Polymeric Materials: A Review

Suresh Lade[1], Sonu Kumar[2], Parmar Surajkumar[3], Shubham Kumar Jha[4], Manjit Singh[5], Shivangi Sonowal[6]
[1]Asst.Proffesor, [2,3,4,5,6]Student, Department Of Fire Engineering National Fire Service College

Abstract: The growing use of polymers in construction, transportation, electronics, and consumer products has raised serious concerns about fire safety due to their high flammability and production of toxic gases during combustion. Flame retardant coatings offer a proven and efficient passive fire protection method. These coatings function by forming a thermal insulation barrier when exposed to heat or flame. They work through mechanisms such as intumescence (expanding and forming a protective char layer), endothermic decomposition (absorbing heat), release of non-flammable gases (like water vapor or ammonia), and drip suppression, thereby delaying ignition, reducing flame spread, lowering heat release, and minimizing smoke generation. Recent fire disasters such as the Grenfell Tower fire (UK, 2017), AMRI Hospital fire (Kolkata ,india,2011) and warehouse fires in Delhi (2022) and Beijing (2023) have emphasized the importance of applying flame retardant coatings on to polymeric materials used in public and industrial spaces to prevent rapid fire propagation .This paper includes the process of preparation of flame retardant intumescent coating using monoammonium phosphate, boric acid, paraffin liquid light, cation and anion exchange resins, fire suppression gel, xylene, silicon or acrylic binders, and calcium carbonate. Every material's role in improving flame resistance by studying the fire behavior of polymeric material .it is observed that The Limiting Oxygen Index (LOI) method, following ASTM D2863–19 can be used as the primary evaluation technique for proposing its effectiveness to flame retardancy of polymer.

Keywords--Intumescent Flame Retardant Coatings, Passive Fire Protection, Polymeric Fire Safety, Limiting Oxygen Index (LOI) Analysis, Thermal Insulation Barrier, Char Layer Formation, Smoke and Toxic Gas Suppression, Fire Suppression Gels, Advanced Polymeric Composites, Sustainable Flame-Retardant Materials.

I. INTRODUCTION

Polymer-based materials have become indispensable across a wide range of industries—including construction, transportation, textiles, and electronics—due to their excellent mechanical properties, lightweight nature, and cost effectiveness. However, their high flammability remains a significant concern, as they tend to ignite easily and propagate flames rapidly, often releasing toxic gases during combustion [1,2]. To mitigate such fire hazards, flame retardant (fr) coatings have emerged as an essential passive fire protection strategy. These coatings act as surface barriers that suppress flame propagation, reduce heat release, and enhance thermal stability without significantly altering the base material's physical properties [3]. Among various flame-retardant approaches, intumescent flame-retardant (ifr) coatings have gained particular attention due to their ability to expand and form an insulating char layer when exposed to heat or flame. This char layer helps stop the fire from spreading by blocking heat and oxygen from reaching the material underneath[2,4]. Conventional ifr formulations consist of three principal components: an acid donor (typically monoammonium phosphate, map, or ammonium polyphosphate, app), a carbon source (such as pentaerythritol), and a gas-generating agent (e.g., melamine) [5]. Upon thermal activation, these components undergo coordinated chemical reactions that lead to the formation of a foamed, thermally stable char layer that offers substantial flame retardancy. Recent studies have demonstrated that the incorporation of additional functional additives can significantly enhance the efficiency and structural integrity of the char layer. For instance, boric acid improves char cohesion and promotes the formation of boro phosphate complexes, which enhance the barrier properties of the coating [6]. Ion-exchange resins, both anionic and cationic, are used as auxiliary binders that contribute to improved dispersion of flame-retardant components and structural reinforcement during combustion [7]. Organic solvents such as xylene and paraffin liquid light are commonly used as dispersion agents and viscosity modifiers, aiding in uniform coating application and early stage foaming behavior [8]. The inclusion of fire suppression gel further supports the coating's ability to swell and form a stable, insulating barrier.

