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Review Paper

Applications of Different Optimization Methods for Metal Cutting Operation – A Review

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Abstract

Optimum selection of the cutting conditions effectively contributes to the increase in the productivity and reduction in the production cost, therefore utmost attention is paid to this problem. Optimization of cutting parameters is essential for a manufacturing unit to respond effectively to severe competitiveness and increasing demand of quality product in the market. In cutting process, optimization of cutting parameters is considered to be a vital tool for improvement in output quality of a product as well as reducing the overall production time. An optimization technique provides optimal or near optimal solution of optimization problem, which can be implemented in the actual metal cutting process. Quality and productivity play a major role in today's manufacturing market. From a customer's viewpoint, quality is very important because the extent of quality determines the degree of satisfaction of the customers. Apart from quality, there exists another important criterion called productivity which is directly related to the profits of an industry and also to its growth. Every manufacturing firm aims at producing larger number of units with in short time. Productivity can be increased by having sound knowledge of all the optimization techniques for machining. In this research paper, a comparison has been made between different optimization including their approaches. The proposed research can be very helpful for industries to determine the optimal cutting parameters and improve the process quality. The comparison will also be beneficial in minimizing the costs incurred and improving productivity of manufacturing firms.

Keywords: Cutting, optimization techniques, productivity, quality.

Introduction

Traditionally, the selection of cutting conditions for machining was left to the machine operator. In such cases, the experience of the operator plays a major role, but even for a skilled operator it is very difficult to attain the optimum values each time. Machining parameters in metal cutting are cutting speed, feed rate and depth of cut. The setting of these parameters determines the quality characteristics of machined parts. Agapiou[1] formulated single-pass and multi-pass machining operations. Production cost and total time were taken as objectives and a weighting factor was assigned to prioritize the two objectives in the objective function. He optimized the number of passes, depth of cut, cutting speed and feed rate in his model through a multi-stage solution process called dynamic programming. Several physical constraints were considered and applied in his model. In his solution methodology, every cutting pass is independent of the previous pass; hence the optimality for each pass is not reached simultaneously. Armarego and Brown[2] investigated unconstrained machine-parameter optimization using differential calculus. Brewer and Rueda[3] carried out simplified optimum analysis for non-ferrous materials. For cast iron (CI) and steels, they employed the criterion of reducing the machining cost to a minimum. A number of nomograms were worked out to facilitate the practical determination of the most economic machining conditions. They pointed out that the more difficult to machine materials have a restricted range of parameters over which machining can be carried out and thus any attempt at optimizing their costs is artificial. Brewer[4] suggested the use of Lagrangian multipliers for optimization of the constrained problem of unit cost, with cutting power as the main constraint.

Emer and Kromodiharajo[5] developed a multi-step mathematical optimization model to solve a constrained multi-pass machining problem. They concluded that in some cases, multi-pass machining is more economical than single-pass machining, if depth of cut for each pass was properly allocated. They used high speed steel (HSS) cutting tools to machine carbon steel. Hinduja[6] described a procedure to calculate the optimum cutting conditions for machining operations with minimum cost or maximum production rate as the objective function. For a given combination of tool and work material, the search for the optimum was confined to a feed rate versus depth-of-cut plane defined by the chip-breaking constraint. Some of the other constraints considered include power available, surface finish and dimensional accuracy. Gilbert[7] studied the optimization of machining parameters in turning with respect to maximum production rate and minimum production cost as criteria. Petropoulos[8] investigated optimal selection of machining rate variables, viz. cutting speed and feed rate, by geometric programming. Sundaram[9] applied a goal-programming technique in metal cutting for selecting levels of machining parameters in a fine operation on AISI 4140 steel using cemented tungsten carbide tools. Following the pioneering work of Taylor[10] and his famous tool life equation, different analytical and experimental approaches for the optimization of machining parameters have been investigated. Walvekar and Lambert[11] discussed the use of geometric programming to selection of machining variables. They optimized cutting speed and feed rate to yield minimum production cost. It has long been recognized that conditions during cutting, such as feed rate, cutting speed and depth of cut, should be selected to optimize the economics of machining operations. Machining of composite material substantially differs from metallic materials due to its mechanical properties. The machining of this material may generate delaminating of drilled holes on work piece. The objective of this research is to compare and analyze different optimization techniques by studying the effect of cutting speed, feed, diameter of cut, machining time on metal removal rate, specific energy, surface roughness, volume fraction and flank wear. Taylor showed that an optimum or economic cutting speed exists which could maximize material removal rate. Considerable efforts are still in progress on the use of hand book based conservative cutting conditions and cutting tool selection at the process planning level. The need for selecting and implementing optimal machining conditions and most suitable cutting tool has been felt over the last few decades. Despite Taylor's early work on establishing optimum cutting speeds in machining, progress has been slow since all the process parameters need to be optimized. Furthermore, for realistic solutions, the many constraints met in practice, such as low machine tool power, torque, force limits and component surface roughness must be considered.

