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Bauschinger Effect in spring Back Prediction of High Strength Steel: A Theoretical Approach

Patel Chintankumar K[1], Anish H. Gandhi[2]
[1]*Research Scholar, Mechanical Engineering Department, Rai University, Ahmadabad*
[2] *Research Supervisor, C.K.Pithawala College of Engineering & Technology, Surat*

***Abstract**: Press formed components are in huge demand now a days. Especially high strength steels are widely acceptable by different industries because of their high weight to strength ratio. Due to Poor formability, it is quite difficult to work with high strength steels. Dimensional inaccuracy is main concern with the metals having poor formability which leads to springback. So for better control over dimensions especially in assembled component springback must be predicted in advance. Accurate Springback prediction is a very crucial for commercial aspect. Many of process parameter directly or indirectly influences the springback during forming process of high strength process. Bauschinger effect is one of parameter which play important role during forming process. Many researchers already develop springback prediction model but most of them avoid consideration of Bauschinger effect due to complexity involved in Bauschinger effect. The springback results obtained from such model are far away when we consider them with experimental results. So it is very crucial to consider Bauschinger effect during springback prediction which gives near by results with experimental results. This paper deals with theories of Bauschinger effect and its impact on springback prediction modelling.*
***Keywords**: Bauschinger effect, Springback, Bending, formability, High strength steel*

I. INTRODUCTION

High strength steel covered majority share in sheet metal industries in last few years due to its good strength to weight ratio. High strength and advance high strength steel are in high demand especially in automotive and aerospace industries. While dealing with sheet metal process, springback is the one of the most critical issue. High strength steel offers a higher rate of springback because springback rate is increase with material strength. Springback is a shape change of final geometry after removal of load. It is an elasticity driven incident which is mostly manages by the stress state obtained at the end of a deformation. Depending on the product geometry and deformation regime, there are several types of springback in sheet metal forming: bending, membrane, twisting and combined bending and membrane [1]. Springback is a phenomenon to describe the elastic recovery of sheet metal after a forming operation in which the strip unbends itself after forming. Sheet metals are prone to some amount of springback due to elastic deformation. Springback prediction is a major issue for the sheet metal manufacture to evaluate the desired shape of a product. Springback refers to the shape discrepancy between the fully loaded and unloaded configurations.[2] Accurate prediction and controlling of spring back is essential in the design of tools for sheet metal forming. High strength steel sheets have played a key role in weight reduction for environmental considerations and improved crashworthiness in the automotive industry in recent years. But at the same time sheet metal forming of high strength steel is itself a critical issue since such high strength metals offer poor formability and springback problem.

(a) Under loading (b) After Loading

Fig. 1 Springback effect

Springback modeling is a vital matter in sheet metal forming process for dimensionally accurate product and better dealing with proper bending angle. By considering the literatures, it is clearly found that m any researchers have worked with bending fact and also developed different models for springback prediction. For the problem of pure bending, Gardiner [3] derived a simplified mathematical analysis of the springback for elastic and plastic metals during pure bending. Wang et al. [1] explain a mathematical model for plane strain sheet bending to predict springback and the maximum bending force on the punch and the die. Tan et al. [4] derived formulae for the springback and residual stresses in sheet metal under bending. Huang et al. [5] conducted an experimental study for steel sheets and conclude effects of process variables like punch radius, die radius, punch speed, friction coefficient, strain hardening exponent, normal anisotropy and etc., on V-die bending process. Gary [6] described statistical inconsistency in material properties on springback. Kim et al. [7] proposed an analytical model to predict springback and bend allowance simultaneously in air bending process. Song et al. [8] conclude springback prediction approaches such as analytical model, numerical simulation using finite element methods and the mesh free method.