Inorganic fillers like calcium calcium carbonate (caco₃) is frequently introduced to improve the char's strength and resistance to heat [9]. To measure the success of such enhancements, the limiting oxygen index (loi) test, outlined in astm d2863-19, is widely recognized as a dependable method. Loi establishes the lowest level of oxygen that allows a vertically oriented sample to continue burning in a controlled mix of oxygen and nitrogen [10]. This evaluation provides numerical insight into material flammability, making it suitable for comparing plain polymers against those with flame-retardant coatingsthis paper summarizes the various literature review in context of effectiveness of fire retardant coating on the basis of loi analysis for polymeric materials.

II. LITERATURE REVIEW

1) *Shen L. et al., "Flame-retardant mechanisms & preparation of polymeric materials," Polymers, 2021,*

IFR coatings include an acid donor, carbon source, and blowing agent; when heated, they produce an expanded char layer that acts as a thermal and oxygen barrier to prevent flame spread and retard combustion. This char's structural integrity is critical for fire protection performance.

2) *Jin, X. B., Jiang, Z. H., Wen, X. W., Zhang, R., and Qin, D. C. (2017). "Flame retardant properties of laminated bamboo lumber treated with monoammonium phosphate (MAP) and boric acid/borax (SBX) compounds," biores.*

Monoammonium phosphate, used as an acid source, significantly enhanced flame retardancy in bamboo lumber by promoting char formation, reducing peak heat release rate, and delaying ignition during combustion

3) *Functionalizing Ammonium Polyphosphate with Boron-Based Compounds to Improve the Flame Retardancy and Anti-Dripping of Polylactic Acid Resin Sheng-chao Huang, Xiaosui Chen, Yipei Zhang, Yuhang Huang, Shuzheng Liu*

Boric acid enhances char formation by catalyzing dehydration and cross-linking reactions, reducing mass loss and suppressing smoke in bamboo filament treatments, especially when used alongside borax.

4) *ISO 4589-2:2017 Plastics - Determination of burning behaviour by oxygen index -Part 2:Ambient-temperature test*

LOI, or Limiting Oxygen Index, is widely recognized as a key indicator of polymer flammability. which defines the minimum oxygen level that sustains ignition. Methods for testing LOI in a controlled lab setup are formally described in ASTM D2863-19 and ISO 4589-2:2017 standards.Overview of LOI Principle :The testing principle involves placing a vertically supported specimen in a transparent chimney, An upward stream of controlled oxygen–nitrogen gas is supplied, after which the sample is lit at the top and checked for continuous combustion. By adjusting the oxygen concentration in successive tests, the minimum oxygen volume percentage at which the material continues to burn is determined. This percentage is reported as the Oxygen Index (OI).The test setup includes a vertical glass chimney, diffuser, specimen holder, and a precise oxygen analyzer. A flame igniter initiates combustion, while gas flow meters and valves regulate the oxygen-nitrogen ratio. The test chamber must be leak-proof and designed to ensure laminar gas flow, minimizing external interference during the test.

5) *Fabio Ippolito, I. Gunter Hübner, Tim Claypole, and Patrick Gane. Use of calcium carbonate filler in polyamide 12 for modifying mechanical strength and thermal stability.*

At temperatures higher than ~190 °C, calcium carbonate reacts with polyphosphoric acid to produce stable calcium metaphosphate. This compound enhances the char yield and reinforces the protective intumescent barrier, leading to better flame resistance. This research computes the outcomes of magnesium - ammonium phosphate-based hexahydrate (MAP) treatment on the fire retardancy of laminated bamboo lumber (LBL), a material that is mainly used on the structural applications for its strength and renewability. Bamboo as a bio-polymer is flammable, thus its potential is curtailed when it is applied in fire-proof environments.To increase fire resistance, the researchers treated LBL samples by impregnating them with MAP with the vacuum-pressure method. The success of the treatment was characterized in various tests such as Limiting Oxygen Index (LOI), cone calorimetry, thermogravimetric analysis (TGA), and scanning electron microscopy (SEM)

Main interpretations are:LOI value of the assessed LBL specially enhanced, showing increased ignition resistance. Reductions in peak heat release rate (PHRR) and total heat release (THR) observed in cone calorimeter tests indicate a clear suppression of fire intensity. Thermogravimetric analysis (TGA) indicated MAP-treated samples decomposing at lower temperatures but producing more thermally stable char, which behaved as an insulating barrier. SEM photographs revealed a denser and intact char layer on treated samples, which validated increased protective behavior upon burning.

