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Review Paper

Applying Wear Maps in the Optimisation of Machining Parameters in Drilling of Polymer Matrix Composites – A Review

Rao Sathish U. and Rodrigues L.L. Raj
Department of Mechanical and Manufacturing Engineering, Manipal Institute of Technology, Manipal, INDIA

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Abstract

The use of polymeric composite materials (CFRP and GFRP) has increased considerably in aerospace engineering, automobile engineering, medical applications and structural application etc. over the last decade. These developments lead to an increase in the number of technical research papers focusing on relevant aspects concerning the machining of such materials. In conventional machining, drilling is the most applied method accounting for as much as 40% of all material removal processes. However, problems in composite material drilling, particularly the heterogeneity and anisotropy of composite materials, increase delamination, surface roughness and tool wear etc. makes the machining more complex compared to metal machining. It was also investigated that drilling of fibre reinforced composites with conventional tools often results in defects like fiber debonding, fibre pullout, etc. Therefore the principal aim of this research paper is to screen through the literature on machining of composite materials, more specifically on drilling of glass/carbon fibre reinforced epoxy composites focusing on the factors such as tool materials and geometry, machining parameters and their influence on the tool wear. In this particular context, many researchers have worked on metals, conducting series of experiments on tool wear and wear rate, and developed the wear mechanism map for different combinations of cutting tools and metals in order to optimize process parameters. Lack of research work has been recorded so far on the tool wear mapping of drills on composite materials. This made the authors to develop the different wear mechanisms during drilling of polymer matrix composites so as to arrive at "safety zone" process parameters. Also, the observations and outcomes of this research paper would significantly contribute to the methodology that can be adopted to find the wear mechanism of drill bit while machining polymer matrix composite materials and the findings of this study can lead to the identification of improved and optimised operational parameters.

Key words: composite material, wear mechanism, safety zone.

Introduction

Polymeric composites are finding increasing applications in aerospace, chemical industry, electrical industry, automotives, machine elements, sports equipments and many other areas. Advantages of polymeric composites over conventional materials include high specific strength and modulus, good damping properties, superior mechanical properties and design flexibility. Most FRP composite products are generally made by any of the standard primary manufacturing processes such as molding, filament winding, pultrusion, etc. A certain degree of intricacy in the component design necessitates assembly of sub-components to manufacture the final product.

Hole generation thus becomes an integral part of the product manufacturing technique. A number of manufacturing processes have been tried to make holes in composite materials; however, conventional drilling is the most widely acceptable and frequently practiced machining operation. Machining of composite materials incorporates conditions and requirements that are not usually encountered in metal machining. Tool material selection and tool design, optimization of the operating conditions and environment, evaluation and characterization of the product damage, and mechanisms of material removal are some of the key aspects in this regard.

In machining of polymer composites is a proper choice of cutting conditions is difficult due to the coexistence of hard abrasive fibers and a soft matrix. In conventional machining, the drilling by twist drill is the most applied method which accounts for as much as 40% for all materials removal processes. A research investigation reports that over 100,000 holes are required in a small engine aircraft, mostly for fasteners.

During the past four decades, researchers have developed many types of drills, including multi facet drill, saw drill, candlestick still, core drill, step drill and trepanning drill, all aimed at making better holes. With increasing demand for advanced composite materials, not only new concepts of tooling but also different realms of cutting conditions, tool condition monitoring is needed.

The study of wear of multi-point tool, which is the primary focus of this research paper, is a complicated phenomenon, in comparison to a single point tool, owing to the fact that the tool itself has two motions viz. rotational and linear motion unlike the single point tool where the work-piece rotates and the tool has two linear motions. More than that the drill tool wear has a strong effect on hole quality and hole dimensional accuracy during drilling.

