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Assessment of Factors Influencing the Microstructure and Porosity of PM 316L Austenitic Stainless Steel

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Abstract: Austenitic stainless steels are widely used in medical, industrial as well as in domestic applications because of its outstanding mechanical properties and corrosion resistance. Attempts are being made to use stainless steel powder in order to achieve dimensional accuracy for near net-shape part fabrication, increased productivity, to overcome loss of material and minimize energy consumption. Use of stainless steel in powder form poses certain disadvantages mainly because of the poor densification and increased porosity of the sintered compacts which limit the use of PM stainless steel for certain applications. This paper presents a brief assessment of the various factors influencing the microstructure and porosity of PM 316L austenitic stainless steel.
Keywords: Powder metallurgy, Stainless steel, Microstructure, Porosity

I. INTRODUCTION

Stainless steels are highly resistant to corrosion (rusting) in a variety of environments, especially the ambient atmosphere. Their predominant alloying element is chromium (min 11 wt%). Corrosion resistance may also be enhanced by nickel and molybdenum addition. A wide range of mechanical properties combined with excellent corrosion resistance make stainless steels very versatile in their applicability. [1]

Powder metallurgy (PM) is a metal manufacturing process that makes semi-finished or finished components from plain or alloyed powders. This process involves the following steps: production of powder metal, metalloids, metal alloys or compounds, blending and mixing of powders, compaction, sintering, and, in some cases, repeating the operation [2, 3, 4]. PM, therefore, is the production and exploitation of metal powders. Particles whose size is less than 100 nm (1 mm) are referred to as powder [5]. Metal powder attributes depend on the following parameters: particle shape and size, particle size distribution, compressibility, apparent density, and flow rate. Notwithstanding the exceptional qualities of PM processes, porosity, production of parts with complex shape and features, and high strength are challenges [6]. There are pores in almost all of the PM parts and this has both advantages and disadvantages. One of the advantages is being able to produce self-lubricating bearings. The pores that are linked to the surface are impregnated with oil [5, 7].

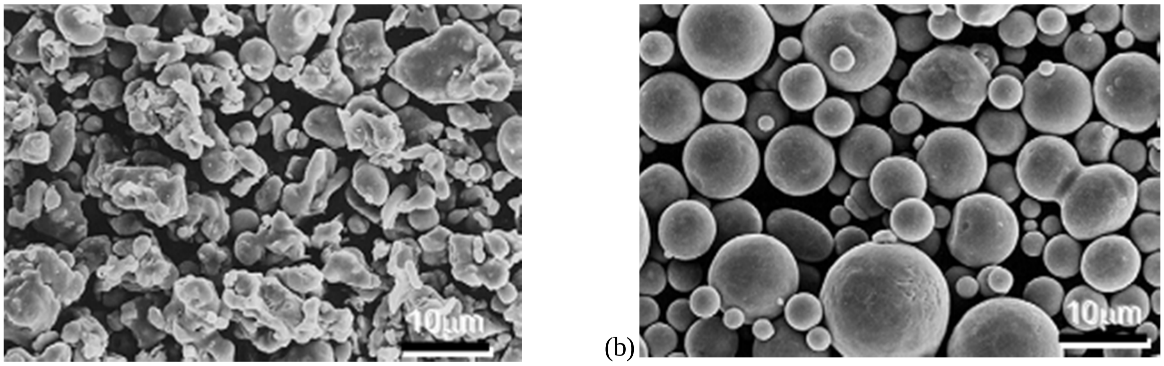
Metal matrix composites (MMCs) are currently being developed as possible structural materials, offering improved elastic modulus, strength, good properties at elevated temperature and control over the coefficient of thermal expansion [8, 9]. The addition of high modulus refractory particles to a ductile metal matrix produces a material with properties intermediate between the matrix alloy and ceramic reinforcement. However, the optimum properties of metal matrix composites depends additionally on a proper selection of the metallic matrix material, the reinforcing phase, the methods of producing and the parameters of these methods [10, 11].

