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Optimization of environmentally benign micro-drilling process with nanofluid minimum quantity lubrication using response surface methodology and genetic algorithm

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ABSTRACT

This paper discusses the optimization of environmentally benign nanofluid MQL micro-drilling process using nanodiamond particles based on a response surface methodology (RSM) and genetic algorithm (GA) in the cases of base fluid of paraffin oil and vegetable oil. In order to obtain regression functions of drilling torques and thrust forces in terms of process factors such as drill diameter, feed rate, spindle speed and nanofluid volumetric concentration, a series of micro-drilling experiments are conducted by using a design of experiment (DOE) approach. Then, the multi-objective optimization for minimizing drilling torques and thrust forces and maximizing material removal rate (MRR) is carried out by introducing GA, and the optimal values of process factors such as drill diameter, feed rate, spindle speed and nanofluid volumetric concentration are obtained. The micro-drilling experiments with the optimal process factors are conducted, and their results are very similar to calculated ones. Thus, the validity of the regression models of drilling torques and thrust forces are demonstrated.

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1. Introduction

Recently, rapid industrial growth in many countries has caused significant environmental pollution problems. In the field of manufacturing, metal working fluid (MWF), which has been widely used for lubrication and cooling in various mechanical machining processes, is one of major substances that have hazardous effects on environment and workers' health. Therefore, many researchers have been studying environment-friendly lubrication and cooling techniques such as dry, compressed air lubrication, minimum quantity lubrication (MQL), nanofluid MQL, and so on for mechanical machining processes to minimize the usage of MWFs. Among them, increased attention has been paid to MQL and nanofluid MQL techniques.

In the case of a MQL machining process, Tawakoli et al. (2011) investigated the performance of the MQL grinding process, and they found that the MQL condition was effective for reducing the grinding forces and improving the surface roughness while compared with dry, air and wet lubrication conditions. Hadad and Sadeghi (2013) studied the MQL turning process by comparing its performances such as machining force, surface roughness and temperature distribution with those of dry and fluid turning processes. In their research, the machining force in the case of the MQL turning process was lower than that in the cases of dry and fluid turning process, and its machining temperature was also much reduced. In addition, its surface quality was significantly enhanced due to reduced tool wear and damage at the tool tip with the application of MQL. In the case of the MQL drilling process, Kilickap et al. (2011) studied the influence of machining parameters on the surface roughness in the case of the MQL drilling of AISI 1045, and obtained the optimal condition for minimizing the surface roughness using response surface methodology and genetic algorithm.

In a nanofluid MQL machining process, mists of nanofluid that contain nanoparticles such as CNT, C_{60}, TiO_2, Al_2O_3, MoS_2, diamond, and so on are usually applied to a machining region. Those nanoparticles can significantly enhance thermal conductivity of base fluid with very small volumetric concentration. In addition, it is also

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known that tribological characteristics at a machining region can be enhanced due to ball bearing effect, third body effect, chemical/mechanical protective film effect, mending effect and polishing effect by using nanofluids (Oh et al., 2001; Wang et al., 1996). Due to its superior thermal and tribological characteristics, a nanofluid MQL has been applied to various machining processes such as grinding, milling, drilling, and so forth with environment-friendliness.

In the case of a nanofluid MQL grinding process, Malshe and Verma (2006) proposed the grinding technique using MoS_2 nanoparticles (≤500 nm) suspended in grinding fluid to provide effective lubrication effect to the contact zone between a grinding wheel and a workpiece. Shen et al. (2008) conducted the analysis on forces and tool wear during the nanofluid MQL grinding process using MoS_2 nanoparticles, and showed significant reductions in grinding forces and tool wear. In particular, it was reported that the maximum reduction in grinding force occurred in the case of MoS_2 nanoparticles having the size of 100 nm and the volumetric concentration of 1.5%. Sridharan and Malkin (2009) studied nanofluid MQL grinding processes using MoS_2 and CNT (20–30 nm) nanoparticles, and they showed that the nanofluid MQL could effectively improve the ground surface quality and decrease the specific grinding energy. Zhang et al. (2015) also used MoS_2 nanoparticles having the size of 50 nm in the MQL grinding process, and their experimental results showed that the palm oil based nanofluid with MoS_2 nanoparticles was best for reducing the grinding forces and surface roughness because of the high saturated fatty acid and high film-forming property of carboxyl groups in palm oil.

Meanwhile, Lee et al. (2012) studied the nanofluid MQL micro-grinding process using nanodiamond (30–150 nm) and nano-Al_2O_3 particles (30–150 nm) with the base fluid of paraffin oil. It was experimentally demonstrated that the nanofluid MQL was effective for reducing grinding forces and improving surface quality. In addition, it was found that the micro-grinding performances were critically influenced by type, size and volumetric concentration of nanoparticles.

