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Developing Full Range S-N Curve of Aluminium Alloys using Mathematical Model

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Abstract: ***Recent studies have proved that there is no fatigue limit for metallic materials. The stress life curve continuously drops even after 10^7 cycles. However, existing design codes assume that there is a fatigue limit. Therefore, it is important to use appropriate safety factors if existing codes are used for life evaluations. This paper consist of developing the full range S-N curve from low cycle region to high cycle region upto giga cycle fatigue region of Aluminium alloys using the mathematical model. Combining monotonic test based empirical fatigue formulae and a Wholer field mathematical model, a new formula for developing full range stress life curves for medium strength material is proposed. The accuracy of proposed formula is verified using experimental fatigue data of two aluminium alloys. This formulae is used for prediction of stress life curve of one steel and comparing the obtained results with experimental fatigue data of steel for checking the application of formulae for other materials also.***

Keyword: ***Full range S-N curve, Monotonic test, Wholer field mathematical model, Emperical formulae, Aluminium alloys, Steel.***

I. INTRODUCTION

Fatigue failure is a common phenomenon in structures that are subjected to cyclic loading therefore designing against fatigue is important. Fatigue damage of structures is determined by using stress – life (S–N) curves in high cycle fatigue (HCF) and gigacycle fatigue (GCF) regions, while strain – life (e–N) curves are used in low cycle fatigue (LCF) region. Laboratory fatigue testing based S–N curves developed using material samples from structures concerned (structure and material specific S–N curves) produce realistic fatigue damage predictions for those structures. However, fatigue testing is costly, time consuming and requires sophisticated equipment or much time if conventional equipment is used especially in GCF region. Therefore, monotonic test (tensile and hardness tests) based empirical formulae such as the Basquin and Manson–Coffin equation for LCF and HCF regions and Murakami formulae for GCF region are widely used. Where experimental fatigue data is available, regression analysis based functions such as Strohmeyer function, Palmgren function and recently developed Kohout and Vechet function are useful for constructing S–N curves. However, there are no empirical formulae which are able to accurately describe the entire (full) range of the S–N curve from the first cycle to gigacycle. Therefore, we use monotonic test method to construct a full range S–N curve by employing monotonic test based empirical formulae and Palmgren function(a Wholer field mathematical function).

II. LITERATURE REVIEW

A. Alan Vasko , Milan Vasko

The paper deals with the comparison of fatigue tests of nodular cast iron at high and low frequency cyclic loading. Fatigue tests were realized at high and low frequency sinusoidal cyclic push-pull loading (stress ratio R = –1) at ambient temperature (T = 20 □ 5 °C). High frequency fatigue tests were carried out with using the ultrasonic fatigue testing device KAUP-ZU (frequency f □ 20 kHz); low frequency fatigue tests were carried out with using the fatigue experimental machine Zwick/RoellAmsler 150HFP 5100 (frequency f □ 120 Hz).

B. S. Schoenborn , H. Kaufmann , C.M. Sonsino , R. Heim

This paper describes that the cumulative damage calculation method generally applied in the automotive sector is the Palmgren Miner Hypothesis with its modification according to Haibach. In several design codes the theoretical Palmgren Miner damage sum $D_{th} = 1.0$ still recommended as the allowable damage sum D_{al} despite the fact that it renders unsafe calculated fatigue lives.

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Results obtained with modern high strength cast iron alloys such as EN-GJS-500-7 , SiboDur 700-10 and MADI (MachinableAustempered Ductile Iron) under a standard Gaussian spectrum for chassis applications and also under a fuller injection pump spectrum suggest the allowable damage sum $D_{al} = 0.3$ for fatigue life estimations.

C. M. Jimenez , J. Martinez , U. Figueroa , L. Altamirano

In this paper durability assessment is performed to establish the damage applied by loads and the number of load cycles versus S-N curves. This information is evaluated using a fatigue damage hypothesis. A new relationship is proposed to estimate the S-N curve of nodular cast iron, based on its ultimate strength, using a case study of a steering knuckle component under bending load. Finite element simulation was performed to obtain the maximum stresses in the component using Patran V2012.2 and Nastran V2008 software. Correction factors accounted for surface finish, type of load and level of reliability.

Actual and proposed predictions were evaluated using experimental results. The main aim of this work was to design a fatigue test, with a limited amount of information, through finite element simulation and tensile strength. The main advantage of this relationship over the other methods for estimating an S-N curve, is to improve life prediction at the boundary of low and high cycle fatigue with a simple relationship and without a series of tests to identify the S-N curve, thus simplifying durability assessment with a limited amount of information. The proposed relationship improved the life prediction by an average of 10% in the case study.