The 316L austenitic stainless steel is nowadays a widely used engineering material due to its excellent corrosion and oxidation resistance and good formability [12]. Powder metallurgy (PM) is a suitable technology to fabricate complex parts with net shaping capabilities, appreciable dimensional precision and high productivity [13]. PM of stainless steel components constitutes an important and growing segment of the PM industry [14]. PM stainless steel is generally used in special applications, where enhanced properties are required as compared to the low alloy steel [15]. However the wider application of PM stainless steel is limited due to their poor mechanical and corrosion properties. Therefore, there is a need to improve the corrosion resistance and mechanical properties of PM stainless steel by modifying the microstructural characteristics through the addition of second phase dispersiods or by utilizing novel sintering techniques [16] such as microwaves.

The aim of the present investigation was to study the various ways by which the microstructure and porosity of PM 316L austenitic stainless steels (ASS) composites can be modified as compared to plain samples.

II. FACTORS INFLUENCING MICROSTRUCTURE AND POROSITY:

A. *Powder Morphology*



(a) (b)

Fig.1: SEM images of (a) water-atomized and (b) gas atomized 316L ASS powders [17].

Generally two methods are employed to produce metal powder i.e water and gas atomization. Morphology of the powders, observed using scanning electron microscopy is given in fig.1 (a) & (b). The water atomized powders are irregular in shape due to rapid cooling and the gas atomized powders are spherical, as it gets enough time to attain spherical shape due to the action of surface tension during auto cooling.

R.P. Koseski et.al [17] have tabulated various characteristics of water and gas atomized powders, some of which are enlisted below in order to understand possible reasons causing difference in microstructural features and porosity of sintered compacts made of these powders.

Table 1: Particle characteristic of stainless steel powders

Characteristics	Water atomized	Gas atomized
Shape	Irregular	Spherical
Pycnometric density (g/c^3)	7.93	7.96
Angle of repose (^{o})	50	45

The microstructural evolution of the gas-atomized powders is given in Fig.2 (a) and that of water-atomized powder is given in Fig.2 (b). The morphology of powders greatly influences the densification of plain sintered products. Experimental works have proved that compacts made of water atomized powder could be sintered to 97% of theoretical density Fig.2 (a) while compacts made of gas atomized powders could be sintered to near full density Fig.2 (b) [17].

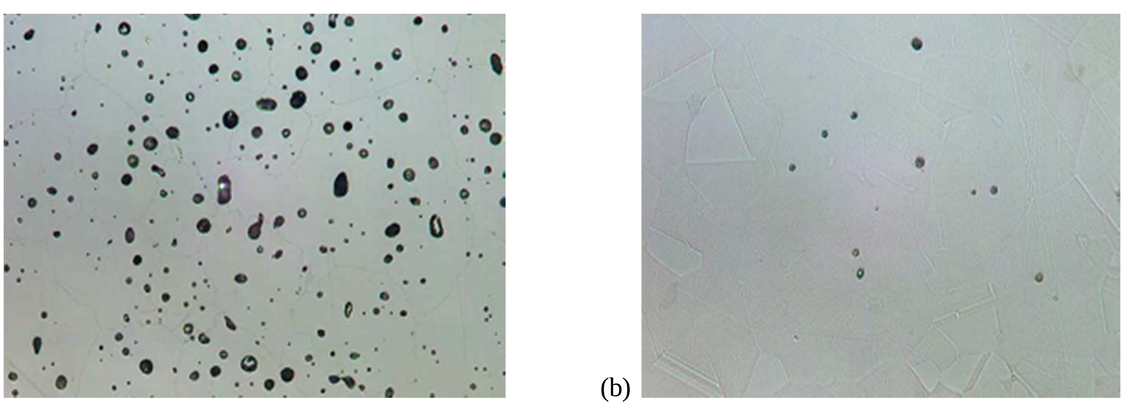
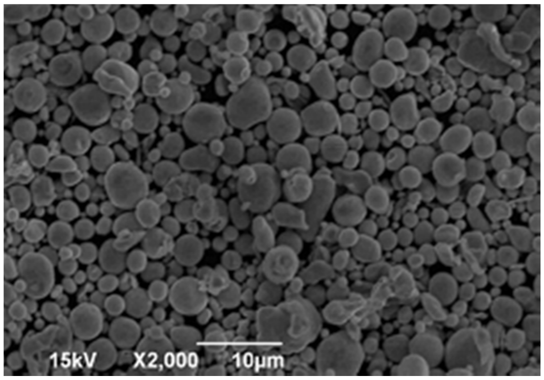

