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Study of effect of nanofluid concentration on response characteristics of machining process for cleaner production

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A B S T R A C T

With the ever-increasing concern for reducing environmental pollution and waste minimization, "green manufacturing" has been successful to draw sufficient amount of attention towards it. Minimum Quantity Lubrication (MQL) is one such technique that has revolutionized the manufacturing industry by not only reducing the amount of working fluid dramatically but also enhancing cutting tool life and reducing material costs. Past studies have reported the use of experiments in MQL based manufacturing but limited computational modeling for optimizing the process parameters Based on the past experimental procedure of machining process (micro-drilling), a computational framework such as Adaptive Neuro Fuzzy Inference System (ANFIS) and Genetic Programming (GP) in quantification of three response characteristics (torque, thrust forces and material removal rate (MRR) is proposed. The performance analysis based on the cross-validation, error metrics, curve fitting and hypothesis tests reveals that among the two models, the GP models have performed better. 2-D and 3-D surface analysis were performed to validate the robustness of the models. Among the three response characteristics, It was found that the nanofluid concentration influences torque the most, which is an important aspect for power consumption. At nanofluid concentration values of 1.4 and 4, the minimum values of torque and thrust forces is achieved respectively. When drill diameter is minimum and the spindle speed is maximum, the values of torque, thrust forces and MRR is the lowest. Thus, the feed rate, nanofluid concentration and drill diameter are most critical for obtaining higher MRR and lower values of torque and thrust force, thus enabling cleaner production and environment.

1. Introduction

With the growing concern towards minimal waste and environment friendly manufacturing, those concerned with industry and academia has started laying more and more importance in "green manufacturing". Lubrication is one of the most important processes in manufacturing as several key parameters like tool wear, cutting tool life, cutting quality depend on it. As an outcome of years of research, a method called minimum quality lubrication (MQL) has evolved that has succeeded in attaining chief position in several processes including cutting/non-cutting work. In MQL technique, minimal quantities of lubricant are delivered to the active site between the tool and work-piece, when cutting operations are involved. Unlike normal cutting fluids, in MQL a very thin layer of high quality lubricant forms a layer at the interface between the cutting tool and the workpiece. Most of the heat produced with MQL is due to chip deformation instead of friction. Thus, majority of the heat is removed with the sheared chip. Consequently, cutting quality is superior and cutting tool life is enhanced with the MQL technique. MQL has been frequently reported as the economic form of lubrication enabling the manufacturers to have the greater advantage and control over tool life, surface roughness, cutting quality and minimum waste disposal (Ghuge et al., 2010).

Several ways of efficient manufacturing, using MQL is widely explored by various researchers in various processes like turning, grinding etc. (Shen, 2008; Emami et al., 2014). Dhar et al. in (2006a) have studied the influence of MQL on cutting temperature, chip and

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product quality in turning steel and compared with dry machining and machining with soluble oil. Results establish that MQL enables substantial reduction in the cutting temperature, dimensional inaccuracy and even makes chip–tool interaction favorable (Dhar et al., 2006a). Dhar et al. (2006b) has also studied effect of MQL in reducing tool wear and surface roughness. A recent review on MQL by Sharma et al. (2015) meticulously highlights MQL methods used in various machining processes like turning, milling, drilling, grinding etc. with different materials. Study brings off how MQL contributes toward reduction of cutting temperature, maintenance of dimensional accuracy and surface integrity of workpiece etc. Zeilmann and Weingaertner (2006) investigates temperature reached during drilling under the application of MQL when the lubricant is applied either with an external nozzle or internally through the drill. Shen et al. (2008) in his thesis claims the inclusion of nanofluids in MQL for the first time and opines that adding nanofluids could improve tribological properties of base fluid, if not provide superior cooling. Similar to this, Nam et al. (2011) also carries out the rigorous experimental investigation of micro-drilling process using nanofluid MQL. They conclude that use of nanofluid MQL not only reduces drilling torques and thrusts but also eliminates remaining chips and burrs and enhance quality of the drilled holes. Huang et al. (2015) has combined MQL with MWCNTs in end-milling operation and found that the mixture significantly lowers cutting forces, cutting temperatures, roughness, tool wear etc. The studies involving nanofluid MQL bears particular importance to this present study as this work also involves micro-drilling using nanofluid MQL technique.

