Understanding the drilling burr formation and its dominant parameters is 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 four different categories: (1) parameters affecting the burr formation in drilling, (2) development of strategies to minimize the burrs in drilling, (3) metamodeling techniques and (4) multi-objective optimization methods.

2.1 Parameters Affecting Burr Formation in Drilling

Drilling burr formation is a complex process to analyze because it 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 basic knowledge of burr formation mechanism.

Gillespie [49] was one of the first researchers to study the burr formation at an academic level in drilling. He studied the effects of process conditions, drill geometry and material properties on burr formation over a wide range of test conditions. Gillespie's studies on titanium alloys covered hole quality issues and emphasized the influence of drill wear land size on burr size. No influence was found in that study. Importantly, most of Gillespie's tests were done with hand fed drills (unknown and uncontrolled feed rates). So, the influence of feed rate is confounded with other parameters.
studied. Gillespie [51] also carried out certain experimental studies to investigate the influence of various related process parameters on drilling burr formation and proposed several burr formation mechanisms.

Previous research by Sofronas et al. [175] shows that drilling burr formation is influenced by many factors. Among the factors, workpiece material, drill geometry and process conditions are known to be more influential and much of the investigations have focused on their effects on drilling burr formation. The various parameters contributing to burr formation are shown in Table 2.1.

Table 2.1: Parameters Affecting Drilling Burr Formation

<table>
<thead>
<tr>
<th>Category</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process Conditions</td>
<td>Cutting Speed, Feed, Use of Coolant</td>
</tr>
<tr>
<td>Drill Geometry</td>
<td>Point Geometry, Point Angle, Lip Clearance Angle, Helix Angle</td>
</tr>
<tr>
<td>Material Properties</td>
<td>Ductility, Hardness, Tensile Toughness, Strain Hardening Characteristics, Temperature Dependence Properties</td>
</tr>
<tr>
<td>Others</td>
<td>Tool Wear, Tool Material, Use of Packing</td>
</tr>
</tbody>
</table>

Stein [180] analyzed the formation of burrs in drilling precision miniature holes in stainless steel 304L material using fractional factorial design of experiments. The effects of feed rate, cutting speed, pecking and tool material on burr height, thickness and shape have been reported.

Stein and Dornfeld [181] determined the sensitivity of feed, speed, drill wear and exit surface geometry in drilling of 0.91 mm diameter through holes in stainless steel 304L material. Increase in feed, cutting speed and drill wear were found to increase burr height and thickness. A proposal for using the drilling burr data as part of a process planning methodology for burr control was also presented. However, the influence of drill geometry on burr size was not considered for the above investigations.

Gillespie and Blotter [52] developed simple analytical models for poisson and roll over burrs and these models were able to predict burr
thickness with some success for a limited range of conditions. Further they reported that the basic factors like thrust, uncut chip thickness, relative energies for bending and shearing the chip etc., govern the mechanism of burr formation.

Ko and Dornfeld [100] proposed a quantitative burr formation model for ductile materials during orthogonal cutting. 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.

Chern and Dornfeld [23] 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 Taraman [176] and it was reported that, increasing helix angle and lip clearance angle and decreasing feed and point angle on drills could reduce the exit burr thickness. Shikata et al. [167] 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 gather data on cutting thrust, torque and hole quality as measured by the nature of the burrs formed on the workpiece.

Sofronas [177] experimentally investigated the influence of work material properties like shear strength and hardness on the size of exit burrs while drilling steels. He showed that the exit burr size increases with increase
in hardness of the workpiece and system stiffness has negligible effect on burr size.

Sugawara and Inagaki [183] found that the quantity of the burr increases with a decrease in drill diameter ranging from 0.2 - 2.5 mm, whereas the quantity of the burr decreases 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 cause was not clear for the latter case.

Sugawara and Inagaki [184] also investigated the burr formation process through model experiment. The effects of drill edge shapes and working conditions on the burr formation were studied. They reported that the dullness of edges causes the larger burr formation so that the cutting ability becomes worse.