Material and Methods

Different techniques of optimization for cutting process: Fuzzy logic: Fuzzy logic has great capability to capture human commonsense reasoning, decision-making and other aspects of human cognition. It overcomes the limitations of classic logical systems, which impose inherent restrictions on representation of imprecise concepts. Vagueness in the coefficients and constraints may be naturally modeled by fuzzy logic. Modeling by fuzzy logic opens up a new way to optimize cutting conditions and also tool selection importance of integration between fuzzy and ANN-based technique for effective process control in manufacturing. Several applications of fuzzy set theory-based modeling of metal cutting processes are reported in the literature.

Hashmi, El Baradie, and Ryan[12] applied fuzzy set theory logic for selection of cutting conditions in machining. Lee, Yang, and Moon[13] used fuzzy set theory-based non-linear model for a turning process as a more effective tool than conventional mathematical modeling techniques if there exists 'fuzziness' in the process control variables. Al-Wedyan, Demirli, and Bhat[14] used fuzzy modeling technique for a down milling cutting operation. Ip used a fuzzy rule based feed rate control strategy in mild steel bar surface milling operation for improvement in cutting efficiency and prolonging the tool life. Kamatala, Baumgartner, and Moon[15] developed a fuzzy set theory-based system for predicting surface roughness in a finished turning operation. Chen and Kumara[16] use a hybrid approach of fuzzy set and ANN-based technique for designing a grinding process and its control. Fuzzy set theory-based techniques suffer from a few shortcomings, such as rules developed based on process expert's knowledge, and their prior experiences and opinions are not easily adjustable to dynamic changes of underlying cutting process. It also does not provide any means of utilizing analytical models of metal cutting processes

Implementation of Fuzzy Logic: Fuzzy logic involves a fuzzy interference engine and a fuzzification-defuzzification module. Fuzzification expresses the input variables in the form of fuzzy membership values based on various membership functions. Governing rules in linguistic form, such as if cutting force is high and machining time is high, then tool wear is high, are formulated on the basis of experimental observations. Based on each rule, inference can be drawn on output grade and membership value. Inferences obtained from various rules are combined to arrive at a final decision. The membership values thus obtained are defuzzified using various techniques to obtain true value.

Genetic algorithm (GA): These are the algorithms based on mechanics of natural selection and natural genetics, which are more robust and more likely to locate global optimum**.** It is because of this feature that GA goes through solution space starting from a group of points and not from a single point. Several applications of GA-based technique in metal cutting process parameter optimization problems have been reported in the literature. Liu and Wang[17] claimed that by reducing the operating domain of GA, by changing the operating range of decision variables, convergence speed of GA increases along with significant increase in milling process efficiency. Cus and Balic[18] used GA-based technique to determine the optimal cutting conditions in NC-lathe turning operation on steel blanks that minimize the unit production cost without violating any imposed cutting constraints. Schrader[19] demonstrated the usability of GA based technique for simultaneous process parameter optimization in multi-pass turning operations. Onwubolu and Kumalo[20] proposed a local search GA-based technique in multi-pass turning operation with mathematical formulation in line with work by Chen and Tsai[21] with simulated annealing-based technique. Choudhary, Pratihar, and Pal[22] applied a GA-based optimization technique for near optimal cutting conditions selection in a single-pass turning operation, and claim that GA outperform goal programming technique in terms of unit production time at all the solution points. Wang, Da, Balaji and Jawahir[23] apply GA-based technique for near-optimal cutting conditions for a two-and three-pass turning operation having multiple objectives. Krimpenis and Vosniakos[24] used a GA-based optimization tool for sculptured surface CNC milling operation to achieve optimal machining time and maximum material removal. The cutting conditions are encoded as genes by binary encoding to apply GA in optimization of machining parameters. A set of genes is combined together to form chromosomes, used to perform the basic mechanisms in GA, such as crossover and mutation. Crossover is the operation to exchange some part of two chromosomes to generate new offspring, which is important when exploring the whole search space rapidly. Mutation is applied after crossover to provide a small randomness to the new chromosomes.