Numerical modeling of these MQL based techniques is another thrust area of research. A few literature do exist that deal with modeling of these MQL/nanofluid-MQL based machining processes. Ali and Dhar (2010) develop an artificial neural network (ANN) model to optimize cutting process in turning steel under MQL. They claim the model to be successful and opine its usage for forecasting tool wear and surface roughness in turning operations. Kilickap et al. (2011), studies influence of machining parameters on the surface roughness, using response surface methodology (RSM) and genetic algorithm. The optimum model is claimed to save noticeable machining time and product cost. Sarhan (2015) presents a method of predicting tool flank wear in a turning operation using ANFIS with an average prediction accuracy of 92.42%. Another review done by Adnan et al. (2015) highlights the application of artificial intelligence (AI) techniques in modeling of machining process. Study says that fuzzy logic (FL) is effectively used in modeling of various machining processes such as to predict the surface roughness and to control the cutting force etc. Fratila (2016), does a study concerning orthogonal cutting of alloyed steel with respect to cutting parameters.

The literature suggests that the effectiveness of nanofluid MQL in machining processes is inclusively investigated. However, parametric studies analyzing parameters influencing performances are fewer and almost none as per optimizing with nanofluid MQL is concerned. In this study, we try to optimize the process parameters for a micro-drilling process using nanofluid MQL technique based on computational intelligence methods such as genetic programming (GP) and adaptive neuro fuzzy inference system (ANFIS). ANFIS combines the advantages of neural networks and fuzzy inference system and thus considered a powerful modeling approach. The complete procedure comprising of the experimentation planning and computational modeling is shown in Fig. 1. Unlike statistical methods such as response surface methodology and analysis of variance, the computational intelligence methods are void of statistical assumptions such as correlated residuals, structure of the model, etc (Panda et al., 2016; Garg et al., 2015; Zhao et al., 2014a, 2014b; Gandomi et al., 2015a). Therefore, these methods are capable for processing the limited information (data) from the process to a comprehensive model, which can be used by experts for predictive monitoring and control (Zhao et al., 2015, 2016a; 2016b). In this study, the experiments on the micro-drilling process for measurement of three response characteristics (drilling torque, drilling thrust force and material removal rate (MRR)) based on the four process parameters (drill diameter, feed rate, spindle speed and nanofluid volumetric concentration) is referred from the literature (Nam et al., 2015). Experimental data is then fed into the frameworks of GP and ANFIS. The performance analysis based on the statistical metrics, cross-validation and hypothesis tests is performed on the formulated models for the three responses. Further, 2-D and 3-D analysis is performed on the best models for establishing the main and interactive effects between the process parameters. The environmental implications and arising from the analysis is discussed in the end.

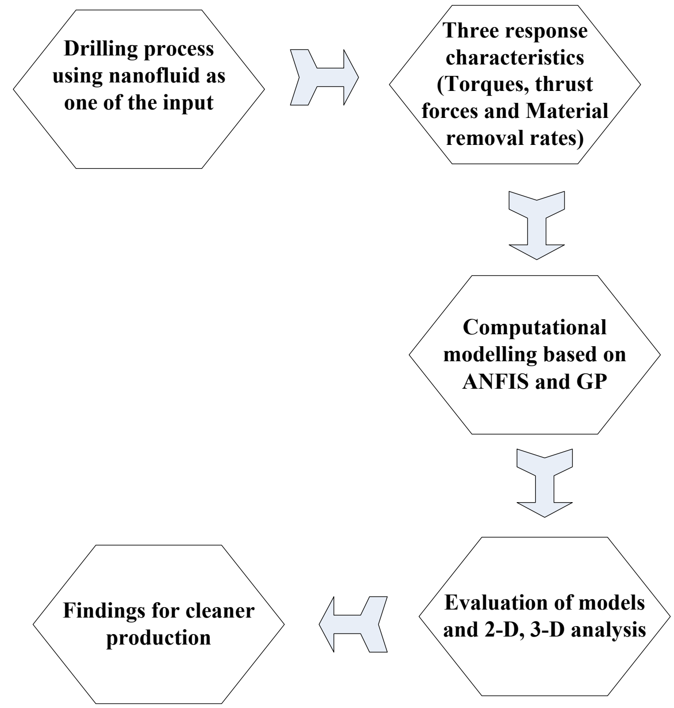

Fig. 1. Comprehensive procedure in experimentation and numerical modeling of micro-drilling process.

2. Materials and methods

2.1. Experimental set-up of micro-drilling process

The experimental study on the micro-drilling process with the measurement of the three response characteristics namely, torque, thrust forces and material removal rates (MRR) is referred from Nam et al. (2015). In their study, the Design of Experiment approach was used for sampling the data points for performing the experiments. The four inputs considered in this experiment were drill diameter (mm), feed rate (mm/min), spindle speed (rpm) and nanofluid concentration (% vol.). There were 25 experimental runs were performed for the collection of three response characteristics using the Vegetable oil as the base fluid (Nam et al., 2015). The range for the inputs used for the collection of the responses is kept same as mentioned in the study by Nam et al. (2011). Table 1 shows the range of the inputs used for the collection of the three responses values.