Min et al. [135] observed that the burr height varies as a function of grain orientation in drilling of poly crystalline copper. Since, the tool diameter used was of the order of grain size, in most cases, the cutting physics taking place at the tool edge 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 [189] 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 increased smoothness of chip flow through the hole.

Kim [89] 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. No coolant was used. 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.

Dornfeld et al. [43] also studied 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. They reported that the cutting conditions had little effect on the burr sizes 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.

Kim and Dornfeld [96] developed an analytical model for burr formation in drilling of low alloy steel. The proposed burr formation mechanism was based on the principle of energy conservation and metal cutting theory. Based on the model, the effects of several important parameters on burr formation were investigated.

Kim [91] developed a probabilistic model for prediction of drilling burrs and data updating procedure with the Drilling Burr Control 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. It 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.
Heisel et al. [68] presented a method for the determination of the burr dimensions in short-hole drilling, simultaneously taking the parameters into consideration, which influence the burr formation. These parameters are yield stress, forces and the geometry of the inserts. The method is based on empirical cutting examinations and takes account into the correlation between different burr parameters and the machining conditions such as cutting speed, feed and tool geometry. Using Schaefer’s burr value, it is possible to make a quantitative evaluation of the burr dimensions. The method was verified for the materials 16MnCr5 and Ck45 in case of dry machining.

Shefelbine and Dornfeld [166] investigated the effect of dry machining on burr size. They 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. It was shown that the burrs formed are larger due to increased ductility at elevated temperatures.

2.2 Strategies to Minimize Burrs in Drilling

A lot of research on burr minimization has been done 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 these areas have been summarized in this section.

Based on the literature survey 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.
2.2.1 Optimization of Process Parameters to Minimize Burrs

Nakayama and Arai [140] classified the machining burrs according to the cutting edge involved and the mode and direction of the burr formation. By combining these two systems of classification, most of the machining burrs can be adequately designated. The size of the sideward burr is minimized by decreasing the undeformed chip thickness and shear strain of the chips and by increasing the including angle. The size of the forward burr is minimized by the fracture at the root of the chip.

Pande and Relekar [147] observed the burr formation tendency especially with reference to burr height and thickness at entry and exit of the holes during drilling by changing the drill diameter, feed rate, length of hole to drill diameter ratio and BHN of the work material. They also reported that the drill diameter in the range of 8-10 mm yields minimum exit burr height. In addition, an attachment has been designed and developed to provide continuous modification of feed during drilling.

Sugawara and Inagaki [185] studied the difference in workpiece structure on burrs produced during drilling. Workpieces of different structures were machined with drills of several sizes and found that increasing the grain size of the workpiece could reduce the burr. This effect of grain size becomes especially important when the drill diameter is very small and its tool edge is dull or worn.

Hewson [69] has carried out analysis in drilling operations on Ti-6Al-4V titanium alloy to identify the relationship between the exit burrs, cutting fluid, supporting backplate material and tool geometry allowing a further understanding of the formation modes of burrs between layered materials. Uniform burr shapes would not have been formed at these cutting conditions without the backplate and fluid. Burrless regions were the direct result of the support provided to the workpiece by the backplate. Exit burr sizes were found to be significantly lower than those found in Kim’s experiment [93], which was done without cutting fluid or a backplate.
Kim *et al.* [93, 94] and Min *et al.* [133] developed empirical drilling charts to choose suitable cutting conditions for AISI 304L stainless steel and AISI 4118 low alloy steel materials in order to reduce the burr size. They developed control charts for prediction of burr type and size in drilling by split point twist drills. One of the two parameters used for the chart was found by the concept of similarity. The other one was the indicator of the cutting speed of the process. It was shown that the chart could predict burr type and size with feed rate and spindle speed even if the drill diameter changes. Since the drill geometry and the material were fixed, the important parameters to be considered were the process conditions and the drill diameter. Feed rate and spindle speed were two control parameters in drilling process. However, the use of these control charts is limited to the drilling through a single layered material over limited ranges of drilling.