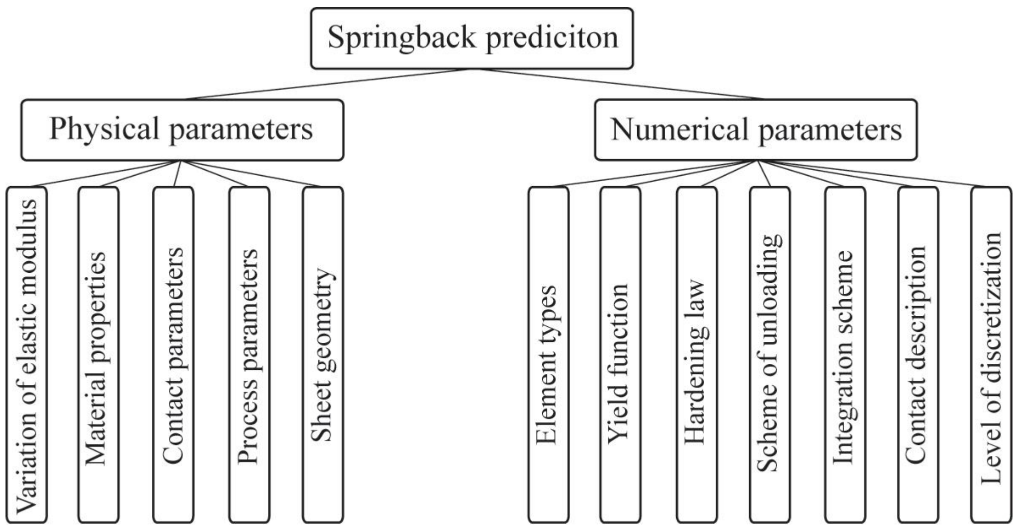


Fig. 2 Parameters affecting springback prediction [11]

In addition, the springback formulas for bending with stretching without considering the Bauschinger effect have been developed by other researchers such as Kuwabara et al. [9] and Gau and Kinzel [10]. I.Burchitz [11] and Aryanpour [12] did dissertations on springback and sidewall curl due to springback in AHSS. A new equation to determine the spring back in the bending process of metallic sheet is formulated by Ning ma [13]. Yilamu et al. [14] explained Air bending and springback of stainless steel clad aluminum sheet. Wagoner and Lee [15] also discussed various advanced issues in springback prediction. Furthermore, An analytical model for springback of bimetallic sheet in bending is proposed by A. H. Gandhi et al. [16] and springback behavior of bi-layer sheet in V-bending is investigated by Chintan K. Patel [17]. Recently Seo et al. [18] discuss the effect of constitutive equations on springback prediction accuracy in cold stamping with various deformation modes. They concluded that, to predict the springback present in AHSS cold stamping, it is necessary to use appropriate constitutive equations according to the forming process.

II. THE BAUSCHINGER EFFECT

The Bauschinger effect is named after Johann Bauschinger, a German engineer, who in 1881 observed that when materials are loaded uniaxially in one direction (e.g. in tension) into the plastic region, loaded to zero stress level, then reloaded in reverse direction (e.g. in compression), they may yield during the reloading at a stress level lower than in the original direction. The Bauschinger effect may be encountered in forming processes subjected to cyclic loading such as bending, drawing, stamping and many more.

In elastic range, metals have the same stress-strain relation in compression as in tension, (i.e. same elastic modulus). However beyond the elastic region, this is not the case. In 1881, Bauschinger discovered that this symmetry between tension and compression was destroyed by plastic deformation. If metal is stretched plastically in tension, its yield stress is lowered with respect to the subsequent application of a compressive stress, but in raised with respect to subsequent application of tensile stress. The effect of lowering yield stress is called the Bauschinger effect and the effect of raising yield stress is called strain hardening.[19]

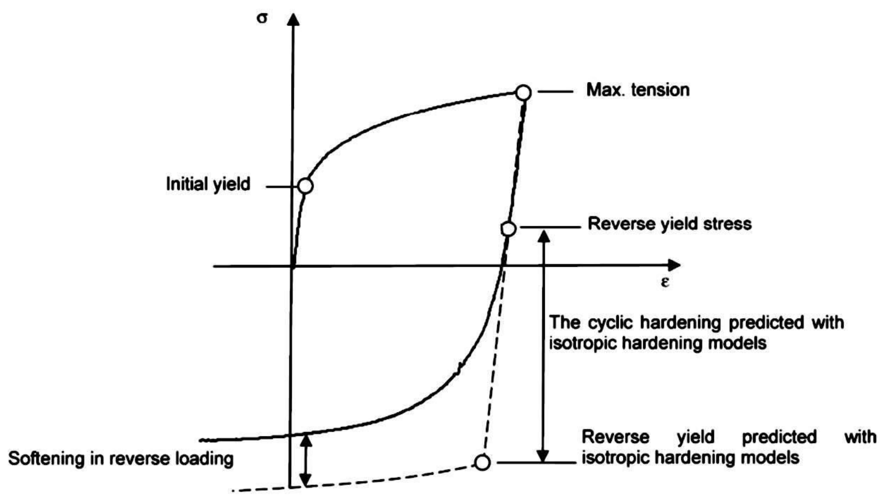


Fig. 3 The Bauschinger effect (Softening in reverse direction)[11]

III.POPULAR THEORIES ABOUT THE BAUSCHINGER EFFECT

For understanding and explanation of the Bauschinger effect, there are two principal Bauschinger effect theories available one of them is back stress theory and other is Orowan theory. Both theories explain the Bauschinger effect based on moving dislocation of grain structure due to loading.

