REVIEW ON INVESTIGATIONS CARRIED OUT ON BURR FORMATION IN DRILLING DURING 1975 TO 2020

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Abstract

Burr formation during machining process is a vital role in the assembly lines, even though it is a non value added process but also care should be taken while machining due to non avoiding output generated at the end of material removal process. At present almost all manufacturing sectors faces lot of problems due to these issues and invest more money towards deburring still advanced manufacturing methods available. So, complete burr removal is not possible and only thing is reducing utmost by applying better optimizing techniques, to develop good mechanization methods, selecting optimum process parameters and their conditions. The aim this paper deals about research methods implemented by earlier authors on burr formation especially in drilling. The reason why the present authors selected the drilling is number of automotive and aircraft engineers struggling during structural building works because of these burrs wherever precise measurement needed. In this connection, the authors concentrate their study on previous researcher works related to investigations on experimentation, developing new theoretical mechanisms to minimize burrs, adapt a new technologies available to modify drill bit geometries such that improvement in the minimization of burrs. Finally found that research contributions by changing their drill bit geometry and cutting process parameters have been focused on utilizing the methodologies, changing time to time. In analyzing the performance characteristics with that of input process parameters, several mathematical and empirical models were developed by many researchers so far in their works. Efforts have been made in the direction of optimization of process parameters in drilling for minimizing burr size.

Keywords

Burr formation, Design of experiments, Modeling and Simulation, FEM, Deform-3D

1 INTRODUCTION TO BURR FORMATION

As manufacturing processes became advanced, precision components require more attention to both the generation of surfaces and dimensions with tight tolerances. High quality products should be precisely manufactured according to the design specifications with minimal costs. To satisfy these requirements, the manufacturing process should be understood and its parameters need to be optimized [1]. Drilling is one of the final operations among structural assemblies used in aerospace and automotive sectors [2,3]. An unwanted projection of material formed during the drilling process, termed as burr as a part size errors (Fig.1). Burr is plastically deformed material, generated on the part edge during cutting or shearing [4,5]. Wherever conventional drilling is carried out, the burr formation of sheared edge is inevitable.

Removal of burr is essential for any component to avoid damage of component after assembling due to abrasion, injuring workers while assembly and other related problems. So elimination of burr is mandatory which involves some cost, literally known as deburring cost. Gillespie [6] and Lee [7] discussed about cost incurred due to removing of burrs on the components in their work (Fig. 2) and also presented the expenses incurred due to presence of burrs by category wise.

![Figure 1. Micro image of burr formation on Flange [30]](image)

![Figure 2. Category of expenses due to presence of burr](image)

![Figure 3. Breakdown of Manufacturing Expenses & Image of Milled part after deburring](image)
Aurich et al. [8] also identified, the investment on removing of burrs is non value added process while estimate manufacturing cost and diagrammatic representation (shown in Fig. 3) of cost incurred on burr removal process in an excellent manner to understand why the present industries affected more towards non value added deburring cost? The problem of deburring and edge quality (EQ) in the manufacturing environment is directly linked to the final use of the component [9,10]. The EQ is a function of the part design and is only necessary to edge finish within the design limits. To estimate cost of deburring and edge finishing operations certain standard procedure, human resources and extra machining time are required. If such a straight forward EQ standards are available, then find out expenses over post processing operations. This cost is non added value to the manufacturing cost, so must be minimize the burr to save money and to reduce manufacturing lead time. For a long ago, the only standard relating to burrs was the DIN standard (6784), which was updated in 1974. A new ISO 13715 [38] standard is being ratified under the guidance of three committees (measurement, surface roughness and engineering drawing) based on DIN 6784. There is some concern about the application of this standard to EQ problems and several groups worldwide have been defining standard, which was better suited to burrs and edge quality from design, then to manufacturing. Within the framework of the World Wide Burr Technology Committee (WWBTC) proposed two standards, first, an integrated international standard for burrs and edge finishing, provides a broad overview on deburring issues, where as second one, an edge quality code has also been developed, which enable to a clear and concise breakdown of the designer’s edge requirements and how these edges must be finished and inspected. It is crucial that before deburring and edge finishing work was carried out that the required edge quality is known. Using clear standards, international or in-house, will allow for the correct selection of process and process parameters with respect to the economics, quality and time.

Understanding the drilling burr formation and its more influential parameters are essential for predicting and reducing the burr size. Thus, process modeling and optimization are the two important issues for burr size minimization in drilling and hence it is essential to understand the current status of work in these areas. This chapter reviews the literature in the following key areas of focus, which is divided into three different categories viz., (1) parameters affecting the burr formation in drilling, (2) development of strategies to minimize the burrs in drilling and (3) analytical modeling techniques. The detailed review of literature under these three sub sections are discussed in detail in a chronological manner and the following sections are highlighted about the sequential information about the three different categories.