Control charts and Bayes theory was used by Kim and Dornfeld [95] to identify the process parameters that would control the burr size. Using previous studies of material properties and burr formation, the third axis on the burr control chart was developed by Riech-Weiser *et al.* [157]. Ideally, one could create a dimensionless number, which is a function of the material properties affecting the burr formation.

Lin and Shyu [122] adapted variable feed machining for improving cutting tool life and exit burr height for hard and difficult to machine materials. Four coated drills were tested and results indicated that the TiN and TiCN coated drills were more suitable than the CrN and TiALN coated drills when drilling stainless steel.

Huang and Lin [72] 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.
Ko and Lee [103] investigated the effect of drill geometry on burr formation during drilling. The main geometrical parameters that influence the burr sizes are point angle, corner radius, chisel edge and helix angle. Larger point angle, smaller corner radius and shorter chisel edge of the drill reduced the burr size.

Drilling tests were carried out by Ko et al. [104, 105] using drills of various shapes like general carbide drills, round drills, chamfer drills and step drills. Burrs were generated under various cutting conditions using different materials such as steel and aluminium alloys. Chamfer drill, round drill and step drill form smaller burrs than the non-modified conventional drill. As a result of the experiments, step drill with specific step angle and step size was suggested for burr minimization. Wada and Yoshida [204] emphasized on burrless drilling of various metals. The roundness of the drill’s corner reduced the burr to a very small size.

Another approach given by Adachi et al. [1] involves a modification of the drilling process, which makes use of ultrasonic techniques to reduce the burr formation. They found that the burr size produced by the low frequency vibratory drilling of aluminium is smaller than that produced by conventional drilling. Moreover, the relationship between the burr size and the cutting force was examined and the effect of the cutting force on burr size was also investigated. The size of the burr formed on aluminium was also compared with that formed on carbon steel.

Takeyama et al. [190, 191] also reported that the burr around the hole exit can be minimized by applying ultrasonic vibration in the direction of drill feed and by utilizing the newly developed radial periphery lip drills during drilling of aluminium and glass fiber reinforced plastics.

Simon et al. [170] highlighted the use of ultrasonic assistance, where the high frequency and low-amplitude vibrations are added in the feed direction for the reduction of burr size in drilling of Al 1100 aluminium
workpieces. The results demonstrated that the burr size could be reduced in comparison to conventional drilling under suitable ultrasonic vibration conditions.

Bakkal et al. [8] identified two distinctly different types of burrs: roll over shape at the entry and crown shape at the exit edges of drilled bulk metallic glass holes. The size of burrs in the exit edge is typically larger than that in the entrance edge. High feed rate helps to reduce the size of burrs in both entrance and exit edges.

Lee [114] presented a method to minimize the burr formation in drilling intersecting holes using design of experiments. Three controllable parameters, namely, tool geometry, feed and speed were optimized through iterative design of experiments. 88 % reduction in burr size was reported in the study.

Tosun [200] introduced grey relational analysis for optimizing the drilling process parameters for the workpiece surface roughness and burr height. Various drilling parameters, such as feed rate, cutting speed, drill and point angles of drills were considered. An orthogonal array was used for the experimental design. Optimal machining parameters were determined by the grey relational grade obtained from the grey relational analysis for multi-performance. Experimental results have shown that the surface roughness and burr height in the drilling process can be improved effectively through the new approach.

2.2.2 Development of Finite Element Models to Reduce Burr Formation

Numerical simulation by finite element models (FEM) was also successfully applied in investigating the drilling burr formation mechanisms by several researchers.
Iwata et al. [74] observed the burr formation during machining inside a SEM and experimentally determined the effect of exit angles of workpiece on burrs. They explained the fracture of the workpiece at the tool edge using the strain obtained by a FEM analysis.

A three-dimensional FEM program was developed by Hashimura et al. [66] to predict the 3D burr formation. The simulation showed good agreement with the experimental data on both burr shape and cutting forces.

Guo and Dornfeld [64] developed three-dimensional FEM drilling models with two sets of backup materials to investigate the influence of backup material on drilling burr formation and showed that the burr size could be minimized by use of a bushing having a hole with the same diameter as that of the drill.