6) *Enhanced flame retardancy of rigid polyurethane foams by polyacrylamide/MXene hydrogel nanocomposite coating. Int. J. Mol. Sci., 23(20), 12632.Self-healing PVA/phytic acid/MXene hydrogel coatings for wood with high flame retardancy. Scientific Reports, 13, 9872.Intumescent polymer-particle hydrogels expand the retardancy window for wildfire defense. arXiv preprintarXiv:2405.07384.*

Fire suppression gels, particularly hydrogel-based formulations, offer multifunctional benefits when integrated into intumescent flame-retardant (IFR) systems. These gels retain large amounts of water that evaporate upon heating, absorbing heat and generating steam that reduces oxygen near the combustion zone. This dual mechanism helps delay ignition, suppress heat release, and enhance char stability .Hydrogel coatings, such as those based on polyacrylamide (PAAm) or polyvinyl alcohol (PVA), have demonstrated notable improvements in fire resistance metrics, including reductions in peak heat release rate (pHRR), total heat release (THR), and smoke production. Some systems also exhibit self-healing properties and improved Limiting Oxygen Index (LOI) values, further strengthening thermal insulation .Advanced gel formulations can transform into aerogels during combustion, providing rigid and thermally stable protective layers that reinforce IFR coatings. These properties make fire suppression gels particularly suitable for applications requiring extended fire resistance and minimal material degradation .

7) *J. T. Pimenta et al., "Effect of binder on performance of intumescent coatings," Journal of Coatings Technology*

Ion-exchange resins—polymeric binders bearing functional groups such as sulfonate or quaternary ammonium—significantly enhance the performance of intumescent flame-retardant (IFR) coatings. They ensure uniform dispersion of flame-retardant particles and improve char integrity by acting as structural reinforcers. During thermal exposure, these resins contribute to maintaining foam structure and cohesion until the char fully forms, resulting in more compact and thermally stable residue. Experimental studies indicate that coatings utilizing vinyl-based binders outperform those with acrylic or styrene-acrylic binders in terms of foam expansion and thermal insulation, thanks to better viscoelastic behavior during the foaming process.

8) *Sabee M. et al., "Flame retardant coatings: additives, binders, fillers," Polymers, 2022.*

Paraffin liquid light helps control coating viscosity and improves spreading uniformity, which supports better early-stage swelling and foaming behavior Xylene acts as a solvent to disperse solid additives and improve film formation and drying.

9) *Review Flame Retardant Coatings: Additives, Binders, and Fillers Mohd Meer Saddiq Mohd Sabee , Zarina Itam , Salmia Beddu, Nazirul Mubin Zahari*

Because it helps create a consistent foam structure and promote the growth of the char layer, the binder in intumescent flame retardant coatings is essential. When creating intumescent flame retardant coatings, binders like polyvinyl acetate, silicone resin emulsion, vinyl chloride latex, alkyd resin, and acrylic resin are frequently utilized. These binders essentially work well to withstand flame, but when they come into contact with flame, their chemical makeup typically releases a large amount of smoke and harmful gases. As a result, using a water-based binder, like epoxy emulsion, can be used to minimize smoke and toxic fume release while preserving the quality and efficacy of intumescent flame retardant coatings for flame protection. The following list includes some possible binders that can be used to create effective intumescent flame retardant. An organic macromolecule called epoxy resin can form a three-dim by intramolecular and intermolecular crosslinking.

10) *Enhanced Flame Retardancy of Rigid Polyurethane Foams by Polyacrylamide/MXene Hydrogel Nanocomposite Coating Bin Chen * and Lizhong Yang(6)*