2 PARAMETERS AFFECTING BURR FORMATION IN DRILLING

Drilling burr formation is fundamentally a three-dimensional process affected by many parameters such as drill geometry, material property and process conditions. Experimental data collection and analysis provide a basic knowledge of burr formation mechanism. Gillespie is one of the early researchers studied about the burr formation at an academic level in drilling, the effects of process conditions, drill geometry and material properties on burr formation and proposed several burr formation mechanisms over a wide range of experimental conditions. In addition, the works carried out on drilling of titanium alloys covered hole quality issues and emphasized the influence of drill wear land size on burr size. But, most of Gillespie's tests were done with hand feed drills (unknown and uncontrolled feed rates). Burr formation in drilling is influenced by many factors, among those workpiece material like shear strength and hardness on the size of exit burrs while drilling of steels, drill geometry and process conditions are known to be more influential and much of the investigations by Sofronas et al. [11,12] have focused on their effects on burr formation. The various parameters reported by the authors to contribute on burr formation summarized and depicted in Table 1.

| Category                                    | Parameters                                           |
|---------------------------------------------|------------------------------------------------------|
| Process Conditions                          | Cutting Speed, Feed Rate, Use of Coolant             |
| Drill Geometry                              | Point Geometry, Point Angle, Lip Clearance Angle, Helix Angle |
| Material Properties                         | Ductility, Hardness, Tensile Toughness, Strain Hardening Characteristics, Temperature Dependence Properties |
| Others                                      | Tool Wear, Tool Material, Use of Packing             |

Analysis of the formation of burrs in drilling precision miniature holes in stainless steel material (SS 304L) using fractional factorial design of experiments [13]. The effect of feed rate, cutting speed, pecking and tool material on burr height, thickness and shape has been reported. Stein and Dornfeld [14] determined the sensitivity of feed, speed, drill wear and exit surface geometry in drilling of 0.91 mm diameter through holes in stainless steel material (304L). The results reveal that increase in feed, cutting speed and drill wear were found to enhance the burr height and thickness. A proposal for using the obtained burr data as part of a process planning methodology for burr control was also presented. However, the influence of drill geometry on burr size has not considered in the investigation. The control charts obtained are found to be useful for many researchers in the controlling burr formation especially in the case of 304L stainless steel. Gillespie and Blotter [15] identified three basic mechanisms (as shown in Fig. 4) involved in the formation of burrs: lateral deformation of material, bending of the chips and tearing of the chips. An alternative but similar classification based on its formation mechanism regardless of machining process (Table 2) has been proposed by Nakayama and Arai [16].

A quantitative burr formation model proposed by Ko and Dornfeld [17] for ductile materials during orthogonal cutting reveals that the influence of machining parameters on burr size was evaluated with machining tests performed in a scanning electron microscope (SEM). Furthermore, Equations for the calculation of burr height and burr thickness were developed based on cutting conditions, tool geometry and the workpiece material, if measured shear angle and tool-chip contact length are known. Chen and Dornfeld [18] extended the analytical model of burr formation with more realistic machining operations and conditions. Their study mainly focused on understanding the burr formation and edge breakout. However, no analytical or empirical Equations are available that are generally acceptable for predicting and controlling burr formation in oblique cutting processes. Theoretical and experimental investigations were carried out by Sofronas and Taranam [19] and was reported that, increased lip clearance angle and decreasing feed and point angle on drills could reduce the exit burr thickness. Shikata et al. [20] also reported similar trend of results under different
experimental conditions in carbon steel sheet drilling and proposed a basis for characterizing burr size. Five drills, each with a different point shape, were employed to collect the data on cutting thrust, torque and hole quality as measured by the nature of the burrs formed on the workpiece.

Sugawara and Inagaki [21, 22] investigated to know the effects of drill edge shapes and working conditions on burr formation, conducted a model experiment by selecting ten drill bits of each different diameter (Fig. 5) and found that the quantity of the burr increases with a decrease in drill diameter ranging from 0.2 - 2.5 mm, where as the quantity of the burr reduces with a decrease in diameter in case of drills having a diameter of less than 0.2 mm. The behavior in the former case was due to duller drill edge with a decrease in drill diameter. The reason for increment in the burr by decreasing diameter from 2.5 mm to 0.2 mm is not concluded clearly in their work. From the work of Min et al. [23], observation reported that the burr height varies as a function of grain orientation in micro drilling of poly crystalline copper (Fig. 6). Since, the tool diameter used was of the order of grain size, in most cases, the cutting action as per physics point of view at the tool edge, which varies as the tool moves from one grain to another. A single material may produce a ductile like cutting mode in one grain and brittle like cutting in another, indicating that favorable and non favorable cutting orientations for good surface and edge condition exist as a function of crystallographic orientation.

Takazawa [24] has explored several techniques that can be used for observing the effect of part material on burr formation in drilling. It was claimed that the drilling burrs produced by a drill with a nick on the cutting lips were smaller than the burrs produced by conventional drills. The decrease in burr size was due to increased cutting force and smoothness of chip flow through the hole. 