(a) (b)

Fig.2: SEM images of sintered compacts (a) water-atomized, (b) gas atomized [17].

Here flowability of the powder plays an important role in compaction. In table.1, the angle of repose for water and gas atomized particles is 50^o and 45^o respectively. It is obvious that smaller the angle of repose greater is the flowability of material. The change in angle of repose is mainly because of the morphology of powder particles, i.e gas atomized particles are spherical exhibits greater flowability as compared to water atomized particles having irregular shape. Therefore the compacts made of gas atomized stainless steel powders exhibit lesser porosity as compared to compacts made of water atomized stainless steel powders as seen in fig.2.

B. Powder Size

Joo Won Oh et al. [20] have analyzed compaction and sintering behavior of 316L stainless steel nano/micro bimodal powder. They used stainless steel powders of two different particle sizes i.e micro (4 µm) and nano (100 nm) as shown in below SEM images.

(a) 

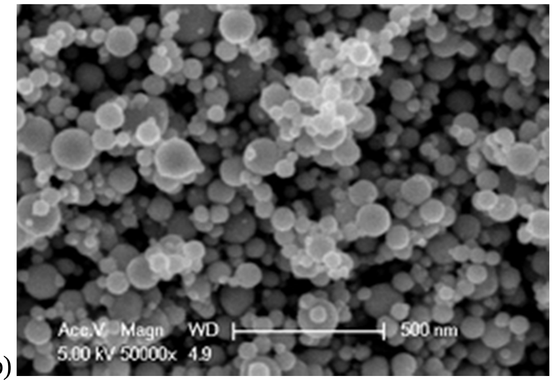
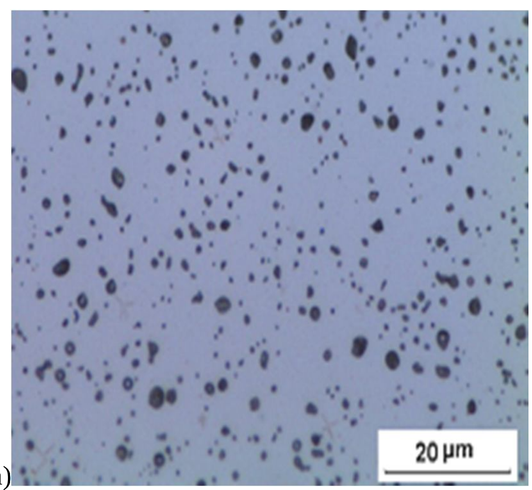
(b) 

Fig.3: SEM images of 316L ASS powders: (a) micro and (b) nano [20].

The sintered compacts made from micro and nano powders reveals the difference in porosity in terms of pore size and number as shown in the optical images magnified 1000 times after polishing (fig.4). This can be attributed to number of particles in a given volume and sintering behavior the powders. Larger the particle size less is the number of particle in a unit volume and lesser is the number of pores but larger pore size in sintered compacts, whereas it is opposite in case of sintered samples nano powder.