The data related to the tool wear can be presented in a number of ways. The more complete approach is through the linking of the wear rates and wear mechanisms over a much wider range of contact conditions in the form of a wear-mechanism map. So, the study of wear mechanism of cutting tools has been a very important area of research since the past several decades, as it provides vital inputs to the optimization of operating parameters, operating conditions and the cutting tool geometry. An optimal machining process is one where the maximum material removal rate is obtained with the minimal amount of tool wear. This can be attained through the appropriate choice of machining conditions. So, the wear mechanism map is also a good means of selecting suitable machining conditions to the machinist, which can reflect wear rates and wear mechanisms under different operating conditions in one map, and shows the transformation relation of one dominant wear mechanism to another. It is the most forceful implement to wear resistant design at present. The wear map not only provides a multi-(most of the time, two-) dimensional graphical presentation of wear data, it also provides an overall framework for the wear behavior of a particular contact system into which individual wear mechanisms observed under various operating conditions. Generally, wear-mode, wear-transition and wear-regime maps tend to focus on the description of the mode of wear, namely, mild wear, severe wear and the transition between them. In the case of wear mechanism maps, details of the dominant wear mechanisms are given and the regions of their dominance are indicated. Apart from these as more and more automotive or computer controlled machines are employed, manufacturers need to increase the service life of cutting tools in order to increase the machining effectiveness and lower the cost of manufacturing.

Owing to this fact, many researchers have worked on metals since the last two decades, who have conducted series of experiments on wear and wear rate, and developed the wear mechanism map for different combinations of tool and work materials. But no significant work has been recorded so far on the wear mapping and tool wear characteristics of HSS drilling on composite materials. Hence, the observations and outcomes of this research would significantly attribute to the body of knowledge of tool wear mechanism of drill bit while machining composite materials. Moreover, owing to the high strength to weight ratio of composite materials, it has become one of the important materials in several applications including, aerospace engineering, automobile engineering, medical applications, structural application etc. Hence, the study of wear mechanism is an important area of research in metal cutting and a lot of research is in progress in this direction. The current study is an attempt to investigate the different wear mechanisms during HSS drill on composites so as to arrive at optimum process parameter and hence drilling of composites is inevitable as they have to be fastened to other components during the assembly operation. Hence the findings of this study can lead to the identification of improved operational parameters [1,2,3].

Researchers presented the effects of spindle rotational speed and feed rate on the crater wear along the lip of a drill. A theoretical model was developed to correlate the cutting parameters with crater wear through the cutting forces. An empirical relationship between crater wear and the cutting parameters at any point on the lip was developed. The correlation coefficient between the experimentally measured and empirically calculated values of crater wear was found to be 0.9821. Crater wear was recommended for acceptance as a performance index. Close relationships between the experimental and theoretical results were found[4].

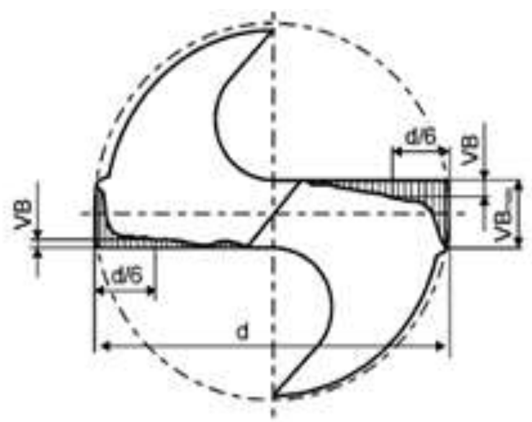

Figure - 1
Tool wear types as abasic for determing tool life of drill tools

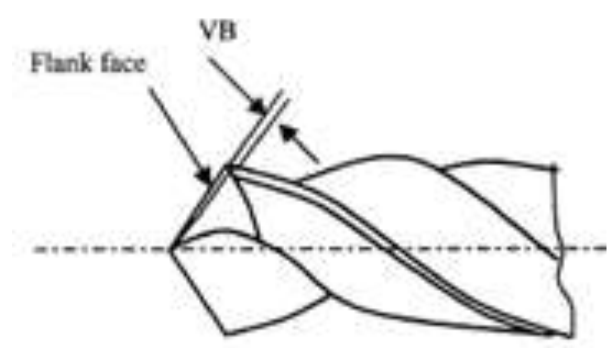

Figure - 2
Flank wears measurement of HSS drilling tools

wear characteristics of uncoated HSS. A map describing the flank wear characteristics of uncoated high-speed steel (HSS) tools is constructed under the condition of drilling die-cast aluminium alloy[5].