Kim [25] carried out preliminary experiment to investigate the drilling burr formation on Ti-6Al-4V titanium alloy, which is most widely used in aircraft industry because of its high specific strength. Two different types of carbide drills were used to observe the effects of variation of feed rate and cutting speed on drilling burr formation. Quantitative measurement of height and thickness of burrs did not yield much useful information because relatively uniform and small burrs were formed under all conditions. The effects of tool geometry and process conditions on burr formation during drilling of Ti-6Al-4V Titanium alloy plates with solid carbide and high-speed cobalt drills [26]. The authors reported that the cutting conditions (Fig. 7) had little effect on the burr size formed and drill geometry such as helix angle, split point versus helical point, lip relief angle and point angle had significant effect on burr height and burr thickness. Concerning the style of the drills, the helical point drill proved to be very suited to minimize the
exit burr formation. The burr height and thickness were reduced by 51% and 20% respectively with a helical point drill due to the smaller thrust force compared to the split point drill.

![Figure 7 Correlation between the burr formation and the cutting conditions](image)

Kim [27] developed a probabilistic model for prediction of drilling burrs and data updating procedure with the Drilling Burr Chart (DBCC). Probabilistic prediction provides a more feasible tool to control the burr formation in mass production, and the procedure of data upgrading shows how to use new data obtained in subsequent drilling process. The chart shows the specific distribution of burr types depending on the process parameters and drill diameter for a fixed combination of workpiece material and drill geometry. A Bayesian parametric modeling approach was adapted in this study. The Beta probability density function was selected here to represent the probability density of formation of a certain type of burr. The Beta probability density function is useful for modeling the probabilistic behavior of certain random variables constrained to fall in the interval (0, 1), which is the case of formation of a certain types of burr.

A method for the determination of the burr dimensions in short-hole drilling, simultaneously taking the parameters into consideration, which influence the burr formation [28]. These parameters are yield stress, forces and the geometry of the inserts. The method is based on empirical correlations drawn between burr parameters and cutting conditions of inserts from evaluation of experimentation. Using Schaefer's burr value $'g'$, it is possible to make a quantitative evaluation of the burr dimensions (Fig. 8). The method was verified for the materials 16MnCr5 and Ck45 in case of dry machining with indexable inserts and identified the deviation occurred in calculated values from the measured values due to inaccurate values for the yield stress to be considered for the experiment.

![Figure 8 Cross section and measured parameters of a burr](image)

Machining dry, without any coolant can be advantageous because of reduction in costs associated with the use of coolant and decrease in possible negative effects on worker health and the environment. Many problems associated with dry machining because of increased ductility at elevated temperatures, the burrs formed are larger. Recently, as awareness of the environment has moved from reactive to compliant to proactive, manufacturers have been pushing to transform processes more ecfriendly [29]. The use of lubricant in a machining process is expensive and the environmental effects are not completely known. As much as 16% of the cost of manufacturing can be attributed to the use of coolant, compared to tooling that accounts for 4% [30,31]. When the increased cost associated with faster tool wear is limited as much as possible by adjusting cutting parameters, dry machining can lead to a net cost savings. Enough money can be saved by eliminating the coolant to make dry machining economically advantageous. In addition to economics, the use of coolant can be bad for workers’ health and the environment. The possible health hazards associated with some coolants include toxic vapors, dermatological problems and bacteria cultures in the coolant. The environmental cost of lubricant used include polluting the atmosphere and water, storage, the cleaning of the swarf before recycling and the disposal of coolant. The cost breakdown of lubricant use is shown in Fig. 9.

![Figure 9 Breakdown of costs associated with coolant use](image)

Many of the problems associated with dry machining occur because the metal reaches higher temperatures than during machining with cooling lubricant. For example, Klocke et al. [32] showed that the temperature of the tool can rise from 150°C with flood coolant to nearly 400°C when drilling AISI 1045 steel. Without lubrication, more heat is generated during the machining process and without cooling effect; it cannot be as efficiently removed from the interface of the tool and the workpiece. The dimensional accuracy is often not as good during dry machining because of the high temperatures produced. Surface finish can also be negatively affected. The increase in temperature increases the ductility of the metal, changing the formation of chips and burrs. Shefelbine and Dornfeld [33] investigated the effect of dry machining on burr size and reported that machining dry without coolant could be advantageous because of decreased costs associated with the use of coolant and a decrease in possible negative effects on worker health and the environment. However, many problems associated with dry machining occur because of the elevated temperatures and the burrs formed are larger due to increased ductility at elevated temperatures.
3 STRATEGIES TO MINIMIZE BURR FORMATION IN DRILLING

A lot of research on burr minimization has been carried out experimentally and several attempts have been made analytically. The state of the art of burr minimization in drilling and some of the authors’ contributions in the area has been summarized in this section. Based on the literature on the development of strategies to minimize the burrs in drilling, three different approaches have been proposed. The first approach involves the optimization of the process parameters in order to reduce the formation of burrs and as well as the optimization of drill geometry in order to minimize the burr size. The second approach is the development of finite element models to reduce the burr formation. The third approach is the method for on-line monitoring of burr formation to control burr.