D. A. Laksimi , X. L. Gong & M. L. Benzeggagh

In this paper the object of the study is to investigate the damage and failure mechanisms in a glass-fiber/epoxy composite under monotonic tensile loading. The testing was carried out on unidirectional specimens with and without a circular hole. The damage initiation and failure mechanisms were studied by means of scanning electron microscopy and acoustic emission monitoring. In addition, for specimens with a circular hole, a novel strain-gage instrumentation method is suggested. These different techniques permitted the determination of the damage parameters e, v, D, F, which characterize qualitatively and quantitatively the initiation and evolution of damage. It was found that the amplitude distribution of acoustic emissions is a very efficient tool for identifying damage mechanism such as micro cracking in the resin, fracture and friction of the interface between fiber and matrix, and fiber pull-out

E. M. Sonsino

Conventional design codes base their recommendations still on the common prejudice that an “endurance limit” exists. However, several investigations prove clearly that in the high-cycle regime a decrease of fatigue strength with increased number of cycles still occurs, even if corrosion or temperature effects are excluded. Therefore, the fatigue design of components submitted to loadings below the knee point of the S-N curve must consider this fact in order to avoid failures. With regard to the course of the S-N curve in the very high cycle area, material and manufacturing dependent recommendations are given.

used t estimate σ_k as given in Eq. (8),

$$\sigma_k = 0.5\sigma_u \tag{8}$$

The knee point fatigue strength can be written using Eq. (7) as,

$$\sigma_k = \frac{{\sigma_u}^{1/3}}{1000}(H_v + 120) \cdot (155 - 7\log N_k) \tag{9}$$

Substituting for σ_k from Eq. (9), N_k is obtained and given in Eq. (10),

$$N_k = 10^{\left(\frac{0.155(H_v+120)\cdot {\sigma_u}^{1/3} - 0.5\sigma_u}{0.007(H_v+120)\cdot {\sigma_u}^{1/3}}\right)} \tag{10}$$

Accordingly, the modified Palmgren function is given in Eq. (11),

$$\sigma(N) = \left(\frac{\sigma_{GCF}-\sigma_k}{N_{GCF}^b - N_k^b}\right)\cdot (N + B)^b + \frac{1}{2}\left\{\frac{(\sigma_{GCF}+\sigma_k)\cdot\left(N_{GCF}^b - N_k^b\right) - (\sigma_{GCF}-\sigma_k)\cdot\left(N_{GCF}^b + N_k^b\right)}{N_{GCF}^b - N_k^b}\right\} \tag{11}$$

The slope b is determined substituting the coordinates of the first knee point located in LCF region in Eq. (11) and doing iterations. It was found that the best global value for b is -0.2. This formula does not require experimental fatigue test data for developing S-N curves. Therefore, this is no longer a regression besed function. Hereafter, in this paper, this Wholer field mathematical formula is named as the proposed formula for full range S-N curves.

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Table 1 shows data for two aluminium alloys used in the study for verifying the proposed formula. These aluminium alloys are from literature [5] and there properties are from reference [8, 9]. Table 2 shows the data for steel used in the study for verifying the proposed formula and its properties are taken from reference [10].

Table .1 Aluminium used for verification of proposed formula

Material	References	σ_u(N/mm^2)	H_v(Kgf/mm^2)
AA 2024	[8]	469	137
AA 7075	[9]	572	175

Table .2 Steel used for verification of proposed formula

Material	References	σ_u(N/mm^2)	H_v(Kgf/mm^2)
Steel 1045	[10]	565	170

III. PREDICTION OF S-N CURVE USING THE PROPOSED FORMULA AND COMPARING IT WITH EXPERIMENTAL S-N DATA

For calculation it is assumed that N_{GCF} for all the material taken is 1×10^8 cycles and experimental S-N data is taken from literature [6]. Results obtained after solving using all the equations mention above are stated in table given below for all three material;

Table .3

S.No.	Materials ↓	σ_{GCF}(Eq.7) N/mm^2	N_k(Eq.10)	σ_k(Eq.9) N/mm^2	α(Eq.6)	c(Eq.6)	B(Eq.6)
1	AA 2024	197.670	232064.487	234.5	620.186	182.080	47.185
2	AA 7075	242.430	287294.633	286	780.082	222.847	55.670
3	Steel 1045	237.340	203898.939	282.5	733.090	218.928	42.650

On putting these values in Eq(11) the general equation is obtained in which stress is obtained for different values of life cycle. The results obtained is displayed below in following tables for all three metal differently.