Several wear mechanisms are revealed which describe different wear modes observed by SEM in uncoated HSS tools, including adhesive wear, adhesive and abrasive wear, abrasive wear, and thermal wear.

Scientists developed the maps that have demonstrated that the tool wear rates vary with cutting speeds and feed rates used. They have also shown that there is a range of cutting conditions, called the safety zone, within which tool wear rates are the lowest. Wear maps constructed for the machining of AISI 1045 and 4340 steels show that flank wear is generally more severe when machining the AISI 4340 grade, especially at high cutting speeds and feed rates. Nevertheless, the contour and location of the safety zone on the wear maps for both grades of steels correspond to that revealed in previous work[6].

A resercher developed an approach for damage-free drilling of carbon fibre reinforced thermosetting resins. This approach is based on a combination of Taguchi's experimental analysis technique and a multi-objective optimization criterion. Experimental factors were cutting speed, feed rate and tool point angle and the analysis of variance (ANOVA) was used to determine the relative significance of process factors. Recommendations from this work are the use of low feeds, in the range of 0.02–0.05 mm/rev and speeds ranging from 40 to 60 m/min, to minimize delamination and to produce good hole surface finish[7].

Scientists have taken the experimental approach which resulted in the development of both optimized tool geometry and optimized cutting conditions for dry drilling of aluminium alloys. Apart from this several basic causes of tool wear have been investigated and discussed; like abrasion, adhesion and diffusion. The effect of tool-chip interface temperature on tool wear was also discussed[8].

Researchers have investigated and discussed the change in wear mechanisms as a function of cutting speed and coating material. The cutting tests were performed on a rigid instrumented drilling bench without the use of cutting fluids. AA2024 aluminium alloy was used to investigate the wear mechanisms of cemented tungsten carbide and HSS tools. Three cutting speeds (25, 65 and 165 m/min) and a constant feed rate of 0.04 mm/rev were selected for the experiments. The best results in terms of maximum and minimum hole diameter deviations and surface roughness are obtained for the uncoated and coated tungsten carbide drills[9].

Research works also said that the principal aim of this work is to present a literature survey on the machining of composite materials, more specifically on drilling of glass and carbon fibre reinforced plastics. Aspects such as tool materials and geometry, machining parameters and their influence on the thrust force and torque are investigated [10].

Some eesarchers in their research, have reported how to utilize Taguchi methods to optimize surface finish and hole diameter accuracy in the dry drilling of Al alloy.

The parameters of hole quality are analyzed under varying cutting speeds (30, 45, and 60 m/min), feed rates (0.15, 0.20, and 0.25 mm/rev), depths of drilling (15 and 25 mm), and different drilling tools (uncoated and TiN and TiAlN coated) with a 118° point angle.

This study also included dry drilling with HSS twist drills. The settings of the drilling parameters were determined by Taguchi's DOE method. Orthogonal arrays of Taguchi, the signal-to-noise (S/N) ratio, the analysis of variance (ANOVA), and regression analyses are employed to find the optimal levels and to analyze the effect of the drilling parameters on surface finish and hole diameter accuracy values.

Confirmation tests with the optimal levels of machining parameters are carried out in order to illustrate the effectiveness of the Taguchi optimization method. The validity of Taguchi's approach to process optimization is well established[11].

Research works have developed a wear mechanism map of uncoated HSS under the conditions of dry drilling, die-cast magnesium alloys. Three wear mechanisms (abrasion, adhesion and diffusion) appear based on microanalysis of drilled HSS tools by SEM. On the map a "safety zone" was developed which helps to choose suitable drill parameters when drilling die-cast magnesium alloys[12].

Scientists in their research work conducted drilling tests on a machine center with maximum rotational speed. The thrust force was measured using a Kistler piezoelectric dynamometer .A scanning electronic microscope was used to photograph the cutting tools and a coordinate measuring machine was employed to measure dimensional and geometric deviations (hole diameter and roundness, respectively). A ruby probe with 1mm diameter was employed for this purpose and an average of five measurements was used in order to assess the variations in diameter and roundness of the machined holes[13].