3.1 Multi Objective Optimization Methods

The optimization of machining processes still remains one of the most challenging problems because of its high complexity and non-linearity while solving it. The fundamental observation is that most engineering design problems are multi-objective in nature and involve simultaneously optimizing several conflicting design objectives [34, 35]. It is common to encounter multiple design criteria in a multidisciplinary setting, such as automotive or aircraft design. Most large-scale system design problems can be posed as multi objective optimization problems [36]. The various traditional optimization techniques like Lagrange’s method, geometric programming, goal programming, dynamic programming and branch and bound techniques have been successfully applied in the recent past for optimization of various manufacturing processes [37]. However, traditional methods of optimization do not fare well over a broad spectrum of problem domains. These techniques are not efficient when the practical search space is too large. Moreover, these techniques are also not robust and always tend to obtain a local optimum solution. The techniques for solving the multi-objective optimization problems can be categorized as:

(1) model based optimization techniques i.e., by using the meta models to obtain predictions of the phenomena of interest and then to find the best compromises among the multi objectives for the system through the latest nontraditional optimization tools like genetic algorithms, simulated annealing, ant colony algorithm, scatter search techniques and particle swarm optimization

(2) Taguchi robust design optimization techniques i.e., by allowing the process optimization using Taguchi method with minimum number of experiments without the need for development of empirical models.

3.2 Taguchi Robust Design

The Taguchi robust design focuses on improving the fundamental function of product or process, thus facilitating flexible designs and concurrent engineering. It is the most powerful method available to reduce the product cost, improve the quality and simultaneously reduce the development interval [38 - 41]. The Taguchi robust design uses many ideas from the statistical experimental design and adds a new dimension to it. The two major tools used in robust design are: (1) signal to noise (S/N) ratio, which measures the quality and (2) orthogonal arrays, which are used to study many design parameters simultaneously. The key steps in analyzing the data obtained include computation of S/N ratio for each trial of orthogonal array, calculation of main effects of the factors, performing the ANOVA, determination of optimal level for each factor and predicting the S/N ratio for optimal settings and finally comparing the results of the verification experiment with the predicted one. In the beginning Taguchi technique was designed to optimize single performance characteristic and the same has been employed in the past for the optimization of several manufacturing processes [42-46]. However, the Taguchi technique requires modifications for the optimization of multi-objective problems. Several researchers have suggested the methodologies used for optimizing the multiple quality characteristic problems in Taguchi method [47, 48]. Engineering judgement suggested by Phadke [49] has been used primarily to optimize the multi-response problems in the Taguchi method. Based on the judgement of relevant experience and engineering knowledge, trade-offs are made to choose the optimum factor levels for the multiple quality characteristics problem. However, by human judgement, the validity of the experimental results cannot be easily assured and hence an experienced engineer can only use the approach proposed by Phadke. The Taguchi approach with utility concept entails assigning a weight for each response. A weight to each S/N ratio of the quality characteristic is assigned and the weighted S/N ratio is added for computing the performance of a multi-response problem. But, determining a definite weight for each response in an actual case still remains difficult. Multi-performance characteristic optimization using Taguchi’s quality loss function employs the weighting factors in the total loss function to obtain the multi-response S/N ratio. Saravankumar et al. [50] analyzed the burr height at exit of the holes during drilling of hybrid aluminium matrix composite using TiN coated solid carbide twist drills. For experimentation, design of experiment - full factorial design was adopted and ANOVA was performed to investigate the effects of spindle speed, feed, drill diameter and weight fraction of graphite on the burr height in the drilling of hybrid aluminium matrix composite. A numerical model has been developed using regression analysis to predict the burr height and analysis of variance (ANOVA) in order to study the main effects of machining parameters on burr height and concluded that burr height decreases with increase in spindle speed but increases with increase in feed rate for hybrid aluminium matrix composites.

Rajiv Chaudhary et al. [51], reviewed on experimental investigations in drilling using Taguchi techniques and conclusions drawn as: In industrial applications, it is essential to require the optimal cutting conditions for tool–work piece combination. Taguchi technique has proved to be the best tool for determining the optimum machining conditions and improving performance characteristics. The multi-performance characteristics such as tool life, cutting force, surface roughness as well as the overall productivity can be improved by using Taguchi Techniques. It can also be concluded that at quite large cutting speeds with smaller feed rate, good surface quality along with dimensional accuracy can be achieved. Ugur koklu [52] investigated, the effect of mechanical properties of aluminium alloys, cutting speed, feed rate and drill diameter on burr height and surface roughness of drilling holes, using the Taguchi method. Al 2024, Al 7075 and Al 7050 were selected as the work piece materials for experimentation. The results reveal that the feed rate and the cutting speed minimize significantly both burr height and surface roughness. The cutting speed is the second most significant factor for burr formation. The drill diameter has the least effect on the burr height. Shanti Parkash et al. [53] investigated...
experimentally by Taguchi method for minimizing the Burr height in drilling of Al – Fly ash composite. In their study, the authors investigate the influence of cutting parameters such as cutting speed, feed rate and point angle on burr height produced when drilling of Al-Fly ash composite. From analysis of means and ANOVA, the optimal combination levels and the significant drilling parameters on burr height were obtained. Kilickap [54] presented the use of Taguchi and RSM for minimizing the Burr height and surface roughness in drilling of Aluminium 7075 alloy under dry condition. The results (Fig. 10) showed that the combination of low cutting speed, low feed rate and high point angle is necessary to minimize burr height. From the developed RSM-based mathematical model, the effect of drilling parameter on burr height is examined and observed that at higher values of the cutting speed, the burr height increases with the increase in feed rate at a constant drill point angle of 118°. Gaitonde et al. [55-57] discussed the application of Taguchi optimization techniques for minimization of burr height and burr thickness influenced by cutting conditions and drill geometry by a new concept of fitness function, genetic algorithm (GA) applications to RSM models for each set of experiment found the optimal setting of selected parameters to minimize burr size during drilling of AISI 316L stainless steel. Nouari et al. [58] experimentally tested the effect of the drilling parameters on the hole surface roughness and diameter deviations for different coated drills on aluminum alloys. The results reveal that, low constant feed rate, low cutting speeds are appropriate for the dry machining of AA-2024 and the authors are not focused on variation in drill geometry.