A. Back stress Theory

Moving dislocations interact with different obstacles such as other dislocations, grain boundaries and precipitates which prevent their further propagation during forward deformation causes a back stress around the contact point which resist further progress of dislocations. When the reverse deformation happens, this back stress repels the dislocations from the obstacles in the direction of reverse strain. Thus the stress field helps to move the dislocation in the direction of reverse strain and the reverse yield stress drops by the level of the back stress. Abel [20] investigated that according to the back stress theory, dislocation density increases the number of dislocation interaction sites and thereby the back stress. With an increase in dislocation density it is possible to expect *a* maximum in the Bauschinger effect and then a decrease after some level of pre-strain. According to this theory, larger value of Bauschinger effect observed in a material with a higher dislocation density. However, the number of mobile dislocations can decrease with an increasing in initial dislocation density (and/or pre-strain). This is because of hold of moving dislocations by pile-ups and possible formation of cell structures, where mobile dislocations in the cell interior are more often lower in density than the total number accumulated in the cell walls.

B. Orowan Theory

Orowan [21] proposed that in an alloyed material, precipitated particles also act as interaction sites which increase the level of back stress. Particle chemistry, size and distribution should be considered to describe the influence of precipitates on the Bauschinger effect. Han [22] found that Bauschinger effect increases with pre-strain. He quantitated Bauschinger effect as

$$1 - \frac{|\sigma_{compression}|}{\sigma_{reverse\ point}}$$

with $\sigma_{compression}$ as the yield strength in compression and $\sigma_{reverse\ point}$ as the stress around which the cyclic stress-strain curve is reversed. Since increasing pre-strain increases the strength of the material due to strain hardening, Bauschinger effect increases with the strength of the material.

Most of the researchers have ignored the influence of the Bauschinger effect on

springback due to analytical complexity involvement in consideration of Bauschinger effect.While the sheet metal undergoes cyclic deformation, Bauschinger effect has a significant influence on the stress calculation. Reviews on various aspects of the Bauschinger effect have been contributed by Abel and Muir [20], Sowerby and Uko [23]. The Mroz [24] conclude that multiple surface model can be used to model the influence of the Bauschinger effect. To improve the prediction of springback, the Bauschinger effect has been considered by, Kuwabara et al. [9], Gau and Kinzel [10], I.Burchitz [11], Ning Ma [13], Mahato [25] and Sumikawa et al. [26].

IV. PARAMETERS OF THE BAUSCHINGER EFFECT

While considering about the parameters related to the Bauschinger effect, the stress parameters, the strain parameter and the energy parameters are the main three recognized parameters. These three parameters are generally used to evaluate the absolute value of the Bauschinger effect.

A. Bauscinger stress Parameter (β_σ)

Bauschinger stress parameter describes the relative decrease in the yield stress from forward to reverse deformation. These parameters are reflected to different points on the forward-reverse stress-strain curve.

$$\beta_\sigma = (\sigma_P - \sigma_{y2})/\sigma_P,$$

where σ_P is maximum pre-stress and σ_{y2} is the yield stress in the direction of reverse strain (point of the stress-strain curve deviation from the straight line)

B. Bauschinger Strain Parameter (β_ε)

Bauschinger strain parameter describes the amount of deformation in the reverse direction needed to reach the pre-stressed level of stress.

$$\beta_\varepsilon = \varepsilon_r/\varepsilon_P,$$

where ε_P is plastic pre-strain and ε_r is plastic strain in the reverse direction for the point of equal stress value to the pre-stress.