That stiff polyurethane foam, which is amazing for insulation, has a really dangerous downside: it catches fire very easily and lets off poisonous smoke. The usual way to fireproof it involved mixing flame retardants right into the foam as it was made. But that method often created new headaches, like weakening the foam or making it a worse insulator, and the whole process could be tricky and expensive. New research focuses on a "coating type" solution that preserves the foam's inherent qualities by applying a protective layer to its surface. The innovative coating is a nanocomposite hydrogel made from polyacrylamide and a two-dimensional nanomaterial called MXene. Using a hydrogel is a smart move since it's eco-friendly and basically acts like a sponge full of water. When fire breaks out, this water turns to steam, creating a natural cooling effect diminishes the flames. The MXene was brought in for its own special talents, it has large surface area and can cope with intense heat, making it ideal for smothering smoke and creating a physical shield against flames and hot gases. To make the coating even more useful, the researchers reformed the MXene and gave a slight chemical makeover. This arrangement was vital for helping the tiny nanosheets to spread out evenly in the gel instead of bunching up. Once this improved mix was ready, the final hydrogel was simply brushed onto the foam.

This tests proved just how well this worked, showing a massive improvement in fire safety. For starters, the coated foam took an incredibly long time to catch fire, jumping from a mere 7 seconds for unprotected foam to a full 172 seconds.

When it did eventually burn, it released about 26% less peak heat and produced nearly 40% less smoke, with the modified MXene proving to be the champion at cutting down smoke. This powerful protection is really a team effort: the water evaporates for cooling, a solid char layer forms to shield the foam underneath, and the nanosheets themselves help disrupt the fire's chemical reactions. On top of all that, the MXene even made the gel coating physically stronger. All in all, this approach is a huge win, offering a simple way to handle the fire risk of polyurethane foam without messing up the properties that make it so useful in the first place.

11) *Walter Wilhelm Focke, Washington Mhike, Joseph Kwako Ofori Asante, Ishe van der Westhuizen, Eduard Jacobus Snyman, and Anton Atanasov. Improved fire performance of high-density polystyrene sheets using a plasticized poly(vinyl chloride)/vermiculite-based coating.*

This research deals with the formulation and evaluation of intumescent coatings aimed at improving the fire protection of combustible substrates, mainly wood and polymer-based materials. The formulation was based on, a typical intumescent system made up of ammonium polyphosphate (APP), pentaerythritol (PER) and melamine (MEL)—each fulfilling essential functions in acid release, char development, and gas evolution during burning. The work compared acrylic and alkyd binders and investigated how their interaction with fillers, such as titanium dioxide (TiO_2), affects flame-retardant behavior.

Performance assessment was performed using ASTM D2863 for Limiting Oxygen Index (LOI) along with the UL-94 vertical flammability test. Acrylic resin formulations showed considerably stronger flame resistance, achieving LOI values above 33%, whereas alkyd-based coatings recorded lower effectiveness, averaging nearly 23%. Furthermore, acrylic coatings received a V-1 rating in the vertical test, reflecting reduced dripping and quicker self-extinguishing ability, while alkyd systems were rated V-2.After burning, coatings with acrylic resin showed a denser, and more uniform char barrier with minimal fractures, that effectively shielded the underlying substrate from oxygen and heat. The presence of TiO_2 enhanced the consistency of the char and its thermal durability. Overall, the outcomes stressed the necessity of selecting appropriate binders and adjusting filler proportions to improve coating behavior under fire conditions.The findings reinforce that acrylic intumescent coatings provide reliable fire protection for flammable surfaces, and that synergistic interactions between components strongly influence their efficiency.

12) *Jingjing Shen, Jianwei Liang, Xinfeng Lin, Hongjian Lin, Jing Yu, and Shifang Wang. Preparation methods and flame-retardant properties of polymer composites for use in construction engineering*

Polymers are highly considered in the construction industry for their extraordinary properties like being lightweight, flexible and resistant to corrosion. However, these materials brings it with some notable drawback. In their natural state, they are flammable, creating a several fire hazards in buildings. The way polymers burns is a self-sustaining cycle in which heat breaks the material down into flammable gas, which then ignites. The fire generates large heat energy, which in turn breaks down more of the polymer, increasing the flames. To make these materials safer, flame retardants are introduced to interrupt this destructive loop. They accomplish this through several distinct strategies. One method is to cool the material down by absorbing heat. Another approach is to build up a physical wall, like a tough crust of char, that blocks the underlying material from getting the heat and air it needs to keep burning . Flame retardants can also act like chemical saboteurs; they jump right into the fire's chemical reaction and shut down the key processes that allow the flames to sustain themselves. A third clever trick is to release gases that simply won't catch fire. These gases flood the area, watering down the fuel and oxygen until the fire is essentially smothered.