The desirability function analysis [59] made use of modified desirability functions, which measure the designer's desirability over a range of response values. The response variable can be transformed to a desirability value with the help of the desirability function. Harrington et al developed a new approach using desirability function to multi objective optimization. However, due to the mathematical complexity, engineering community cannot easily or rapidly understand the approach. Deng Julong [60] developed Grey system theory, the concept of the grey system theory is well known in China, which is applied globally in the fields of agriculture, ecology, economy, meteorology, medicine, history, geography, industry, earthquake, geology, hydrology, irrigation strategy, military affairs, sports, traffic, management, material science, environment, biological protection, judicial system etc., whatever the projects implemented with this theory by several researchers [61-67] has been successfully completed with better results.

Huang and Lin [68] developed grey relational analysis approach to optimize the process parameters such as coated deposition, spindle speed and feed rate parameters in drilling of Al 6061 aluminium alloy with multiple performance characteristics like tool life, surface roughness and burr height. It was shown that the multiple performance characteristics were together improved by using this method. Hari Singh et al. [69] conducted drilling experiments using L27 orthogonal array, to optimize the process parameters considering weighted output response characteristics using grey relational analysis. A combination of orthogonal array, design of experiments and grey relational analysis was used to ascertain best possible drilling process parameters that yields minimum surface roughness, burr height and hole diameter error. The results reveal that the combination of Taguchi design of experiment and grey relational analysis improves surface quality of drilled hole. Tosun [70] applied grey relational analysis for optimizing the drilling process parameters for the workpiece surface roughness and burr height (shown in Fig. 11). Various drilling parameters, such as feed rate, cutting speed, drill and point angles of drills were considered. An Ls orthogonal array was used for the experimental design. Optimal machining parameters obtained by comparing the calculated grey relational grade. Experimental results have shown that the surface roughness and burr height in the drilling process can be improved effectively. From the review of literature, it is observed that Taguchi method is a systematic application of planning and analysis of experiments to improve product quality. In recent years, the Taguchi method has become a powerful tool for improving productivity during research and development but it concentrates only on product single response. The industrialists also keen to produce items and maintaining a balance between quantity and quality with minimum production cost to achieve maximum profit. So the multiple quality characteristics optimization is another trial task. Here, the grey relational analysis comes into play, where a mathematical technique optimizes two or more than two quality characteristics.

**Figure 10 3D surface graph of burr height as a function of feed rate and point angle at cutting speed (12 m.min⁻¹)**

The theory of grey system was proposed by Deng (1989), calculates the grey relational coefficients for all quality characteristics either they are of larger the better or smaller the best nature types. A higher grey relational grade corresponds to the best optimal setting of process parameters for multiple responses [60].

**4 SIMULATION OF FINITE ELEMENT MODELS TO BURR FORMATION**

Machining simulation is nowadays an essential tool when it comes to product quality, cost reduction and overall prediction of metal cutting operations, contributing to a reduction or even elimination of trial and error approaches. Fig. 12 shows the increasing
importance of machining simulation through the number of publications released since 1970 until now.

Iwata et al. [71] observed the burr formation images during machining using SEM and experimentally determined the effect of exit angles of workpiece on burrs. The authors explained the fracture of the workpiece at the tool edge using the strain obtained through FEM analysis. A three-dimensional FEM program was developed by Hashimura et al. [72] to predict the 3D burr formation. The simulation results show good agreement with the experimental data on both burr shape and cutting forces. Guo and Dornfeld [73] investigated the influence of backup material on drilling burr formation by 3D FEM drilling models. Guo and Dornfeld [8] also proposed an integrated CAD/FEM system for drill design and drilling burr formation process. Industrial collaborators were modeled parametrically with commercial CAD software (shown in Fig. 13). Engineers are able to simulate the machining process to estimate burr formation. This information needs to be incorporated into the tool path planning system to realize the benefits of the earlier work.

Based on Park's FEM simulation, a two-dimensional FEM model was also developed by Min [76] to investigate the effect of backup material in burr formation (shown in Fig. 15). Backup materials with thickness of various sizes were placed at the end surface of the workpiece with condition of perfect contact between the two materials. As mounting of backup material reduces the size in any resulting burr effectively.