Implementation of GA: GA optimization methodology is based on machining performance predictions models developed from a comprehensive system of theoretical analysis, experimental database and numerical methods. To evaluate each individual or chromosome, the encoded cutting conditions are decoded from the chromosomes and are used to predict machining performance measures. Fitness or objective function is a function needed in the optimization process and selection of next generation in genetic algorithm. Optimum results of cutting conditions are obtained by comparison of values of objective functions among all individuals after a number of iterations. Besides weighting factors and constraints, suitable parameters of GA are required to operate efficiently.

Although GA-based optimization technique works well in many situations, a few shortcomings of this technique may be worth mentioning: i. convergence of the GA is not always assured, ii. no universal rule exists for appropriate choice of algorithm parameters, such as population size, number of generations to be evaluated, crossover probability, mutation probability, and string length, iii. GA may require a significant execution time to attain near-optimal solutions, and convergence speed of the algorithm may be slow. Moreover the repeatability of results obtained by GA with same initial decision variable setting conditions is not guaranteed.

Scatter search technique (SS): This technique originates from strategies for combining decision rules and surrogate constraints. SS is completely generalized and problem-independent since it has no restrictive assumptions about objective function, parameter set and constraint set. It can be easily modified to optimize machining operation under various economic criteria and numerous practical constraints. It can obtain near-optimal solutions within reasonable execution time on PC. Potentially, it can be extended as an on-line quality control strategy for optimizing machining parameters based on signals from sensors.

Taguchi technique: Genichi Taguchi[25] is the name of a Japanese engineer who has been active in the improvement of Japan's industrial products and processes since the late 1940s. Taguchi's major contribution has involved combining engineering and statistical methods to achieve rapid improvements in cost and quality by optimizing product design and manufacturing processes. Taguchi methods represent a new philosophy in which quality is measured by the deviation of a functional characteristic from its target value. Noises (uncontrolled variables) can cause such deviations resulting in loss of quality. Taguchi methods seek to remove the effect of noises. Taguchi[25] described that quality engineering encompasses all stages of product/process development: system design, parameter design, and tolerance design. Taguchi's contribution to quality engineering has been far ranging. 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. 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. Manna and Bhattacharyya[26] used Taguchi method for determining significant cutting parameter setting to achieve better surface finish during turning operation of aluminum and silicon carbide-based metal matrix composites. Shaji & Radhakrishnan[27] applied Taguchi method in surface grinding process, and show the impact of graphite application to reduce heat generation in grinding zones. Singh, Shan, and Pradeep[28] demonstrated the potential and use of Taguchi method to identify critical process parameters that effect material removal in abrasive flow machining.

The drawbacks of this algorithm are as follows: i. Taguchi proposed a short term, one-time improvement technique to reduce the number and cost of experimentations, which may eventually lead to sub-optimal solutions. ii. Taguchi's method refers to optimization without intrinsic empirical or mechanistic modeling during experimentation. This type of technique closes the possibility for greater in-depth knowledge of the process, iii. Alternative methods, claimed to be efficient for simultaneous optimization of multiple responses (such as data transformation and using dual-response surface technique).