E-glass fiber reinforced epoxy resin composite was used as work material. The twist drills tested were high speed steel grade A1141, uncoated carbide grade A1163, and titanium nitride coated carbide grade A1163 TiN, all manufactured by Titex Plus and possessing a length of 62 mm, a diameter of 5 mm, and a point angle of 118°.

In order to investigate the influence of the tool material and machining conditions on the thrust force and dimensional and geometric deviations obtained after drilling the composite, the following cutting parameters were used: cutting speeds (V_c) of 55, 71, and 86 m/min and feed rates (f) of 0.04–0.10–0.15, and 0.20 mm/rev. One thousand holes were drilled with the high speed steel tool, 24,000 holes were produced by the uncoated carbide and 10,000 holes were drilled using the TiN coated carbide drill. After drilling, the following conclusions were drawn:

Tool wear resulted in sharpness loss and reduction in the diameter of the drills. Abrasion is believed to be the principal wear mechanism involved.

Hole diameter was reduced much after drilling 1000 holes with the high speed steel and slightly when the uncoated carbide drill was tested. Using the high speed steel under the lower feed rate resulted in higher diameter reduction. The uncoated and coated carbide drills were able to machine 10,000 holes without an appreciable reduction in hole diameter.

The roundness deviation increased drastically for the high speed steel drill after generating 1000 holes, reaching values as high as 100 mm, whereas the maximum value recorded for the uncoated carbide tool was below 70 mm. Furthermore, the uncoated carbide drill produced 24,000 holes with a negligible increase in the roundness of the machined holes.

Input–Output and In-Process Parameter Relationship Modelling

The first necessary step for process parameter optimization in any metal cutting process is to understand the principles governing the cutting processes by developing an explicit mathematical model, which may be of two types: mechanistic and empirical. The list of applications of modelling techniques of process input–output and in-process parameter relationship based on statistical regression artificial neural network and fuzzy set theory is endless.

Although these types of modelling techniques may be working satisfactorily in different situations, there are constraints, assumptions and shortcomings, limiting the use of a specific technique. Those modeling techniques which are commonly applicable to the metal cutting processes are discussed here.

Statistical regression technique: Regression is a conceptually simple technique for investigating functional relationship between output and input decision variables of a cutting process and may be useful for cutting process data description, parameter estimation, and control.

Several applications of regression equation-based modelling in metal cutting process is reported in literature used a second order multiple-regression model for medium carbon steel turning operation. Researchers showed that for a reasonable large data set, regression analysis generates results comparable to artificial neural network-based modelling for surface roughness prediction in finished metal turning process. They also showed that statistical regression model may make decent tool wear prediction as compared to artificial neural network (ANN) in a typical aluminium metal composite lathe turning operation.

Although statistical regression may work well for modelling, this technique may not describe precisely the underlying non-linear complex relationship between the decision variables and responses. A prior assumption regarding functional relationship(s) [such as linear, quadratic, higher-order-polynomial, and exponential] between output(s), and input decision variable(s), is a pre-requisite for regression equation-based modelling. Prediction of output(s) for an unknown set of input(s) based on regression technique is valid only over the region of the regressor variable(s) contained in the observed cutting process data. It is only an aid to confirm cause-effect relationship, and does not imply a cause and effect relationship. Moreover, error components of regression equation need to be mutually independent, normally distributed, and having constant