Three-dimensional FEM was also developed by Guo and Dornfeld [77] for the simulation of drilling burr formation processes of 304L stainless steel based on von mises stress distributions and progressive strains of the workpiece edge obtained from simulation, a drilling burr formation mechanism was proposed and divided into four stages (Fig. 16): initiation, development, pivoting point and formation stages with cap formation. The burr thickness is largely determined by the distance between the pre-defined machined surface and the pivoting point, while the burr height is determined by the positions of the pivoting point and the cap formation. Finally, concluded that the developed simulation model able to predict characteristics of drilling burr geometry consistent with observations from actual drilling process effectively.

The FEM simulation carried out by Min et al. [78] discussed on the role of negative shearing and bending mechanisms in the drilling burr formation process to develop the simulation models. The authors, proposed
that using the model as a template, related burr formation problems that have not been physically examined can be simulated and the results used to control process planning resulting in the reduction of burr formation.

Gardner et al. [79, 80] reported, a comparative study is presented on three commercially available finite element analysis software packages detailing their applicability for performing machining simulations, specifically to study burr formation. The three packages presented are DEFORM, AdvantEdge and ABAQUS. Each software package is discussed first and its advantages and disadvantages are presented. Then, the packages are compared and the suitable package for different scenarios is suggested. The various software packages’ features are compared in Table 4.

### Table 4

| Stages                        | Burr formation mechanism | FEM simulation |
|-------------------------------|--------------------------|---------------|
| Steady-state cutting          |                          |               |
| Burr initiation               |                          |               |
| Plastic deformation at the (center) |              |               |
| Development                   |                          |               |
| Plastic zone expands with little cutting |                  |               |
| Initial fracture              | Fracture at the edge of the drill |       |
| Burr formation                | Bur and cap formation    |               |

In the present days, Deform (Design Environment for Forming) is used for simulation of burr minimization scheme. DEFORM-3D is a very robust computational tool to simulate drilling processes. The process of using DEFORM takes CAD models of a drill bit and a workpiece, creates a mesh, assign boundary conditions for both, sets contact conditions, and finally simulates the drilling operation. The underlying theory of the code cannot be modified, but many other variables can be changed.

### 5 ANALYTICAL MODELING TECHNIQUES FOR BURR FORMATION

In 1952, Shaw, Cook and Smith [81] correlated cutting mechanics of drilling process to the basic three dimensional cutting processes and demonstrated the essential similarities between the drill point and the conventional turning tool (shown in Fig.17). In 1953 an attempt was made by Oxford, Jr [82] to analyze the basic mechanics of the drilling process and demonstrate that the chip formation mechanism is different in different regions of the drill. In 1957, Shaw and Oxford, Jr [83] approached the problems of computing thrust from dimensional reasoning and derived general Equation (Eq.1 & 2) for assessing drill torque and thrust and found to be in good agreement with the experimental data especially for aluminium alloys.

\[
\text{Fth} = \frac{0.55 \cdot f_{u} \cdot c}{d^{2} \cdot H_{b}} \left( \frac{1 - K}{1 + K} \right)^{0.3} + 0.07K^{2}
\]

\[
M = \frac{1}{d^{2} \cdot H_{b}} \left( \frac{1 - K^{2}}{1 + K} \right)^{0.3} + 3.2 \cdot K^{1.8}
\]

Where, \(c\) = chisel edge length and \(d\) = diameter if drill bit in ‘mm’, \(F_{th}\) = Axial force or Thrust Force during drilling, \(M\) = Torque or Moment of a cutting force of the drill on chisel edge, \(H_{b}\) = Brinell hardness of the material (BHN).

![Figure 16 Sequence of burr formation during drilling](image)

![Figure 17 Cutting forces during drilling](image)

Analytical and empirical models of a metal cutting process have been developed by many researchers and implemented so far effectively. The basic model is called the single-shear plane model or Emst-Merchant [84] model widely discussed in literature [85-90] based on the principle of energy conservation. Another analytical model is the theory of Lee and Shaffer [91], who also attempted to solve the metal cutting problems by considering that the material had an ideal rigid-plastic behavior and that the shear plane would be in the maximum shear direction, proposed their shear theory which was the first contribution to the slip-line models. It resulted from an approach to orthogonal cutting with
continuous chip with a simplified plasticity analysis. The above model undergoes many drawbacks and discrepancies with their respective investigative results. Later on, Hill [92], developed a static Equilibrium model to solve the same problem, stating that the velocity is tangentially discontinuous across the shear plane.

Bera and Bhattacharya [93] analyzed the drill geometry and determined that the chisel edge acted as an indenting tool and the lip as a cutting tool and presented the first predictive cutting model to evaluate the torque and thrust in drilling. The authors applied the Merchant thin shear zone cutting model to predict the drilling forces at the cutting edge. The total thrust and torque were found by the summation of the elemental thrusts and torques derived from the elemental deformation forces and the thrust and torque components. Williams [94] further described the secondary cutting edges along with the main cutting edges and an indentation zone around the drill center as the three identifiable zones of interest. The author used an orthogonal cutting analysis to model the thrust and torque at the drill cutting edge. The total forces were calculated by the summation of the force generated by the cutting edge and chisel edge as well as the indentation zone. The difference of model developed from the model of Bera and Bhattacharya was that the cutting action for most of the chisel edge was presented as a classical orthogonal cutting action with continuous chip formation and highly negative rake angles.