(a) 

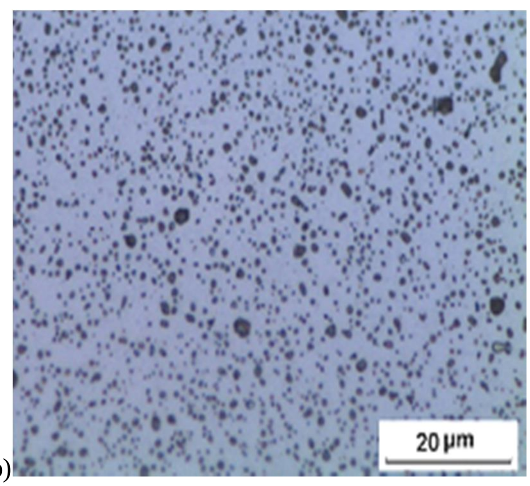
(b) 

Fig.4: Optical images of sintered samples: (a) micro and (b) nano [20].

Densification of 316L ASS during sintering proceeds via lattice or volume diffusion between the adjacent particles, but this diffusion is not enough to fill the gaps between the particles, hence creates pores. Nano powders exhibit agglomeration due to their strong van der Walls force. Densification of agglomerated nano powder takes place via two mechanisms, shrinkage of intra-agglomerate pores and inter-agglomerate pores [20]. The porosity in this case is because of these two shrinkage mechanisms.

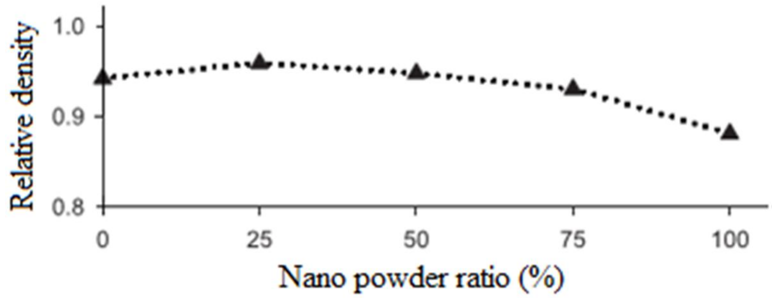


Fig.5. Average value of relative density

Shrinkage of porosity can be understood from density of the sintered samples. Joo Won Oh et al. [20] have plotted the relative densities of micro, nano and bimodal sintered samples as presented in the fig.5. The result indicated that 25:75 nano/micro bimodal powders had the highest sinter density. This is because the nano particles filled the interparticle space between the micro particles during compaction, hence indicates reduced porosity, whereas the nano samples achieved poor density, indicating highest porosity.

C. Reinforcement Powder

Microstructure and porosity of PM 316L ASS can greatly be altered by reinforcing ceramic particles like oxides, carbides, borides etc. Chemical composition of PM 316L ASS (table 2) and melting points (MP) of reinforcement particles (table 3) help us to understand microstructural evolution of these composites.

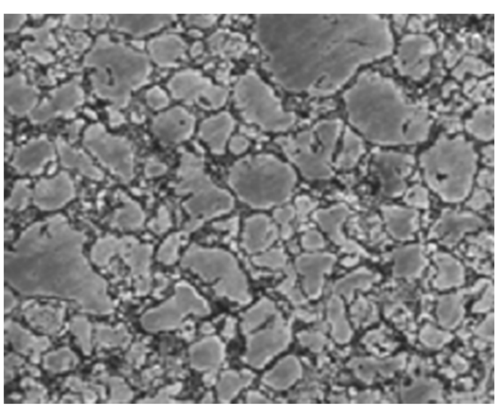
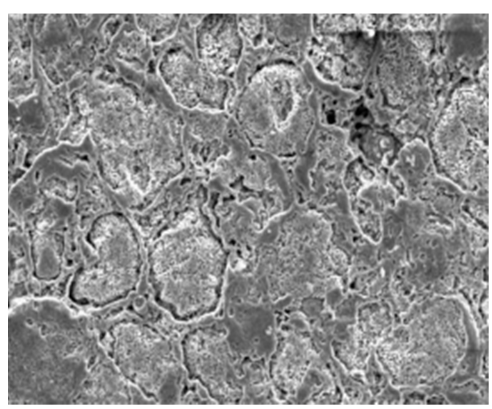
Table 2: Chemical composition of AISI 316L ASS powder