C. Bauschinger Hardening Parameter (β_h)

Bauschinger Hardening parameter describes the relative decrease in yield stress due to the back stress effect.

$$\beta_h = (\sigma_{y1} - \sigma_{y2})/(\sigma_P - \sigma_{y2})$$

D. Bauschinger Energy Parameter (β_E)

Bauschinger energy parameter describes the amount of energy needed during the reverse deformation to reach the pre stress level of stress.

$$\beta_E = E_s/E_P$$

Where, σ_P is pre-strain, σ_{y1} is yield stress and σ_{y2} is reverse yield stress, E_P is energy spent during pre-strain and E_s is energy saved during reverse straining due to Bauschinger effect. [25]

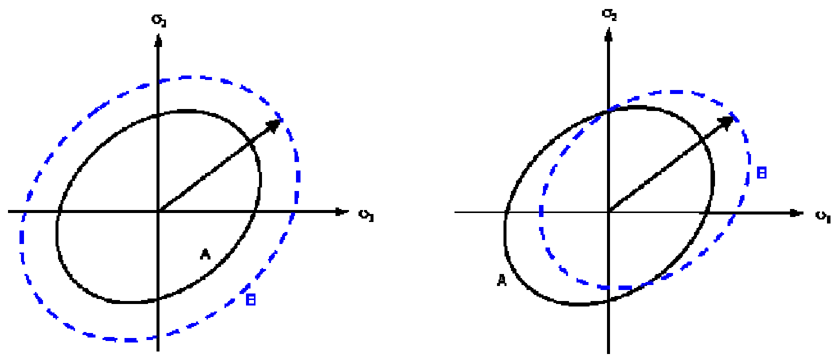
V. KEY CHARACTERISTIC OF THE BAUSCHINGER EFFECT

With an increase in pre-strain the stress parameter β_σ increases and the strain and energy parameters decrease. This may be related to the total dislocation density increase, leading to an increased yield lowering effect, but mobile dislocation density decrease, leading to a faster return of strength, with increase in pre-strain. The appearance of a plateau on the reverse stress-strain curve is related to the dislocation density decrease and the cell structure dissolution during the initial stage of reverse loading both in bcc and fcc materials. With an increase in reverse strain the dislocation density increases and the reverse stress-strain curve goes up. With an increase in test temperature the forward-reverse stress-strain curve goes down and the work-hardening rate in the reverse direction decreases, which corresponds to a decrease in dislocation density due to annihilation at higher temperatures. [27]

VI. HARDENING LAWS

Sowerby [23] explained theoretically that the Bauschinger effect are classified based on either macroscopic or microscopic in nature. The macroscopic approach is based on the continuum theory of plasticity which describes the work hardening behaviour of materials for complex loading history. Work hardening, also known as strain hardening or cold working, is the strengthening of a metal by plastic deformation. This strengthening occurs because of dislocation movements and dislocation generation within the crystal structure of the material. By assuming an initial yielding, the rule of work hardening defines how this is modified during plastic flow. This approach provides a phenomenological description of material behaviour in which the Bauschinger effect is one particular aspect.

The simplest approach, in terms of hardening deals with a one-parameter family of loading surfaces that are affine with regard to the origin is called isotropic hardening. The work on kinematic hardening rules was initiated by Prager [28] and Ziegler [29]. The linear kinematic hardening models developed by them can only provide rough approximations to the Bauschinger phenomena. According to the framework by Ziegler and Prager, the anisotropic hardening models were developed by many authors that include multi surface theory by Mroz [24], and the nonlinear kinematic hardening model by Armstrong and Frederick [30]. In the two-surface model developed by Mroz's multi surface model, the hardening modulus function and the translation direction are defined first, and then the magnitude of the yield surface translation is determined from the consistency condition. In the model proposed by Armstrong and Frederick, the magnitude and direction of the yield surface translation are first defined, and then the consistency conditions are used to derive the generalised plastic modulus [31].



(a) Isotropic Hardening model (b) Kinematic Hardening model

Fig. 4: Isotropic & Kinematic hardening models [32]

The hardening models of these authors have advantages as well as disadvantages. The nonlinear kinematic hardening model proposed by Armstrong and Frederick[30] has difficulties to model the smooth elasto-plastic transition after the load reversal. Based on the work of isotropic-kinematic hardening and Mroz's[24] multi surface model, Gau and Kinzel [10] proposed a hardening model that takes into account the Bauschinger effect and is able to predict springback accurately when the sheet material is subjected to complex deformation path.