Mauch and Lauderbaugh [95], in their model also divided the drill into three regions and implemented the idea of using different cutting processes for each zone. Both the orthogonal and the oblique cutting models were applied to the two elements of the chisel edge and to the main cutting edge area accordingly. In the proposed method, split the main cutting edge into N elements and calculated the total torque and thrust by summarizing the part values generated in each of these regions. Armarego and Wright [96] analyzed the fundamental machining data such as shear stress and chip length and the cutting mechanisms of the cutting edge and chisel edge developed a model which can be used to estimate thrust and torque for the different drill flank configurations (shown in Fig. 18 & 19). The authors observed similarities in the effect of feed rates, spindle speeds and the geometrical characteristics of the drill on the resulting torque and thrust values, regardless of the drill flank configurations used. Armarego and Cheng [97, 98] proposed a new simplified method to predict thrust and torque during drilling for conventional and modified drills. The method of calculation was also based on the implementation of both the orthogonal cutting model and the oblique cutting model.

Chandrasekharan et al. [99] suggested a new approach in predicting the cutting forces for drilling based on the geometric similarity of the drills. In the predicted model, the force and torque Equations were represented in a normalized radial coordinate system. Their model consists of two main points of interest: the primary cutting edge and the chisel edge. In order to describe the cutting forces on the primary cutting edges used the Merchant’s model and the calculations for the chisel edge were based on the slip line field method derived by Kachanov [100]. The authors developed a calibration algorithm to extract the cutting model coefficients and implemented the mechanistic force approach to develop the models for the cutting force system.

Later on, many researchers found similarities in the drilling and the oblique cutting processes. Watson [101-104] also applied the oblique machining theories to drilling by dividing the cutting edges of the drill into small segments, performing calculations for each segment, and summing the results. The Watson cutting force model for the chisel edge was based on the classical orthogonal cutting analysis and included the drilling tests to determine the contribution of the chisel edge to the overall torque and thrust. However, the correlation between the predicted values and the experimental results for the whole drill was not as good as the correlation between the experimental and the predicted results for the cutting edge alone. Rubenstein [105,106] thoroughly investigated the oblique cutting process and derived the expressions for the torque and thrust forces, assuming that the removal process is quasi-orthogonal, but for the drill point it was only sufficient when the drill diameter was large enough in relation to the chisel edge length. Zhang et al. [107] noticed the effect of vibrations and developed a model based on the mechanics of vibrations and the continuous distribution of thrust and torque along the cutting edge and the chisel edge of the twist drill. Wang et al. [108, 109] concluded that vibration drilling is different from conventional drilling and presented a method, which involves the development of a dynamic uncut chip thickness for each cutting element at the cutting edge and chisel edge. The model described by the authors the dynamic cutting process, where the mean thrust and torque increased as feed increases under constant vibration. Yang et al. [110] studied the drilling and reaming processes and proposed a dynamic model which included a representation of the forces generated on the cutting edge, the influence of the chisel edge, the relationship between the machine vibrations and forces and the dynamic machine tool model.

Elhachimi et al. [111, 112], based on the oblique cutting model for the primary cutting edge and the orthogonal cutting model for the chisel edge presented a new theoretical model to predict thrust force and torque.
in high speed drilling. In this model, thrust and torque were calculated in terms of the geometric features of the drill, the cutting conditions and the properties of the machined material. Chen et al. [113] modified the existing force model for the split-point, incorporating the splitting parameters on the secondary cutting edge for predicting the thrust force and torque. By minimizing the thrust force and torque obtained the optimization of the split-point drill geometry.

Kapoor, Chandrasekharan et al. [114-116], Gong et al. [117-119] developed various mechanistic drilling models. Other recent developments in drilling models have utilized the finite element method. Fuh [120] explored the use of the finite element method for drilling. Guo and Domnefeld [121] and Min et al. [23] applied the finite element technique for modeling drilling and exit burr formation. Shatla and Altan [122] using the same approach is determining the drilling torque and thrust force. Bono and Ni [123, 124] predicted the drill heat flux, temperatures and the thermal distortion of the drill holes. Strenkowski et al. [125] developed an analytical finite element technique for predicting the thrust force and torque in drilling with twist drills. The approach was based on representing the cutting forces along the cutting edge as a series of oblique sections and cutting in the chisel edge region was treated as an orthogonal cutting with different cutting speeds depending on the radial location. An Eulerian finite element model was used for each section to simulate the cutting forces. The section forces were then combined to determine the overall thrust force and drilling torque. An extension of the technique for predicting drill temperatures has also been described.