Geometric Programming: The geometric programming technique is a very popular technique for solving non-linear programming problems. It is basically used to minimize the functions which are in the form of posynomials subjected to the constraints of the same type. It is widely applied in optimization of metal cutting operations, especially in the optimization of machining operations with an objective function. The problem of the optimal machining condition selection has been analyzed by many researches. Some of the authors analyzed the optimum cutting speed that satisfies the basic manufacturing criteria's. Basically, this optimization procedure, whenever carried out, involves partial differentiation for the minimization of the unit cost, maximization of production rate or maximization of profit rate. These manufacturing criterions are expressed as a function of cutting speed. Then the optimum cutting speed is determined by equating the partial differentiation of the expressed function to zero. A number of authors used geometric programming to determine the optimum cutting speed and feed rate under different constraints which satisfy minimum cost of single pass turning operation.

It is different from other techniques of optimization as it priorities the objective function instead of the design variables by finding the optimal value of the objective function first and then the optimum value of design variables. This feature proves to be a boon in case where only the optimal value of objective function is all that is desired. Also, the calculation of the optimum design vectors can be omitted. Another major advantage of geometric programming is that it reduces the complicated optimization problem to a set of simultaneous linear algebraic equations. The main drawback of this method is that the entire problem and constraints have to be expressed in special terms called posynomials.

Artificial neural network (ANN): Modeling techniques of ANN 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 offer a cost effective alternative in the field of machine tool design and manufacturing approaches, receiving wide attention in recent year. ANN may handle complex input–output and in-process parameter relationship of machining control problems. 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. Several applications of ANN-based input-output relationship modeling for metal cutting processes are reported in the literature. Grzesik and Brol[29] showed the usefulness of ANN modeling for controlling surface finish characteristics in multistage machining processes. Back propagation neural network, proposed by Rumelhart, Hilton, and Williams[30] have been successfully applied by Sathyanarayanan, Lin, and Chen[31] for modeling 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.

The drawbacks of ANN techniques are: i. 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, ii. model parameters may be un-interpretable for non-linear relationship, 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.

Methodology of Optimization Techniques: Step-1 Define the cutting process optimization problem highlighting its criticality in terms of the selected criteria and also the objective function which has to be optimized.

Step-2 All relevant decision variables and operating levels and ranges need to be identified at this stage. If an optimization problem is subjected to some operating constraints, then, the constraints should also be expressed in terms of decision variables.

Step-3 The pertinent and reliable data related to input conditions, in-process parameters, and response variable(s) are to be collected through discussion with the concerned personnel, reference to the relevant documents, standards and performance statistics, and inputs from the feedback sessions for the cutting process. The whole exercise may be planned in an open and interactive mode.

Step-4 In this step, an empirical model is to be developed to express the complex relationship between input(s), in process parameter(s) and output(s) based on prevailing constraints and assumptions need to be applied. Then, the value of the objective function is found out by the developed model.

Step-5 The designed process model is tested, and validated in a number of dissimilar situations and circumstances. Validation evaluates the relevance of the testing methods determines if the developed model is a representation of real world. Then, graphs and charts are plotted to analyze the results of the model pictorially. It shows the variation of the objective function with change in the values of the decision variables and the optimal range of values of the decision variables.

Results and Discussion

The research shows that various traditional optimization techniques like fuzzy logic, genetic algorithm, Taguchi technique, scatter search technique, geometric programming, artificial neural networks etc. have been successfully applied in the past for optimizing the various cutting process variables. Fuzzy logic, genetic algorithm, scatter search, Taguchi technique and response surface methodology are the latest optimization techniques that are being applied successfully in industrial applications for optimal selection of process variables in the area of machining. In the recent optimization technique Taguchi methods is latest design techniques widely used in industries for making the product/process insensitive to any uncontrollable factors such as environmental variables.. It is also necessary to understand the inherent characteristic features/selection norms indicative of the application potential, and the general condition(s) including constraint(s) under which each modeling techniques are applicable before optimization techniques are selected.