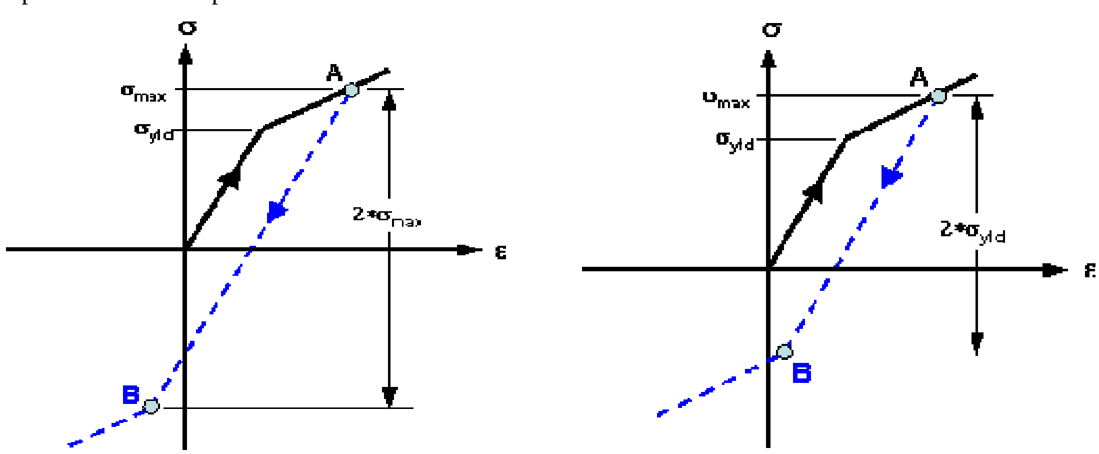


Fig. 5: Cyclic stress-strain responses for isotropic and kinematic hardening[32]

Basic concept of the Frederick and Armstrong model [30] was extended by various authors. The main focus is on model improvement including more complex loading conditions and additional experimental phenomena [33]. The major modification to the Armstrong and Frederick model was done by Chaboche [34] who tried to fragment the total back stress into a number of parts to describe the smooth elasto-plastic transition upon the load reversal. However, the drawback with this type of models is that the generated flow stress in reversal saturates to the monotonically loaded curve which makes it difficult to model for permanent softening.

Geng and Wagoner [35] made an anisotropic hardening model which is based on Armstrong and Frederick model[30] with the modifications of Chaboche[34]. The model comprises of two yield surfaces i.e. the bounding surface and the active yield surface. This two-surface model defines three main principal characteristics of the Bauschinger effect. Chun et al. [36] developed a simple anisotropic nonlinear kinematic hardening model as an alternative to the Geng and Wagoner model[35]. It is based on the Chaboche[34] hardening model. It is able to model the Bauschinger effect satisfactorily with multiple and continuous cycles. The Yoshida-Uemori model [37] includes seven material parameters, which can be identified from cyclic compression-tension experiments. This model describes all the features of the Bauschinger effect which includes the work hardening stagnation and also describes the strain/range dependency of cyclic hardening accurately. The work hardening stagnation is related to the experimentally observed dependency of cyclic stress amplitudes on cyclic strain ranges. Yilamu et al. [14] examined Bauschinger Effect on springback of clad sheet metals in draw bending. Sumikawa et al. [26] showed improvement of springback prediction accuracy using material model considering Bauschinger effect.

Unfortunately, the conditions of deformation in the real forming processes are very complicated and non-proportional strain paths observed even in single stamping operation. To describe the material behavior accurately in non-proportional and multi-axial loading conditions, the phenomenological models are not sufficient. The Bauschinger effect after the load reversal can be described by these models accurately. It is required to introduce much complex equations and material parameters to enhance the ability of phenomenological hardening models to define the material behavior undergoing strain paths change. But, the derivation of material parameters will be much complex. The material behavior in complicated strain paths change can be described by dislocation based anisotropic hardening models.

VII. CONCLUSIONS

Springback prediction and its reparation are the key challenges in the sheet metal industry. Dimensional inaccuracy must be controlled which is possible only with accurate prediction of springback. The governing factors of the development of the internal stresses in the material during loading and unloading have an influence on springback High accuracy of the stress state can only be obtained if an appropriate material model is used considering Bauschinger effect. It must be based on the initial yielding and hardening characteristics obtained from multiple tests. The material model should be able to describe the material behavior as well as the Bauschinger effect. The quantitative sensitivity of springback to the chosen material hardening function and Bauschinger effect must be recognized. The expertise of the analyst will remain crucial in spring back prediction. Many numerical and analytical approaches are available but they offer results which are not in line with practical one. So it is compulsory to consider parameters during modelling of springback prediction or during the development of springback prediction model. The Bauschinger effect is one of the such type parameter which play vital role in cycling loading. As most of sheet metal forming process involving such type of cycling loading, it is very important to consider the Bauschinger effect during springback prediction model for accurate springback result. Literature review showed, results of springback prediction model with Bauschinger effect are in good agreement with experimental data compare to results of model without Bauschinger effect.