Guo and Dornfeld [63] also proposed an integrated CAD/FEA system for drill design and drilling burr formation process. Various drills from the industrial collaborators can be modeled parametrically with a commercial CAD program and be incorporated into a finite element input file automatically with workpiece geometry and material, cutting conditions, and process data. The manufacturing engineer has the capability to simulate the machining process to evaluate burr formation. This information needs to be incorporated into the tool path planning system to realize the benefits of all the previous work.

Park and Dornfeld [149,150] developed two-dimensional FEM models of burr formation in the orthogonal cutting of Al 1100 aluminium and 304L stainless steel materials. A commercial FEM package and a Lagrangian FEM model were used to investigate the burr and breakout formation and suggested four-step burr formation mechanism.

Based on Park's FEM simulation, a two-dimensional FEM model was also developed by Min [131] to investigate the effect of backup material in burr formation. 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. The basis of a FEM to simulate drilling burr formation process was also presented.

Three-dimensional FEM was also developed by Guo and Dornfeld [65] for the simulation of drilling burr formation processes of 304L stainless steel. The nonlinear thermo-elastic-plastic model simultaneously accounts for dynamic effects of mass and inertia, strain hardening, strain rate, automatic mesh contact with friction capability, material ductile failure and temperature-mechanical coupling. Material ductile failure criteria were proposed to simulate drilling burr formation. Based on a series of stress contours and progressive deformation of the workpiece edge obtained from simulation, a drilling burr formation mechanism was proposed and divided into four stages: 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.

The FEM simulation carried out by Min et al. [132] demonstrates the dominant roles of negative shearing and bending mechanisms in the drilling burr formation process. Analytical models are increasingly supplemented with FEM models of the drilling process to predict the effects of drill geometry, process parameters and the workpiece characteristics on size and shape of the burr.

Based on Park, Guo and Min studies, Choi et al. [27] proposed a FEM for inter-layer burr formation in drilling of a multi-layered material used widely in the aerospace industry. It was found that a gap formation was initiated by initial difference in elastic bending of layers and developed by plastic deformation of the first layer. They reported that the gap formation depends on the thrust force of the drill and clamping position only influences the elastic deformation.

Further, Choi et al. [28] introduced simulation results from the FEM model developed in their previous work. Workpiece bending due to the thrust
force from the FEM simulation showed the similar variation observed in the experiment. From the feed and radial direction displacement variation of the observation mode, which was located on the surface at the perimeter of the drilling hole, burr size was estimated quantitatively in drilling through double-layered 304L stainless steel plates.

Vijayaraghavan and Gardner [201] discussed the use of three different FEM softwares, namely, Abaqus, Deform and AdvantEdge to study the burr formation in curved surface drilling and drilling of intersecting holes, drilling of multi layer materials and machining of composite materials. The software packages were described and their advantages and disadvantages were detailed.

Vijayaraghavan [202] also discussed the challenges in finite element modeling the machining of aerospace multi-layered materials. The simulation roadmap was also proposed to study the effect of different materials and drill geometries on burr formation.

2.2.3 On-Line Monitoring of Burr Formation to Control Burr

Peria et al. [151] developed a new monitoring technique to detect burr formation based on internal signals from spindle torque during drilling operations. The selected features were sensitive to the exit burr while comparatively insensitive to changes in the process parameters. The experiments were performed in Al 7075-T6 aluminium workpieces under dry high-speed conditions. The developed algorithm filters the signal and calculates the magnitude related to burr formation. It was reported that the predictability of the algorithm is above 92% for the tested range of process parameters.
2.3 Meta Modeling Techniques

Metamodels are the empirical expressions, used to obtain the relationships that relate the controllable variables to the performance measures of interest. The data obtained from the experimental design is used to construct the metamodels. The advantage of the metamodel is that once it is created, it can yield large amounts of predictions. Understanding the working of different metamodeling techniques, as used by the designers allow us to know the relative merits and demerits of each. The various types of metamodels are presented in this section.