Table .4B S-N data obtained from proposed formula for AA 2024 and data from experimental observation from literature(6).

S.No.	Life cycle(N)	$\sigma(N)$, N/mm^2 (Experimental)	$\sigma(N)$, N/mm^2 (Mathematical)
1	10	470	458.179
2	10^2	420	410.613
3	10^3	350	336.433
4	10^4	300	280.280
5	10^5	270	244.090
6	10^6	230	221.210
7	10^7	190	206.770
8	10^8	150	197.658
9	10^9	120	191.909

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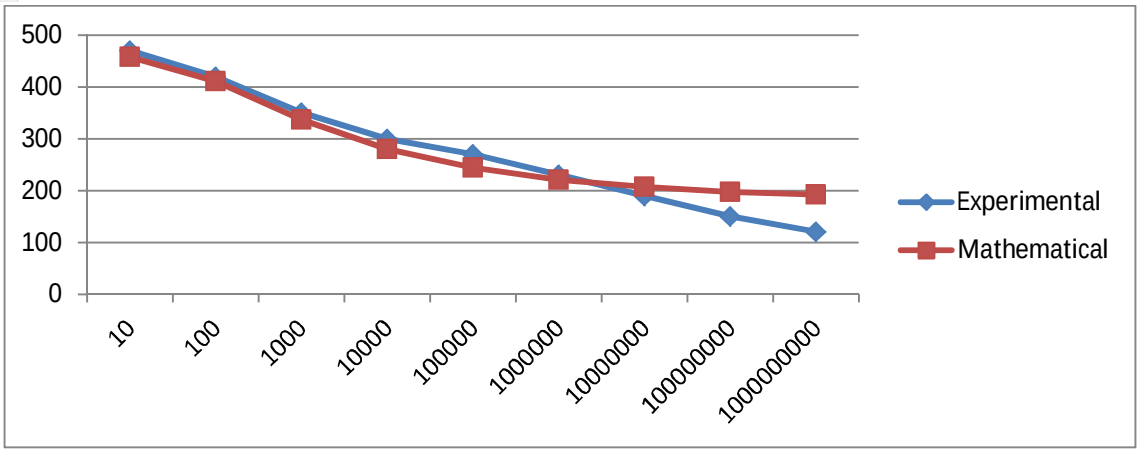

Fig. 2. Predicted S-N curve for AA 2024 using the proposed formula and experimental S-N data (Stress amplitude- y axis, life cycles- x axis)

Table .5 S-N data obtained from proposed formula for AA 7075 and data from experimental observation from literature (6).

S.No.	Life cycle(N)	$\sigma(N)$, N/mm^2 (Experimental)	$\sigma(N)$, N/mm^2 (Mathematical)
1	10	575	560.650
2	10^2	520	507.096
3	10^3	420	416.653
4	10^4	310	346.345
5	10^5	280	300.840
6	10^6	255	272.066
7	10^7	230	253.903
8	10^8	220	242.442
9	10^9	215	235.211