6. MULTI-ATTRIBUTE DECISION MAKING (MADM) TECHNIQUE

To acquire the competitive advantages in order to survive in the global business scenario, the selection of the most appropriate material has become a remarkable concern for many manufacturing companies. It is very crucial in industries where materials are intensively used to prompt production level as well as revenue generation. To survive in the modern economy, companies must be careful in making decisions. Improper decisions, increase companies’ costs in terms of resource wastage as well as affect customer satisfaction. Modern manufacturing companies are now facing some problems like the selection of materials because of time consumption & lack of advanced knowledge as well as experience. The difficulty of the material evaluation and selection problem from available materials has been driven by the researchers to develop models for helping decision-makers.

Decision making is the study of identifying and choosing alternatives based on the values and preferences of the decision maker. Making a decision implies that there are alternative choices to be considered, and in such a case, not only as many of these alternatives as possible are identified but also the best one is chosen to meet the decision maker’s goals, objectives, desires, and values [126-128]. Thus, every decision making process produces a final choice. The selection decisions are complex, as decision making is more challenging now a days. For obtaining the best decision in conjunction with the real-time requirements, a number of MADM approaches are available. MADM methods [129, 130] are generally discrete, with a limited number of pre-specified alternatives. These methods require both intra and inter attribute comparisons, and involve explicit tradeoffs that are appropriate for the problem considered. Most commonly used MADM approaches are weighted sum method (WSM), weighted product method (WPM), Analytic hierarchy process (AHP), Technique for order preference by similarity to ideal solution (TOPSIS), and Compromise ranking method (VIKOR), Graph theoretic approach (GTA).

Yıldız et al [131] reported in detail about proposed works in the literature review in the various sectors of application areas and concluded finally, the importance of MADM techniques in the selection of attributes according to the weightage ratios of each parameter as per the influence in the objective function [Fig. 20].

Figure. 20 MADM methods proposed by the researchers in various sectors [190]

Jian Liu et al. [132] presented the solution procedure to solve multi-attribute decision making problem of limited schemes to determine the weighting coefficient of each attribute index based on basic point and weighting coefficients range. This method provides weighting range of each index, basic point and its comprehensive evaluation value are given. This method not only involves the subjective estimating of the people, but also avoids the comparison and evaluation between various attributes. B. Singaravel et al. [133] applied MADM techniques especially AHP and TOPSIS methods combined in determining optimum machining parameters in turning operation of EN25 steel with coated carbide tools. The authors concluded finally the combined TOPSIS and AHP method consider weight criteria of each objective for a better and accurate evaluation of the alternatives. This method has the advantage of utilizing simple computational steps for simultaneous optimization of multiple objectives.

In the present work, AHP method is applied for decision making regarding the selection of suitable material which yields minimal burr size, high strength and good surface integrity. Initially, the optimum burr size is estimated using Grey based-Taguchi method for different series of aluminium alloys. The output results obtained from Grey based-Taguchi method used as an input to the AHP and TOPSIS approach. Finally, the results generated in MADM suggest the suitable alternative of aluminium alloy with required multi objectives.

Not but not least, lastly discussed on the works done by Sreenivasulu et al. [134-142]. They worked more on study of drilling burr formations in different ways of techniques using lot of experimentation at different levels carried out on different aluminium alloys and compared these results with developed analytical and simulation models in Deform-3D. This elaborate literature review on study of drilling burrs described from past to present available methods and techniques are more helpful to the scholars who are interested to do work in this area of research.
7. OBSERVATIONS AND CONCLUSIONS DRAWN FROM THE REVIEW OF LITERATURE

The following observations can be made from the literature survey:

➢ Most of the research studies on burr formation mechanism reported cutting speed and feed as the affecting process parameters. On other hand, only few investigations have identified that the drill diameter, point angle and lip clearance angle have significant effects on minimizing burr formation during drilling.

➢ Previous studies on burr minimization in drilling considered either burr height or burr thickness as the objective of the optimization. However, there were no reports of simultaneous minimization of burr height and burr thickness by considering effect of thrust force and torque during drilling.

➢ From review of literature also identified that, optimization of process parameters based on Grey relational analysis and Taguchi robust designs are powerful optimization methods for multiple performance characteristics of drilling parameters, which economically satisfy the needs of problem solving and design optimization.

➢ As discussed in the sections, it is found that there was a research gap in the study of the influence of type of material, various stresses and strain rates etc. on the responses like thrust force, torque, surface roughness of the drilled hole and burr size using HSS twist drill bits with variable clearance angle, so far, effect of these variable and also multiple responses are not attempted by earlier researchers in developing analytical models.

Based on the above observations, the following conclusions are drawn.

➢ The optimum settings of cutting speed, feed, point angle and lip clearance angle for a selected drill diameter are to be determined which simultaneously minimize burr height and burr thickness by considering thrust force and torque.

➢ The simultaneous minimization of thrust force and torque in drilling causes reducing the burr size, to acquire this, an optimized multiple performance characteristics of drilling parameters required. Hence, Grey based Taguchi method has been considered for further investigations.

➢ Process modeling by Taguchi based on orthogonal array design of experiments integrated by grey relational analysis proved to be an efficient modeling tool. The methodology not only reduces the cost and time but also gives the required information about the main and interaction effects of responses with input parameters.

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