2.3.1 Response Surface Methodology

Engineering design methods have often borrowed generously from the statistics literature. Response surface methodology (RSM) is a statistical tool [11, 88, 139], primarily developed for fitting analytical models to a set of experimentally collected data. The past two decades have seen the RSM gain popularity as a metamodeling tool for the approximation of computer simulations [172] and RSM is perhaps the simplest and the most widely used approximation tool in industry.

Response surface models constructed using simple quadratic polynomials can generally be used as local approximating surfaces, i.e., their accuracy is restricted to a small region of the design space. Low-order polynomials cannot effectively model the non-linearities, typically present in simulation responses over a large region of the design space. Nevertheless, the RSM, being a regression technique, can be effectively used in the presence of numerical noise. The steps involved in RSM include designing a set of experiments for adequate and reliable measurement of responses and determination of best-fit mathematical models.
The RSM has been used successfully to develop the mathematical models for various processes such as turning [45, 71, 129, 144, 173], drilling [146], milling [33, 127], electro chemical machining [10], electric discharge machining [84], electrochemical discharge machining [162], electro jet drilling [164], magnetic abrasive finishing [174], welding [61, 62, 138], shear spinning [20] and extrusion [195]. This approach has the advantage of taking into account the combined effects of several parameters in a simple and systematic way and prediction of the results of the experiments with different parameter combinations. The RSM also helps to obtain the surface contours of these parameters using experimental and predicted values.

The RSM, being a regression technique, is more appropriate within the realm of physical experiments because it typically smoothes out the random errors present in the experiment [148]. In case of deterministic computer experiments, it is instead more appropriate to use techniques that produce an interpolative fit through all the computed data points instead of a least squares fit. The challenge of interpolative fitting has led researchers to explore the so-called non-parametric metamodeling techniques [73]. Some of these are discussed below.

### 2.3.2 Fuzzy Logic

The fuzzy logic [99, 196] has the great capability to capture human common sense reasoning, decision-making and other aspects of human cognition. Fuzzy logic involves a fuzzy interference engine and a fuzzification and a defuzzification module. Fuzzification expresses the input variables in the form of fuzzy membership values based on various membership functions. Governing rules are formulated in linguistic form and each rule inference can be drawn on output grade and membership value. Inferences obtained from the various rules are combined to arrive at a final decision. The membership values thus obtained are defuzzified using various techniques to obtain the true value. However, fuzzy logic requires fine-tuning, which depends on trial and error procedure and hence time consuming.
2.3.3 Artificial Neural Network

The artificial neural network (ANN) adopts a nonlinear regression strategy. Neural networks involve nonlinear computational elements called neurons, arranged in a specific architecture [67]. The training phase of a neural network consists of an algorithm that iteratively adjusts the parameters of the network to reduce the error between the actual and the predicted output for a set of training input data. The trained network is then used to interpolate between known data points. The performance of the network can depend to a large extent on the type of activation function used for each neuron, for example, sigmoid or linear, the number of neurons, the number of hidden layers and the network architecture.

One of the drawbacks associated with the use of neural networks for function approximation is the uncertainty in specifying several of the network parameters, such as the number of neurons, the number of layers, the type of activation function, and the optimization algorithm used to train the network. Also, the training phase generally needs to be supervised in order to avoid over-fitting. As such, some publications [171] suggest using neural networks only for highly nonlinear data.

2.3.4 Splines

The splines provide a practical alternative to high-order polynomials, which can typically result in numerical difficulties. The splines are piecewise low-order polynomials grouped in such a way that a different polynomial is used in a different region of the design space [153]. Appropriate continuity requirements need to be imposed at the boundaries of these different regions. Extending splines to handle multivariate data points, however, is a challenging task. Multivariate adaptive regression splines [77], for example, have been recently proposed as a metamodeling technique.
2.3.5 Kriging

The kriging [160] is a fundamentally different approach to approximate the irregular data. Most data fitting methods assume that the actual function is equal to the predicted function plus a residual error, where the residuals are independent random variables. The kriging approach differs fundamentally because the assumption is that the residuals are dependent random variables. The kriging approximation function has two parts: a polynomial, and a functional departure from the polynomial. However, this approach is particularly useful for predicting temporally and spatially correlated data [160].