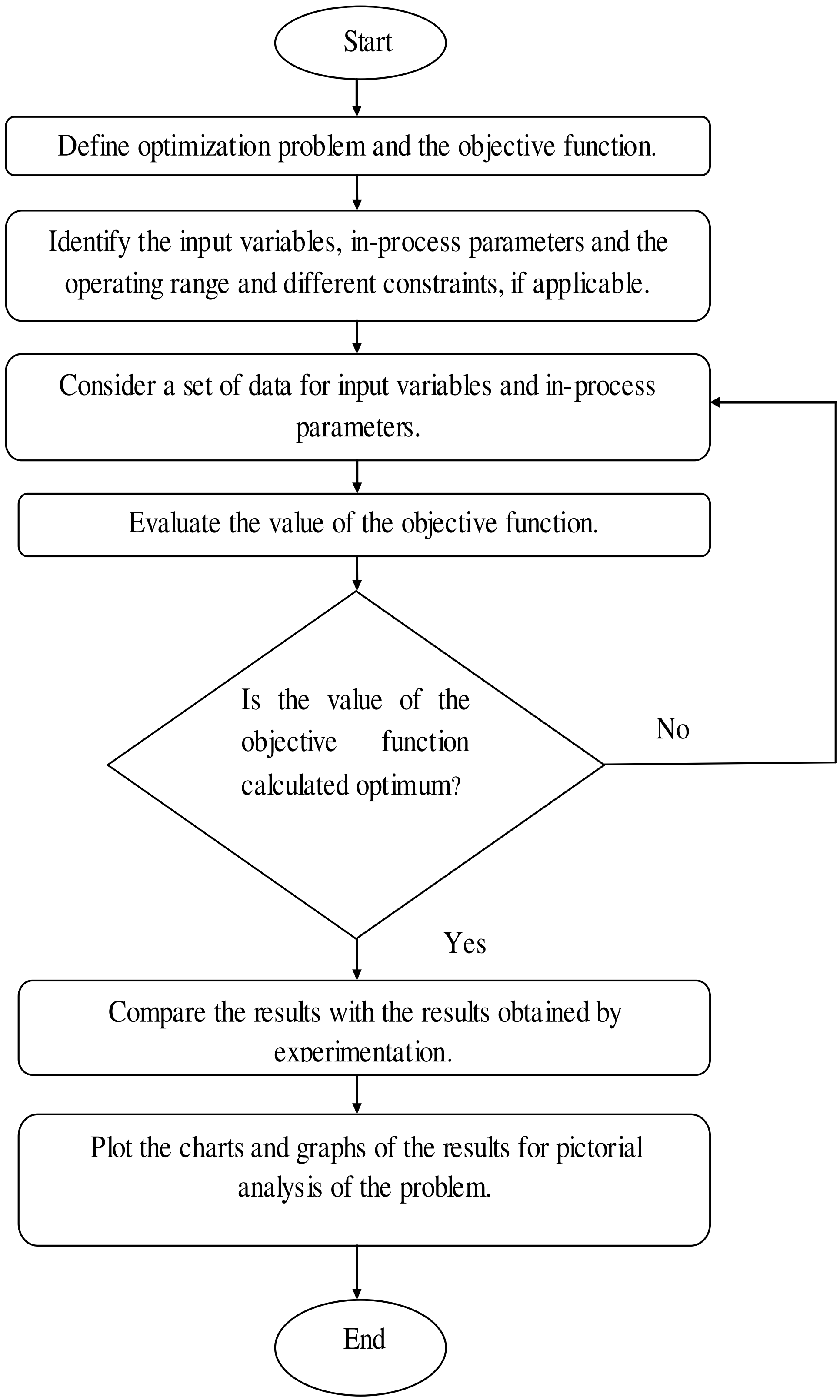

Figure-1
Optimization Algorithm

Conclusion

A systematic approach of modeling and determination of optimal or near-optimal cutting conditions has shown an interesting potential in both product and process quality improvement of metal cutting operation. The generic framework for process parameter optimization in metal cutting operation attempts to provide a single, unified, and systematic approach to determine optimal or near-optimal cutting conditions in various kinds of metal cutting process optimization problems, It incorporates the use of one or more of the existing modeling and optimization techniques, making the framework a unified and effective means. Moreover it attempts to provide the user with flexibility to adopt suitable techniques based on their inherent potential.

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