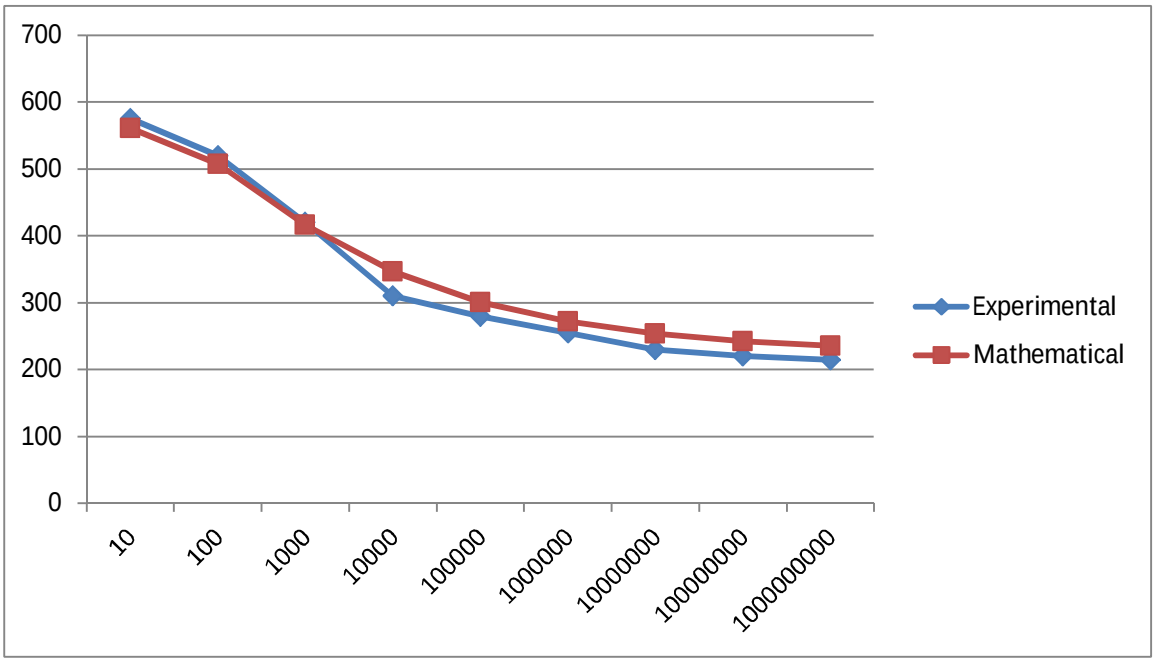

Fig. 3. Predicted S-N curve for AA 7075 using the proposed formula and experimental S-N data (Stress amplitude- y axis, life cycles- x axis)

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Table .6 S-N data obtained from proposed formula for Steel 1045 and data from experimental observation from literature (6).

S.No.	Life cycle(N)	$\sigma(N)$, N/mm^2 (Experimental)	$\sigma(N)$, N/mm^2 (Mathematical)
1	10	570	550.728
2	10^2	520	490.760
3	10^3	440	401.540
4	10^4	350	335.016
5	10^5	330	292.230
6	10^6	320	265.180
7	10^7	320	248.112
8	10^8	320	237.340
9	10^9	320	230.540

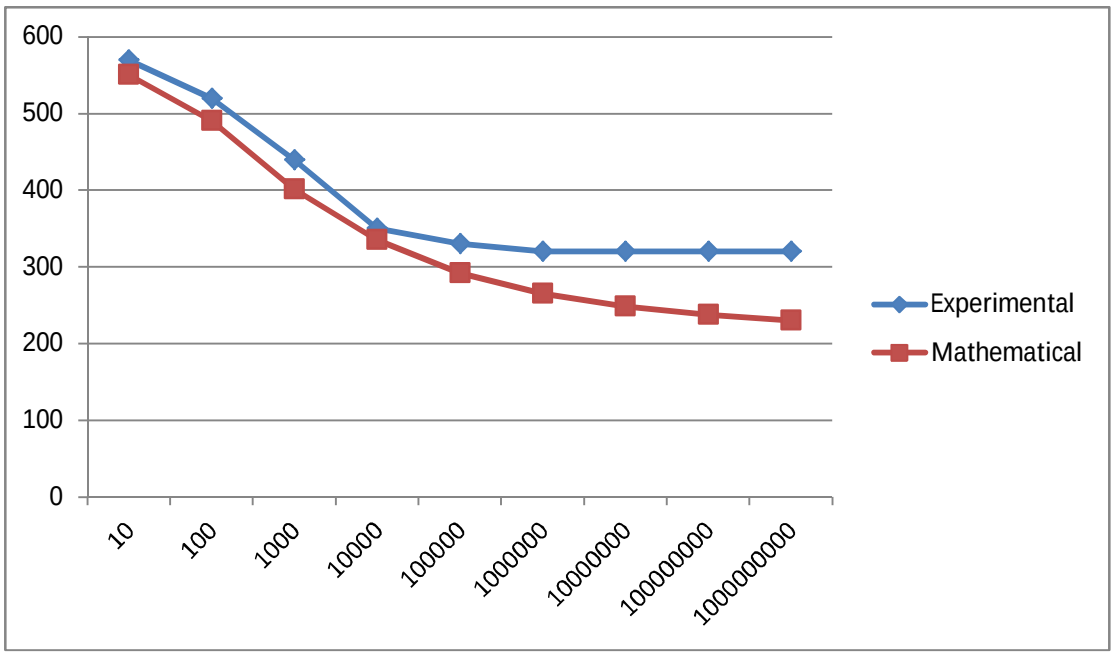

Fig. 4. Predicted S-N curve for Steel 1045 using the proposed formula and experimental S-N data (Stress amplitude- y axis, life cycles- x axis)

IV. CONCLUSION

A. From the above analysis it has been observed that the stress life cycle graph so obtained using experimental data are almost similar to that so obtained using mathematical model. So for prediction of S-N curve mathematical model can also be used instead of experimental based method because experimental based analysis is time consuming and complicated.