2.3.6 Radial Basis Functions

The radial basis function approaches are among the most powerful multidimensional approximation methods whose performances are independent of the dimensionality (number of design variables) of the problem [13, 153]. The radial basis functions have recently generated significant interest as an approximation technique in multi-objectives, because of a combination of desirable attributes. These include ability to accurately model arbitrary functions, ability to handle scattered data points in multiple dimensions and their relatively simple implementation compared to neural networks and kriging [73, 160]. These powerful benefits make the radial basis functions more desirable than the other interpolation techniques, such as spline-based methods, because of difficulties in extending to higher dimensions [13], while the neural networks use trial and error procedure [77] and kriging is impracticable because of the lack of readily available software [171].
2.4 Multi Objective Optimization Methods

The optimization of 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 multiobjective in nature and involve simultaneously optimizing several conflicting design objectives [18, 80]. It is not uncommon 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 multiobjective optimization problems [31].

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 past for optimization of various processes [19]. 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 metamodels 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 non traditional 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 models.
2.4.1 Genetic Algorithms

The genetic algorithms (GA) is a non-traditional search algorithm [60] that emulates the adaptive processes of natural biological systems. The success of many applications in engineering has demonstrated the power of GA [46, 87, 113, 155, 156, 161, 186, 205, 206]. Based on the survival and reproduction of the fittest, they continually search for new and better solutions without any pre-assumptions such as continuity and unimodality. GA has been applied in many complex optimization and search problems, outperforming traditional optimization and search methods.

The solution of the problem that GAs attempt to solve is coded into a string of binary numbers known as chromosomes. Each chromosome contains the information of a set of possible process parameters. Initially, a population of chromosomes is formed randomly. The fitness of each chromosome is then evaluated using an objective function after the chromosome has been decoded. Upon completion of the evaluation, either a roulette wheel method or selected control method is used to select randomly pairs of chromosomes to undergo genetic operations such as crossover and mutation to produce offspring for fitness evaluation. This process continues until a near optimal solution is found.

2.4.2 Simulated Annealing

The simulated annealing (SA) is also one of the non-traditional search and optimization techniques, which resembles the cooling process of molten metals during annealing. The SA procedure simulates this process of annealing to achieve the minimization function value in a problem.

The algorithm begins with an initial point, $m_1$, and a high temperature, $T$. A second point, $m_2$ is created using a Gaussian distribution and the difference in the function values at these points, $(\Delta E)$, is calculated. If the second point has a smaller value, the point is accepted; otherwise the point is accepted
with a probability $e^{(-E/T)}$ [35]. This completes an iteration of the simulated annealing procedure. The algorithm is terminated when a sufficiently small temperature is obtained or a small enough change in the function value is observed.

### 2.4.3 Ant Colony Algorithm

The natural metaphor on which ant algorithms are based is ant colonies. Researchers are fascinated by seeing the ability of near-blind ants in establishing the shortest route from their nest to the food source and back. These ants secrete a substance, called pheromone, and use its trial as a medium for communicating information [39]. The probability of the trial being followed by other ants is enhanced by further deposition by others following the trial. This cooperative behavior of ants inspired the new computational paradigm for optimizing real-life systems, which is suited for solving large-scale problems.

In the first step of ant colony algorithm (ACO), hundred solutions are generated randomly with parameters that satisfy the constraints. The initial solutions are classified as superior and inferior solutions. The following three operations are performed on the randomly generated initial solution: (1) random walk or cross over – 90% of the solutions (randomly chosen) in the inferior solutions are replaced with randomly selected superior solutions, (2) mutation – the process whereby randomly adding or subtracting a value is done to each variable of the newly created solutions in the inferior region with a mutation probability and (3) trial diffusion – applied to inferior solutions that were not considered during random walk and mutation stages.