Element	C (max)	Si	Mn (max)	P (max)	S (max)	Cr	Ni	Mo	Cu (max)
Wt%	0.03	2-3	0.2	0.03	0.03	16-18	10-14	2-3	0.5

Table 3: Melting points of 316L ASS and reinforcement powders

Powder	Melting Point
316L ASS	1375-1400°C
Nb_2O_5	1512°C
Al_2O_3	2072 °C
TiB_2	2970 °C
TiC	3160 °C

Following SEM images (fig.6) reveal the pore profile of the sintered compacts reinforced with ceramic powders having different melting points, sintered at 1250°C. The microstructure of the sintered 316L ASS composites shows increased porosity for the powders with higher melting points as shown in the following SEM images.

(a)  (b) 

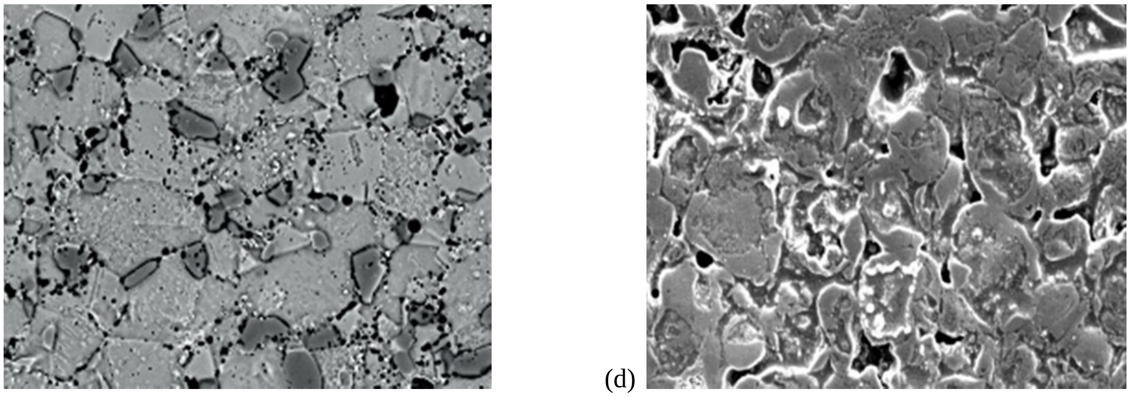

(c) (d)

Fig.6: SEM images of sintered PM 316L ASS composite reinforced with (a) Nb_2O_5 [18], (b) Al_2O_3 [17], (c) TiB_2 [12] and (d) TiC [17]

Among the powders used TiC has highest melting point of around 3160°C and is obvious that, it would not form a liquid phase at sintering temperature which is required to fill the interparticle spaces to reduce the porosity, instead it obstructs the joining of adjacent metal particles resulting in increased porosity of the composite (fig.6.d). Whereas Nb_2O_5 reinforced ASS shows a reduced porosity, which can be attributed to formation of semi-liquid phase at sintering temperature and thereby diffusing in the intergrannular spaces left during the sintering. Composites with Al_2O_3 and TiB_2 showed intermediate percentage of porosity and densification.

Austenitic stainless steels undergo densification via lattice (volume) diffusion during the intermediate stage of sintering [17, 21, 22]. During this regime, surface diffusion is also active. Thus, pore migration occurs by a combination of surface and lattice diffusion. At higher temperatures, lattice and grain boundary diffusion contribute to densification. These mass diffusions and densification process on the other hand depends the rate of heating during sintering. Slower heating rate favors densification.

III. CONCLUSION

With this study following conclusions are made;

A. The sintered compacts made up of spherical powder achieve reduced porosity and could be sintered to near full density.
B. The result indicated that 25:75 nano/micro bimodal powders had the highest sinter density as compared to micro and nono samples.
C. The sintered PM 316L ASS composites reinforced with ceramic particles having lower MP exhibit reduced porosity as compared to composites with high MP ceramic particles.
D. Desired porosity and densification could be achieved by controlling these factors.