In the case of a nanofluid MQL milling process, Park et al. (2010, 2011) conducted the research on the nanofluid ball-milling process using a xGnP lubricant which is a commercially available additive containing nanographene particles (thickness-15 nm). They discovered that the enhanced wetting area and angle of MQL droplets were obtained with the xGnP-based nanofluid and that the central and flank wear was thus decreased. Lee et al. (2010) analyzed and compared the machining forces and surface roughness under the conditions of compressed chilly air and MoS_2 nanofluid MQL during the meso-scale end-milling process. It was experimentally shown that the MoS_2 nanofluid MQL was effective for improving surface roughness and reducing the milling forces.

Meanwhile, in the case of a nanofluid MQL drilling process, there has been little research when compared with that in the cases of grinding and milling processes. One representative research was conducted by the authors and they applied the nanofluid MQL using nanodiamond particles (30 nm) to micro-drilling process (Nam et al., 2011). It was shown that the nanodiamond particles could effectively prolong tool life of micro-drills and that remove burrs and chips in drilled holes. In addition, the effectiveness of micro-drilling process could be influenced by the size and type of nanodiamond particles and base fluids – paraffin oil and vegetable oil. The authors continued their research on the nanofluid MQL micro-drilling process by conducting its parametric analysis (Nam et al., 2013). We investigated the effects of drilling parameters such as feed rate, rotational speed and drill diameter on the nanofluid MQL micro-drilling performances, and found that the nanofluid MQL could more effectively reduce in the case using the drill with small diameter (0.1 mm) than in the case using that with large diameter (0.5 mm) in the case of the nanofluid volumetric concentration of 4%. While using the drill with small diameter, the reductions in drilling torques and thrust forces were more effective in the case of low feed rate and low spindle speed under the nanofluid MQL condition. On the other hand, while using the drill with large diameter, the addition of nanodiamond particles could even increase the drilling torques and thrust forces in the micro-drilling process in the case of the nanofluid volumetric concentration of 4%. Hence, it is necessary to find optimal parameters for enhanced micro-drilling performances.

In the above-mentioned researches, the effectiveness and applicability of and nanofluid MQL technique to various mechanical machining processes were mainly investigated, and a few parametric studies were conducted to find critical parameters influencing machining performances. However, researches on the optimization of nanofluid MQL machining processes have been seldom reported, and there have none in the case of a drilling process, in particular.

Therefore, in this paper, the optimization of environmentally benign nanofluid MQL micro-drilling process is conducted by introducing a response surface methodology (RSM) and a genetic algorithm (GA). A series of micro-drilling experiments are designed and conducted based on a design of experiments (DOE) approach. Total 25 experimental cases are sorted out in each case of base fluid of paraffin oil and vegetable oil by considering three (3) levels of four (4) process factors – drill diameter, feed rate, spindle speed and nanofluid volumetric concentration. Then, the response variables such as drilling torque, drilling thrust force and material removal rate (MRR) are measured and calculated. The experimental results are then used to formulate the response surface models of drilling torque and thrust force in terms of drill diameter, feed rate, spindle speed and nanofluid volumetric concentration. These regression models are then used to obtain optimal drilling conditions to minimize drilling torque and thrust force and to maximize MRR based on a GA approach. Finally, the optimal values of process factors are validated by comparing estimated responses with experimental ones.

2. Micro-drilling experiments

A DOE approach was introduced to find critical variables having significant effects on the micro-drilling performances. In the DOE approach, central composite design (CCD) was applied for the design of micro-drilling experiments. In this research, four controllable process factors – a drill diameter, a feed rate, a spindle speed and a volumetric concentration of nano-diamond particles – and one axial point were taken into considerations, and thus 25 experimental runs were sorted for each base fluid – paraffin oil and vegetable oil – respectively. In addition, responses considered in the experiments were drilling torque, drilling thrust force and material removal rate (MRR). The process factors and levels are selected by considering our previous research (Nam et al., 2011). Table 1 shows the process factors and their levels for the experiments. As can be seen in Table 1, three levels of each process factor were considered.

A series of micro-drilling experiments were conducted in the miniaturized desktop machine tool system, whose photo is given in Fig. 1(a). The 3-degrees-of-freedom (DOF) miniaturized desktop machine tool system was developed based on the horizontal configuration. It had linear slides (MX80S, Parker) for a precision positioning system and the electric spindle (E-800Z, NSK) having the maximum spindle speed of 80,000 RPM for a rotating system. In addition, the load/torque cell was assembled to the linear slide with 2 mm lead, and then the aluminum workpiece was attached to the load/torque cell to measure thrust forces and torques. The overall

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