B. By using this mathematical model for finding out the S-N curve for Steel it has been seen that the empirical relation so obtained is valid for other materials also. The other result so seen that we assume that S-N curve becomes straight line after HCF (high cycle fatigue) region but it is not so. This can be seen in Fig. 4 in which after 10^6 cycle the graph of mathematical observation goes on decreasing.

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C. Having a single formula for predicting fatigue S-N curves for the full range makes fatigue assessments using manual calculations, spread sheets and computer based programming easy. Having S-N curves that require easily testable material parameters (i.e., $\sigma_u$andH_v) makes the experimental work for the construction of S-N curves simple.

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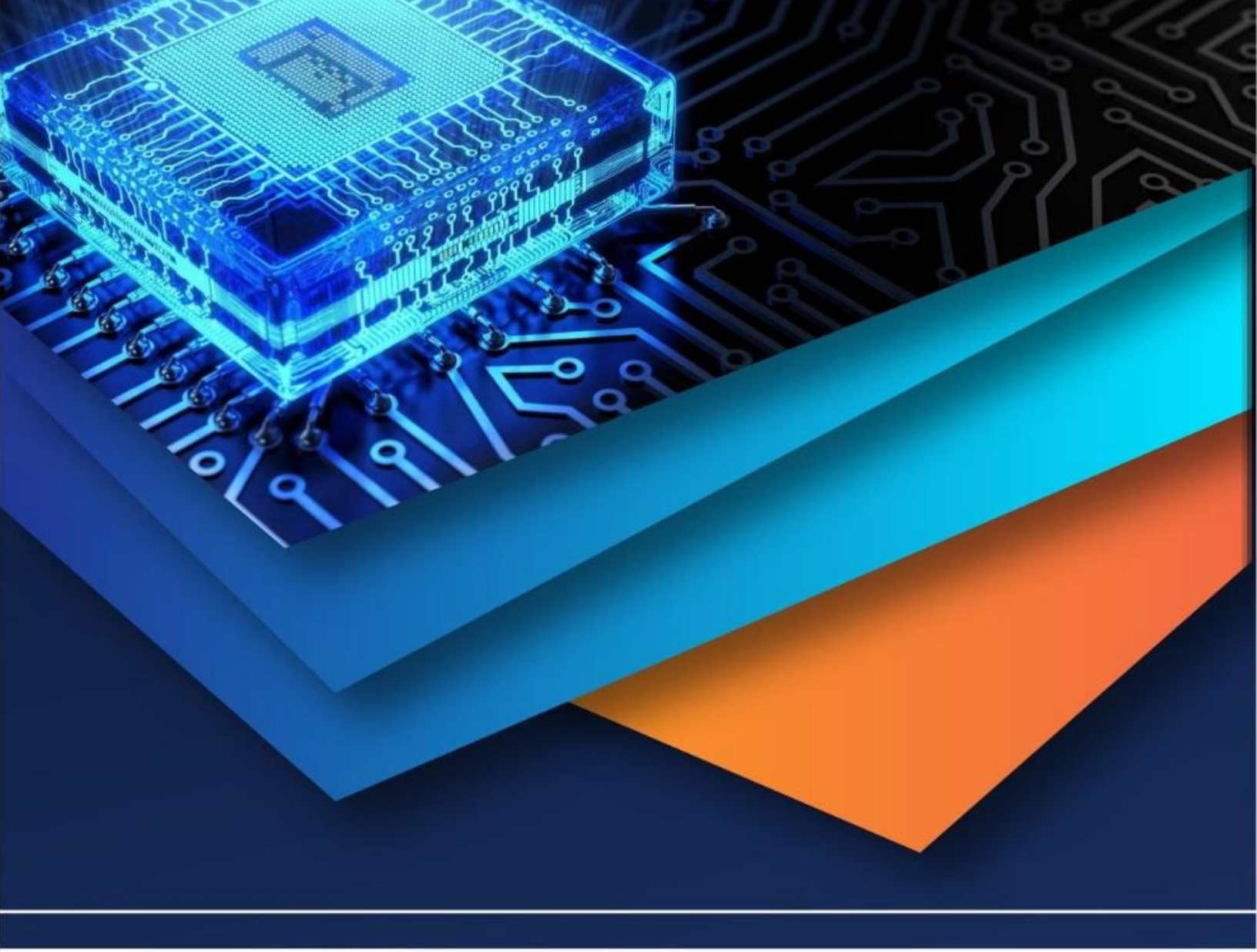

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