### 2.4.4 Scatter Search Approach

The evolutionary approach called scatter search is originated from strategies for creating composite decision rules and surrogate constraints [58,
59]. Scatter search operates with a population of solutions, by combining these solutions to generate new ones. The template for implementing this approach requires the following: diversification generation method (DGM), improvement method (IM), reference set update method (RSUM), subset generation method (SGM) and solution combination method (SCM).

Initially, DGM is used to generate a set of diverse trial solutions. Next to DGM, IM is applied to improve them. RSUM builds and maintains a set consisting of solutions that gain membership according to their quality and diversity. Next, SGM operates on RSUM to produce a sub set of its solutions as a basis for creating combined solutions. At this point, SCM is used to transform a given subset of solutions produced by SGM into one or more combined solution vectors. The new solutions generated by SGM are given as input to IM. RSUM adds a set of improved solutions by IM into the reference set. A solution is added to the reference set according to its value or diversity. The procedure terminates when the reference set does not change and all the subsets have already been subjected to SCM. At this point, DGM is applied to construct a new reference set and the search process restarts another iteration until the maximum number of iterations is reached.

The scatter search is a generalized optimization and problem independent method, since it has no restrictive assumptions about objective function, parameter set and constraint set. This technique has been applied in industrial applications for optimal selection of process variables in the area of machining processes [21, 22,110].

2.4.5 Particle Swarm Optimization

The particle swarm optimization (PSO) is a population based stochastic optimization technique, inspired by social behavior of bird flocking or fish schooling [86]. The PSO shares many similarities with evolutionary computation techniques such as GA. The system is initialized with a population of random solutions and searches for optima by updating
generations. However, unlike GA, PSO has no evolution operators such as
crossover and mutation.

In PSO, the potential solutions, called particles, fly through the problem
space by following the current optimum particles. Each particle keeps track of
its coordinates in the problem space, which are associated with the best
solution (fitness) it has achieved so far and the fitness value is stored. This
value is called "pbest". Another "best" value that is tracked by the particle
swarm optimizer is the best value, obtained so far by any particle in the
neighbors of the particle. This location is called "lbest". When a particle takes
all the population as its topological neighbors, the best value is a global best
and is called "gbest". The particle swarm optimization concept consists of, at
each time step, changing the velocity of (accelerating) each particle toward its
"pbest" and "lbest" locations (local version of PSO). Acceleration is weighted
by a random term, with separate random numbers being generated for
acceleration toward "pbest" and "lbest" locations.

In past several years, PSO has been successfully applied in many
research and wide range of specific applications focused on a specific
requirement [29, 83, 142]. It is demonstrated that the PSO gets better results
in a faster and cheaper way compared with the other methods.

2.4.6 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
[7, 126, 152, 158, 187].

The Taguchi robust design uses many ideas from the statistical
experimental design and adds a new dimension to it. The two major tools
[152] 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 from a matrix experiment 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 prediction.

The original 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 [32, 36, 47, 108, 125,
130, 145, 168, 208, 210]. 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 [76, 80, 199, 203].
Few of them are presented below.

Engineering judgement suggested by Phadke [152] 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 [85, 111, 207] 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 summed for
computing the performance of a multi-response problem. But, determining a
definite weight for each response in an actual case still remains difficult.

The methodology of Taguchi’s quality loss function has proved to be an
efficient optimization tool for multiple characteristics and has been employed
in the past for optimization of several processes [2, 3, 44, 123, 143, 154, 192,
Taguchi used a loss function to calculate the deviation between the experimental value and the desired value. This loss function is further transformed into S/N ratio. 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. However, the optimal factor-level combination may result in very small quality losses associated with some responses, but very large quality losses associated with others, even when the average quality loss is acceptably small.

The principal component analysis (PCA) [75, 79, 182, 209], involves a mathematical procedure that transforms a set of correlated response variables into a smaller set of uncorrelated variables called "principal components (PC)" [78]. The PCA is used to explain the variance-covariance structure through linear combinations of the original variables. Therefore, the multicollinearity problem among the original variables can be solved. But, it is desired that, only a few PC to account for most of the variance in the data have been used rather than using all the variables [165, 197].