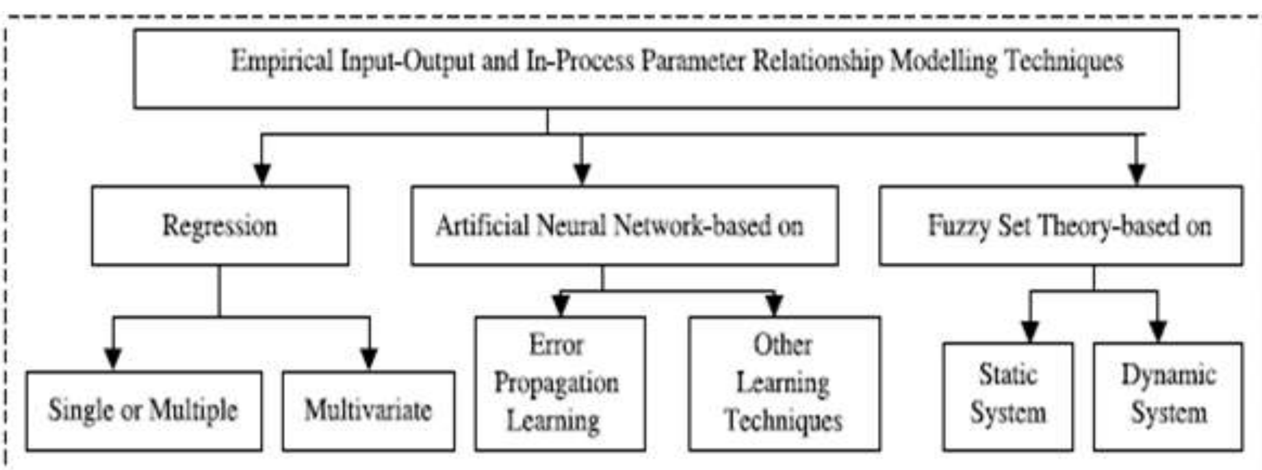

Figure - 3
Classification of modeling techniques in metal cutting processes

Artificial neural network (ANN) Modelling techniques of input–output and in-process parameter relationship using ANN or fuzzy sets offer a distribution-free alternative, and have attracted attention of practitioners and researchers alike in manufacturing when faced with difficulties in building empirical models in metal cutting process control. These techniques may offer a cost effective alternative in the field of machine tool design and manufacturing approaches, receiving wide attention in recent years.

Artificial neural network (ANN) modeling: ANN may handle complex input–output and in-process parameter relationship of machining control problems. The learning ability of nonlinear relationship in a cutting operation without going deep into the mathematical complexity, or prior assumptions on the functional form of the relationship between input(s), in-process parameter(s) and output(s) (such as linear, quadratic, higher order polynomial, and exponential) makes ANN an attractive alternative choice for many researchers to model cutting processes. Being a multi-variable, dynamic, non-linear estimator, it solves problems by self-learning and self organization .The intelligence of an ANN emerges from the collective behaviour of so-called 'artificial neuron', and derives the process knowledge from input and output data set. Scientist has discussed the process modelling techniques by ANN along with its application potential. They also have considered practical aspects of building and validating ANN models, and showed control and monitoring of a machining process by ANN technique.

Several applications of ANN-based input-output relationship modelling for metal cutting processes are reported in the literature. Back propagation neural network, proposed have been successfully applied for modelling a typical creep feed super alloy-grinding, prediction of material removal rate and surface finish parameter of a typical abrasive flow machining, and a honing operation of engine cylinder liners, respectively. ANN modelling also used for controlling surface finish characteristics in multistage machining processes.

There are certain assumptions, constraints, and limitations inherent in these approaches, which may be worth mentioning. ANN techniques are attempted only when regression techniques fail to provide an adequate model. Some of the drawbacks of ANN techniques are: (i) model parameters may be un-interpretable for non-linear relationship, (ii) it is dependent on voluminous data set, as sparse data relative to number of input and output variables may result in over fitting or terminate training before network error reaches optimal or near-optimal point, and (iii) identification of influential observations, outliers, and significance of various predictors may not be possible by this technique. There is always an uncertainty in finite convergence of algorithms used in ANN-based modeling technique, and generally convergence criteria are set based on prior experiences gained from earlier applications. No universal rules exist regarding choice of a particular ANN technique for any typical metal cutting process problem.