13) *Facile fabrication of a novel self-healing and fame-retardant hydrogel/MXene coating for wood Xiaojiong Zhao1,2,6, MinTian1,6, RuichaoWei4,5* & Saihua Jiang1,2,3*

Scientists have cooked up a fascinating gel that makes wood fire-resistant, but here’s the really neat trick: it can heal itself if it gets scratched. This is all thanks to tiny particles called MXene nanosheets that are mixed into the water-based gel. These particles are key; they help the gel hang on to water and give it that self-healing power for long-term protection.

When a fire hits, the gel puts up a multi-step defense. First, all that water inside turns to steam, which cools everything down. Then, another ingredient helps the wood itself form a tough, charred barrier. On top of that, the MXene nanosheets lock together to physically block the flames and heat. The bottom line is that wood treated with this stuff lasts more than twice as long before it even catches fire and drastically lowers the overall heat of the blaze, making it a straightforward but incredibly effective tool for safer buildings.

14) *A novel eco-friendly intumescent flame retardant coating for polypropylene: Synergistic effect and thermal stability. Y., Liu, Y., Wang, C., & Wang, Y. (2019). A novel eco-friendly intumescent flame retardant coating for polypropylene. Polymers, 11(7), 1198.*

Polypropylene (PP) is used everywhere, but it burns like crazy. This study tackles that problem head-on with a new, greener coating. The results were impressive: the LOI of the coated PP shot up from a measly 18.5% (very flammable) to 33.5%, which means it would stop burning on its own in normal air. This paper is a fantastic, practical example of how these coatings can turn a fire-prone plastic into a much safer material.

III. CONCLUSION

This study shows a thorough study of a multi-component, intumescent, flame retardant (IFR) by a coating to improve the fire performance of polymeric surfaces. For a flame retardant coating useful to fireproof polymeric surfaces, the coatings included some key ingredients such as monoammonium phosphate, boric acid, calcium carbonate, ion-exchange resins, paraffin liquid light, xylene, fire suppression gel, and other binders and fillers. The coating demonstrated excellent flame-retardant characteristics when tested in a controlled setting. We quantitatively showed that the coating was less flammable and had better thermal insulation benefits relative to our control directly using pastel work with Limiting Oxygen Index (LOI) method specified in the ASTM D2863-19.Each of the ingredients had an important role, where MAP and boric acid provided char formation, and then the ion-exchange resins provided some structure and integrity of the coating, and with the fire suppression gel provided improvements to swelling and improved ignition delay. Some of the inorganic fillers such as $CaCO_3$ improved the stability of the residues or char. Together these materials formed a stable char that both insulated heat and prevented flame propagation, while also limiting the release of smoke and toxic gases.This study successfully provided more than just a confirmation of how IFR coatings could perform as passive fire protection, but showed different methods in forming and measuring IFR coatings as a helpful study. This study and results are beneficial for multiple applications in the realms of construction, electronics, transport and many other applications where there are polymers used as composites or plastics. The coating developed in this study can be considered an affordable effective, possible scalable and effective solution for improve]E4ng fire safety in real-world scenarios.

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[15] Calcium Carbonate as Functional Filler in Polyamide 12Manipulation of the Thermal and Mechanical Properties by Fabio Ippolito. 1,Gunter Hübner 2,Tim Claypole and Patrick Gane
[16] Enhanced flame retardancy of rigid polyurethane foams by polyacrylamide/MXene hydrogel nanocomposite coating. Int. J. Mol. Sci., 23(20), 1263
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[22] Enhanced Flame Retardancy of Rigid Polyurethane Foams by Polyacrylamide/MXene Hydrogel Nanocomposite Coating Bin Chen * and Lizhong Yang

[23] Fire performance of high-density polyethylene sheets protected by a coating of plasticized polyvinyl chloride/modified-vermiculite Walter Wilhelm Focke1 , Washington Mhike2, Joseph Kwaku Ofori Asante3 , Isbe´ van der Westhuizen1, Eduard Jacobus Snyman1 and Maria Atanasova `1.