The data envelopment analysis (DEA) based ranking approach is proposed to optimize effectively the multi-response problem in the Taguchi method [14, 15]. A set of original responses is mapped into a ratio (a weighted sum of responses with larger the-better manners divided by the weighted sum of responses with smaller-the-better or nominal-the-better manners) so that the optimal experimental factors/levels can be found by the ratio's rank. Since, the DEA is an extreme point technique; noise such as measurement error can cause significant problems. The statistical hypothesis tests are also difficult, as DEA is a nonparametric technique.

In the grey relational analysis (GRA) [37], the experimental data are first normalized in the range between zero and one, which is also called the grey relational generation. Next, the grey relational coefficient is calculated from the normalized experimental data to express the relationship between the desired and the actual experimental data. Then, the grey relational grade is computed by averaging the grey relational coefficient corresponding to each
process response. The overall evaluation of the multiple process responses is based on the grey relational grade. As a result, optimization of complicated multiple process responses can be converted into optimization of a single grey relational grade. The optimal level of the process parameters is the level with the highest grey relational grade. The grey relational analysis based on the grey system theory has been widely applied in the related areas [16, 17, 70, 72, 82, 112, 120, 121, 124, 194, 200]. However, the method utilizes complex mathematics and hence difficult to implement by individuals with little background in mathematics.

The desirability function analysis [38] 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 had developed a functional approach using desirability function to optimize the multi response situation. However, due to the mathematical complexity, engineering community cannot easily or rapidly understand the approach.

The VIKOR method [198] is a compromise ranking method used for multi-criteria decision making (MCDM) to optimize the multi response problems. The method considers both the mean and the variation of quality losses associated with several multiple responses, and ensures a small variation in quality losses among the responses, along with a small overall average loss. The ideal and negative ideal solutions are initially determined from the quality loss. Then, the utility measure and regret measure of each alternative are determined according to the weight of each criterion. VIKOR index of each experimental run is finally obtained using the corresponding utility and regret measures. The main effect of VIKOR index is then determined and the optimal factor level combination is thus obtained. Theoretical analysis herein revealed that the quality concepts of Taguchi's S/N ratio and VIKOR index are compatible. Taguchi's S/N ratio simultaneously considers the mean and variation of a quality characteristic and can be applied to optimize the single response process, while the VIKOR index simultaneously considers utility and regret measure to optimize the multi
response process. However, this method increases the computational process complexity.

2.5 Observations from the Review of Literature

The following observations can be made from the literature survey:

- Many previous researchers have shown that drill geometry, material properties and the cutting conditions are among the most important parameters in drilling burr formation.

- Most of the research studies on burr formation mechanism reported cutting speed and feed as the affecting process parameters. On the other hand, only few investigations have identified that the drill diameter, point angle and lip clearance angle have significant effects on burr formation. However, no investigation has been reported on the main and interaction effects, by considering simultaneously all the five process parameters, namely, cutting speed, feed, drill diameter, point angle and lip clearance angle on burr height and burr thickness.

- 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 during drilling.

- Process optimization based on genetic algorithms and Taguchi robust designs are powerful optimization disciplines, which economically satisfy the needs of problem solving and design optimization.
Based on the above observations, the following conclusions are drawn in order to formulate the research objectives.

- 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.

- The simultaneous minimization of burr height and burr thickness requires an efficient multi-objective optimization tool. Hence, methods based on genetic algorithms and Taguchi robust designs have been considered for the present investigations.

- The multi-objective optimization method using genetic algorithms requires accurate models of burr height and burr thickness. Process modeling by response surface methodology (RSM) based on central composite rotatable design of experiments 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.

- The various modifications suggested to the Taguchi robust design for multi-response optimization problems are highly complicated. Most of the suggested modifications employ weighting factors, which are to be selected based on trial and error methods. Hence, there is a need to develop a simple modification to the Taguchi technique for multi-response optimization.

The details of the research objectives and the methodology are presented in the next chapter.