Conventional Optimization Techniques

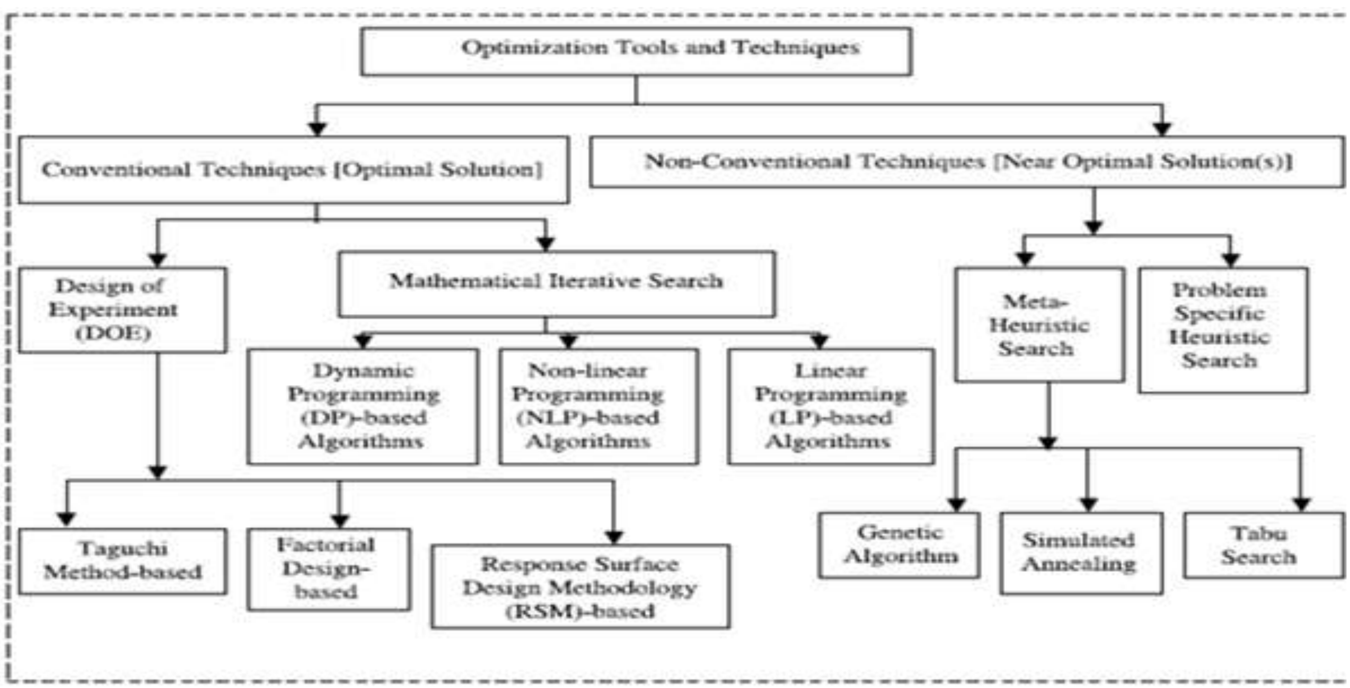

Figure - 4
Classification of optimising techniques in metal cutting process problems

Taguchi Method: Taguchi's contribution to quality engineering has been far ranging. The concept of Taguchi's robust design is based on designing a product or process in such a way so as to make its performance less sensitive to variation due to uncontrolled or noise variables which are not economical to control. Taguchi method is usually appreciated for its distribution-free and orthogonal array design and it provides a considerable reduction of time and resource needed to determine important factors affecting operations with simultaneous improvement of quality and cost of manufacturing.

Taguchi's two-fold technique of parameter design has been successfully applied in a number of metal cutting problems by researchers and practitioners alike. Youssef, Beauchamp, and Thomas (1994) discuss and compare the economical benefits of Taguchi method and fractional factorial experiments with full factorial design technique in lathe turning operations. A researcher presented an application of Taguchi method for multi-response optimization in face milling operation, and shows the effectiveness of Taguchi method for simultaneous optimization and improvement of milling performance characteristics. They also illustrated the potential and use of Taguchi method to identify critical process parameters that effect material removal in abrasive flow machining. Taguchi method was also applied in surface grinding process, and shows the impact of graphite application to reduce heat generation in grinding zones. Taguchi method was also used for determining significant cutting parameter setting to achieve better surface finish during turning operation of aluminium and silicon carbide-based metal matrix composites.