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[25] The Flame-Retardant Mechanisms and Preparation of Polymer Composites and Their Potential Application innConstruction Engineering Jingjing Shen 1,* , Jianwei Liang 2, Xinfeng Lin 1,*, Hongjian Lin 1, Jing Yu 1 and Shifang Wang 1

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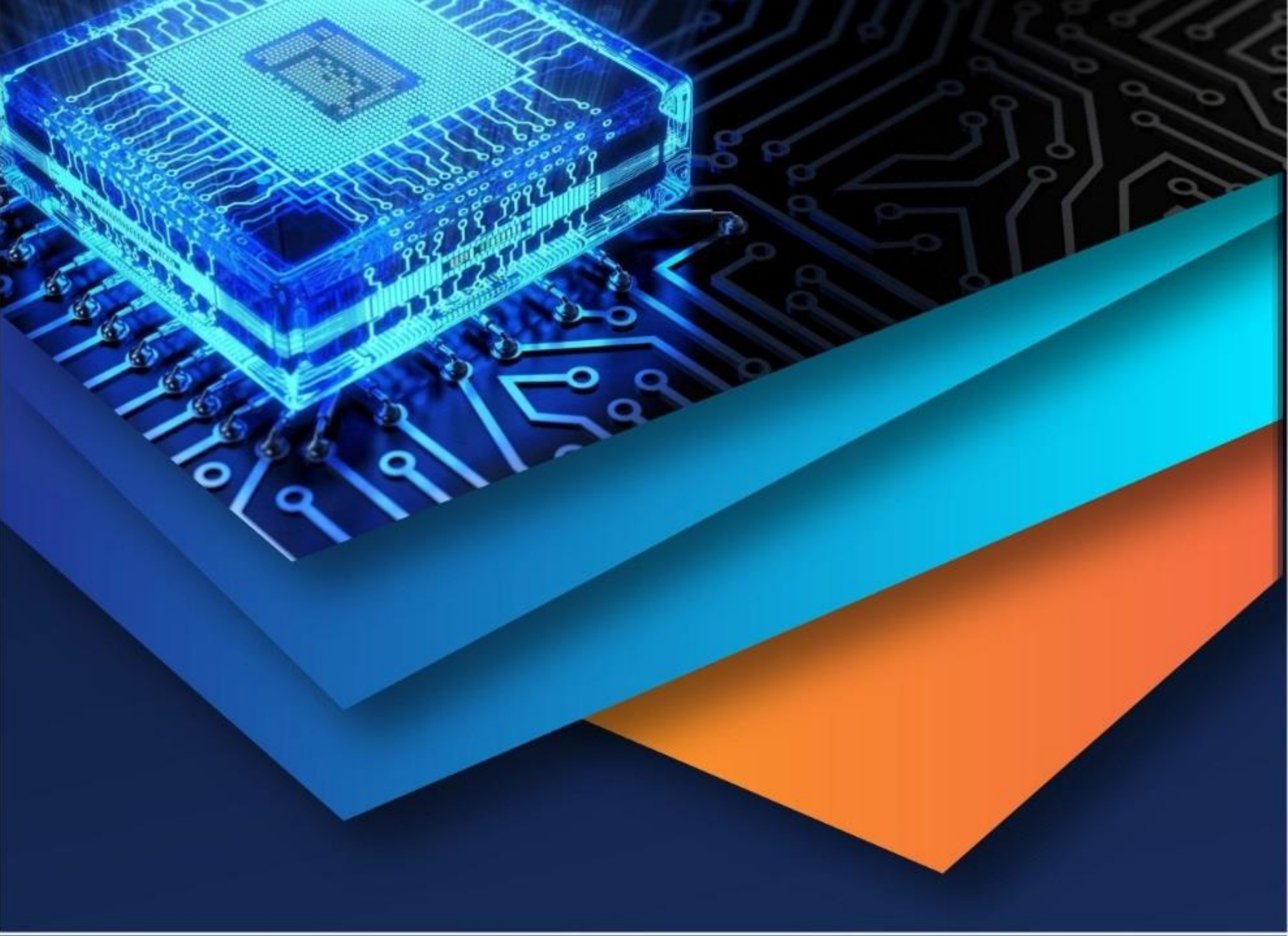

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