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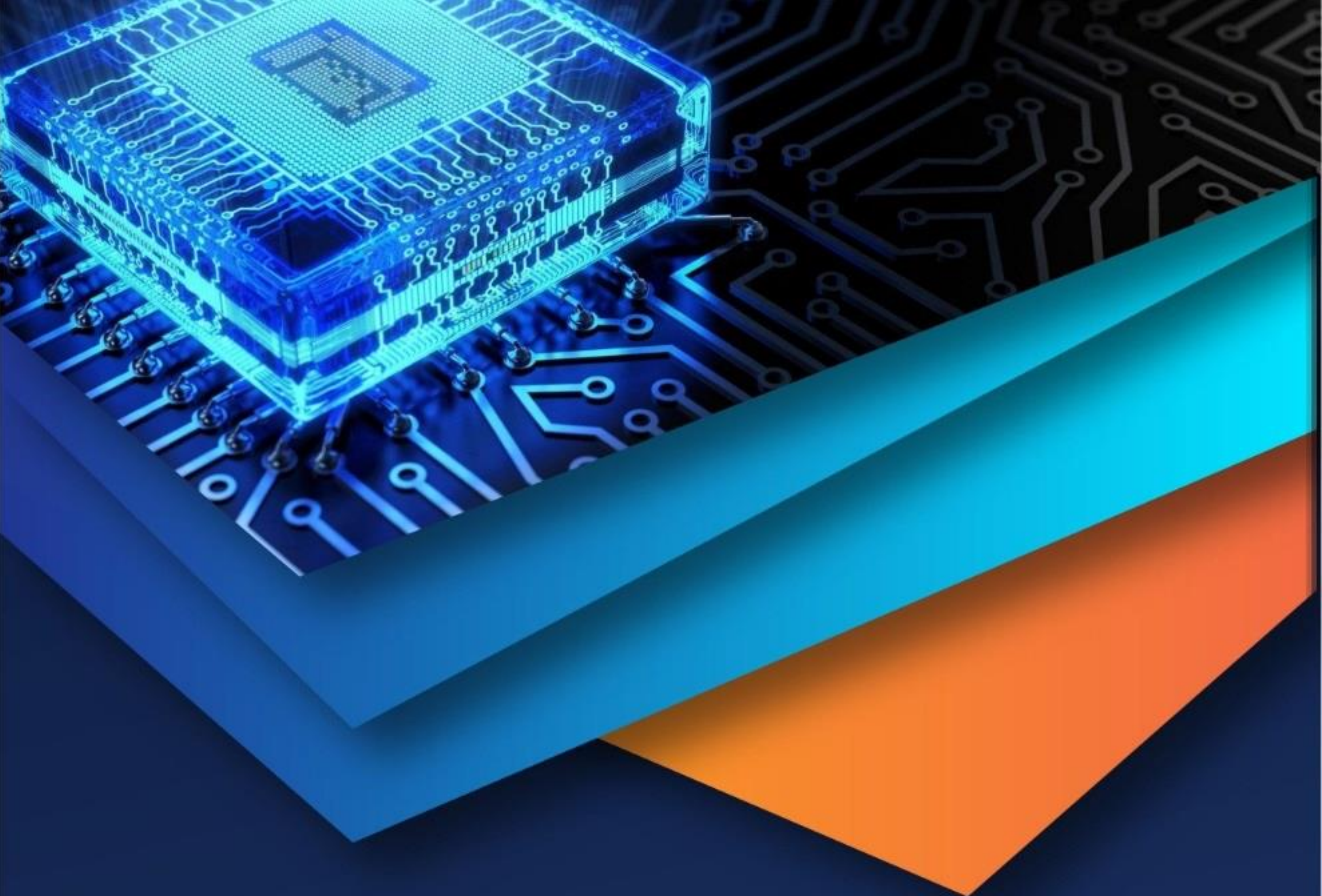

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