Response Surface Design Methodology (RSM): The RSM is a dynamic and foremost important tool of design of experiment (DOE) wherein the relationship between response(s) of a process with its input decision variables is mapped to achieve the objective of maximization or minimization of the response properties. It is a set of statistical DOE techniques, intrinsic regression modelling, and optimization methods useful for any field of engineering. The first necessary step in RSM is to map response(s), Y as a function of independent decision variables (X1,.,Xn). If the model is adequate, hill climbing or descending technique for maximization or minimization problem is attempted and the same mapping technique is repeated. In the vicinity of optimal point, a second order regression model is generally found adequate. Maximum, minimum, or a saddle point is identified by stationary point approach and canonical analysis of the second order model developed, and 'ridge analysis' is attempted if it is a saddle point.

Many researchers and practitioners use RSM in metal cutting process parameter optimization problems. A resercher used a contour plot technique to simultaneously optimize tool wear, surface finish, and tool force for finished turning operation. The scientists also provided an interactive algorithm using both RSM and mathematical modelling to solve a parameter optimization problem in turning operation. They also analysed the effect of change in work piece material and each cutting parameter in various peripheral milling operations, and model the dimensional accuracy by a second order response surface design. Scientists also concentrated on response surface design methodology to model the effect of machining parameters on residual stresses distribution for five different materials in turning operations.

The above literature review indicates that the contemporary research is mainly focused on tool wear and wear mechanism of metals. Also substantial work has been carried out on wear mechanism study. There have been one set of researchers who have focused on the machining parameter of a typical cutting tool on a combination of work materials. The other set of researchers have worked on different tools on a given material and studied the wear mechanism. Ultimately, attempt has been made to obtain optimum operating conditions in both these directions of work. Standard tools such as DOE, Taguchi method for selecting group of experiment and statistical tools such as T-test and ANOVA have been used for correlation studies. Also AI techniques such as Genetic Algorithm, Neural Networks have been used for modeling and simulation. Considering, all the research work, in the present research HSS drill has been chosen as the tool material and the work material chosen is composite material, as it is gaining popularity since the past decade. The contemporary research also provides the necessary tools to be adopted in the research to be undertaken. It includes modelling andsimulation and statistical procedures such as ANOVA for comparing multivariate parameters.

This research deviates from earlier research in the sense that the focus could be on HSS drill performance against composite materials and as the wear mechanism map is not present, an attempt will be made to develop the same which will further open up a new direction for the research in optimizing the operational parameters. Consequently, there will also be enough scope to compare the modelling and simulation results with the experimental results

Objectives

The cardinal objective of this research is to obtain the optimal machining parameters through the study of wear mechanism map of uncoated HSS tool during drilling of composites. To accomplish this objective following sub-objectives have been formulated. i. Identify various combinations of drill geometry and machining conditions and apply DOE procedure for selecting the most appropriate combinations for experimental analysis. ii. Devise the experimental set-up to conduct experiments as per the requirements identified in the above objective and conduct the experiments to obtain wear data. iii. Identify the types of wear mechanisms using SEM (Scanning Electron Microscope) observations and obtain SEM micrograph of the built-up edge to conduct microanalysis of flank worn surface and define the wear characteristics. iv. Design the wear mechanism map of flank wear and perform morphology analysis to identify the 'safety zone'. v. Develop an equation and a model to simulate the process parameters using one of the above mentioned modeling and process optimisation techniques. vi. Determine the optimal machining parameters for the selected work piece and tool combinations.

Methodology

Select the appropriate combination of fibre and matrix material and prepare the type of composite material required to carry out the research work with all the data related to its mechanical and physical properties, on which the machining has to be carried out.