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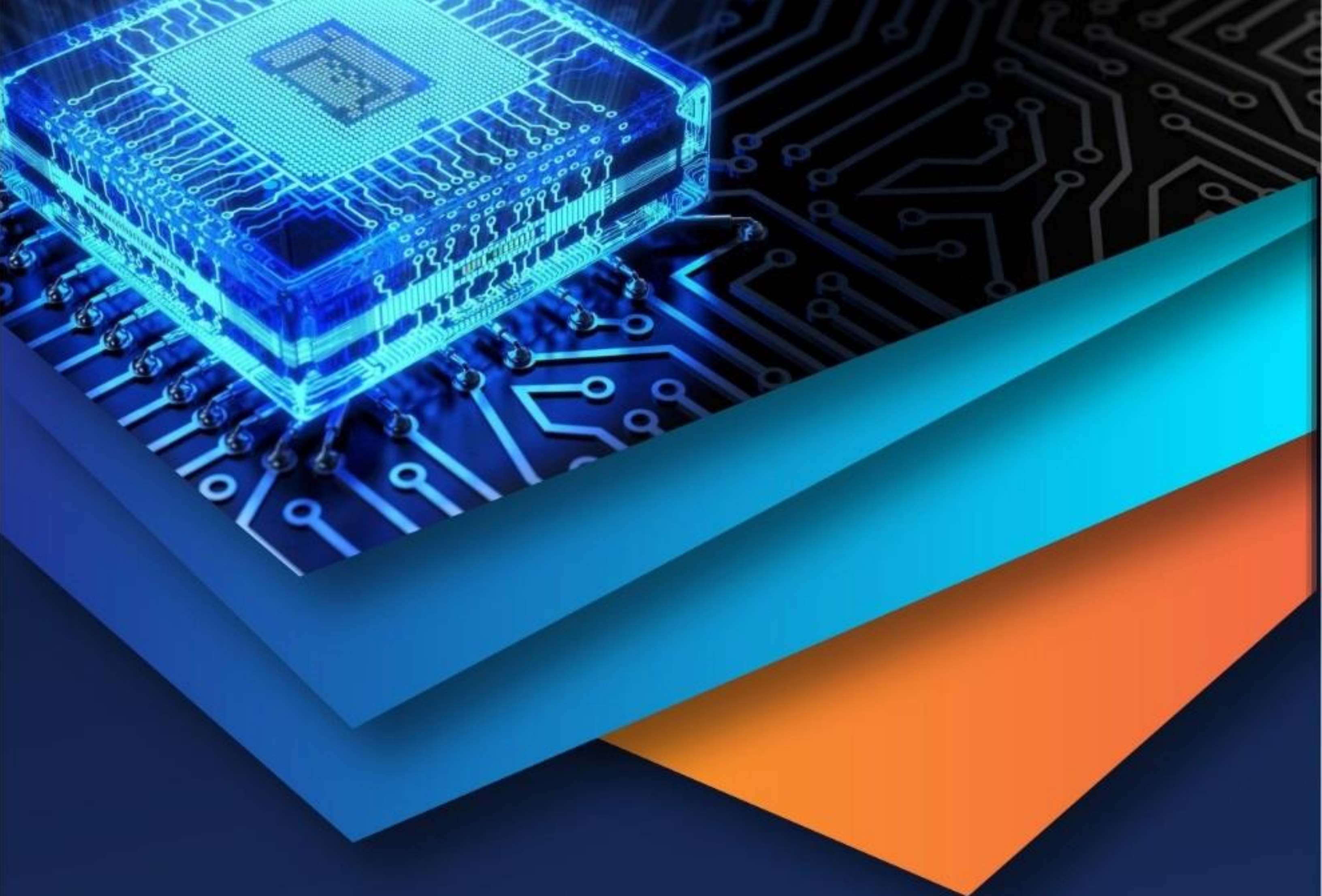

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