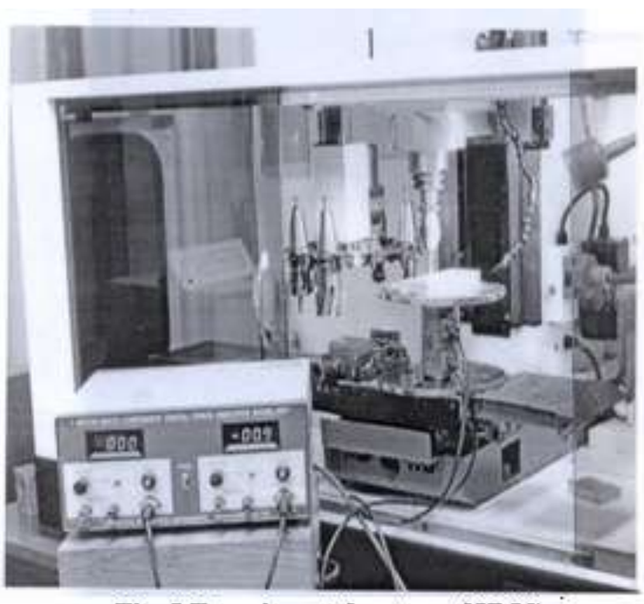

Fig. 5 Experimental set-up of VMC

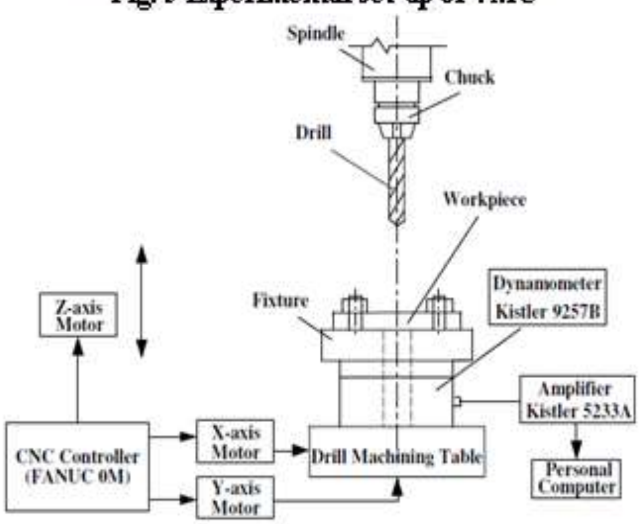

Fig. 6 Schematic of the experimental setup

Select the operational parameters: i. Machine type: CNC VMC. (set up is shown in Figure 5). ii. Type of tool: Preferably HSS drill of either Tungsten type (T-grade) or (M-grade). iii. Diameter of drill bit: HSS drills of diameter 5mm, 7mm and 10mm. iv. Speed (40-60m/min). v. Feed (0.02 – 0.05mm/rev). vi. Machining condition: Dry run. vii. Decide about the no. of holes to be drilled. Carrying out the experiments using DoE using taguchi's approach.

The tool wear can be found by the following methodology: i. The flank wear width of the drilled tool is to be measured by universal tool room microscope. Scanning electron microscopy is used for worn surface analysis.

The two-dimensional map of flank wear of HSS tools was constructed by employing the cutting speed as abscissa, the feed rate as ordinate. The value of the measured wear rate was normalized using a formula of $\log_{10}(VB / L_m)$, where L_m is cutting distance. After normalization, the dimensionless wear rate was obtained. The tool is observed for microstructure under SEM, to study different wear mechanisms. Plot the wear parameters and identify the safety zone. Based on the safety zone data, the optimum operating parameters that minimize the tool wear to be found out. Development of a model for the simulation of process parameters with the help of empirical equations.

Results

This research would result in the following: i. Identification of the critical machining parameters and their levels while machining with HSS drill on Composite materials. ii. Developing wear mechanism maps which would illustrate the dominant wear regions, thus helping in depicting the 'safety zone'. iii. SEM Micrograph of the 'built-up edge'. iv. Wear characteristics of different wear mechanisms. iv. A simulation model to optimize the machining parameters in the drilling operation using statistical analysis and ANN.

Conclusion

Firstly, considerable efforts have been focused on the better understanding of the phenomena associated to the cutting mechanism. As far as the work material is concerned, glass and carbon fibre reinforced composites have been equally investigated however epoxy resin is preferred as the matrix material. Conventional high speed steel twist drill are used as much as cemented tungsten carbide drills, however, it seems to be an agreement among the authors on the necessity of developing tools with special geometry in order to achieve best performance. The principal factors used to evaluate the performance of the process are undoubtedly the damage caused at the drill entry or exit and techniques are also employed to measure the effect of the cutting parameters like cutting speed (usually indicated as rotational speed) and feed rate on this damage. Another point of agreement among the authors is the need of developing devices and/or procedures in order to allow the reduction of the wear area which makes the drilling operation longer and dearer.

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