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Development of electrostatic solid lubrication system for improvement in machining process performance

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A B S T R A C T

Liquid lubricants have traditionally been used to control the high heat generation in machining; however, the use of cutting fluid has become more problematic in terms of both employee health and environmental pollution. Minimization or possible elimination of cutting fluids substituting their functions by some other means is emerging as a thrust area of research in machining. Solid lubricant assisted machining is a novel concept to control the machining zone temperature without polluting the environment. The focus of this study is to explore the possibility of application of graphite as a lubricating medium in drilling of AISI 4340 steel, as a means to reduce the heat generated due to friction, towards finding an alternative to conventional coolants. To this end, an optimized solid lubricant application method, electrostatic solid lubrication experimental setup has been envisaged for effective supply of solid lubricant mixture as a high velocity jet and at an extremely low flow rate to the machining zone, thus meeting environmental requirements. The process performance is judged in terms of thrust force, tool wear, chip thickness, hole diameter and surface finish of machined workpiece keeping the other conditions constant. A comparison with the results obtained in wet and dry machining is also provided. The results obtained from the experiments show the effectiveness of the use of the solid lubricant as a viable alternative to wet and dry machining through reduction in the cutting zone temperature and favourable change in chip–tool and work–tool interaction. The proper selection and application of solid lubricant can lead to low cost, and this concept could emerge as an effective alternative to conventional coolants.

1. Introduction

Drilling is one of the most commonly used machining processes in various industries such as automotive, aircraft and aerospace, dies/moulds, home appliance, medical and electronic equipment industries. The growing demand for higher productivity, product quality and overall economy in manufacturing by machining, particularly to meet the challenges thrown by liberalisation and global cost competitiveness, insists high material removal rate and high stability and long life of the cutting tools. But high production machining with high cutting velocity, feed and depth of cut are inherently associated with generation of large amount of heat and high cutting temperature. Such high temperature causes dimensional deviation and premature failure of cutting tools. It also impairs the surface integrity of the product by inducing tensile residual stresses and surface and subsurface microcracks in addition to rapid oxidation and corrosion [1,2]. Due to the fact that the higher the tool temperature, the faster it wears, the use of cutting fluids in machining processes has, as its main goal, the reduction of the cutting region temperature, either through lubrication reducing friction wear, or through cooling by conduction, or through a combination of these functions.

However, the use of cutting fluid in machining operations has decreased lately due to environmental and human health problems it causes. For the companies, the costs related to cutting fluids represent a large amount of the total machining costs. Several researchers [3,4] state that the costs related to cutting fluids is frequently higher than those related to cutting tools. For the companies, the costs related to cutting fluids represent a large amount of the total machining costs. Consequently, elimination on the use of cutting fluids, if possible, can be a significant economic incentive.

Machining without the use of cutting fluid (dry cutting) is an important objective in the industry to reduce environmental and production costs. The advantages of dry cutting include [5,6]: free from pollution of the atmosphere or water; no residue on the

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swarf, which will be reflected in reduced disposal and cleaning costs; no danger to health, being non-injurious to skin and allergy free. Dry cutting is becoming more and more popular around the world. But, in dry cutting, there will be more friction and adhesion between the tool and the workpiece. This will result in increased tool wear and hence reduction in tool life. So, in reality, they are less effective when higher machining efficiency, better surface finish quality and severe cutting conditions are required.

Therefore, increasing the productivity in the machining industry through cost reduction by abandonment of the cutting fluid, saving the environment and at the same time improving machining properties is the main concern. Application of solid lubricant in machining is a plausible solution in this direction. If friction at the tool and workpiece interaction can be minimized by providing effective lubrication, the heat generated can be reduced to some extent. Advancement in modern tribology has identified many solid lubricants, which can sustain and provide lubricity over a wide range of temperatures. If suitable lubricant can be successfully applied in the machining zone, it leads to process improvement.

The main objective of the present research work is to develop electrostatic solid lubrication setup to supply constant and defined amount of solid lubricant mixture to the machining zone. SAE 40 oil is chosen as the mixing medium with graphite solid lubricant, due to its higher viscosity and hence improvised lubricating properties. Efforts have been made to investigate the role of solid lubricant assisted machining on thrust force, tool wear, chip thickness, hole diameter and surface finish of machined workpiece in drilling of AISI 4340 steel at industrial speed-feed condition by using uncoated carbide tool. Another objective of this work is to compare the effectiveness of solid lubricant assisted machining with that of wet and dry machining under the same operating conditions to have the relative comparison.

2. Literature review

During a machining process, a substantial part of the energy is converted into heat through the friction generated between the tool and workpiece and the plastic deformation of the work material in the machining zone. The rapidly accumulated heat causes the temperature of tool and workpiece contact zone to rise at a fast rate, directly affecting the quality of products. So, heat produced in machining is critical in terms of workpiece quality. Application of cutting fluids influences the performance of machining because of its lubrication and cooling actions. But, the development of governmental pollution-preventing initiatives and increasing consumer focus on environmentally conscious products has put increased pressure on industries to minimize the use of cutting fluids [7]. Moreover, it has also been reported [8] that cutting fluids can pose serious problems, the major ones being those related to the preservation of the environment, workers' health, etc. In case of cutting fluids, these trends have resulted in an emphasis on fluid maintenance in order to minimize the amount of waste generated, to extend the life of the fluid and to mitigate the negative effects of worker health [9]. Although techniques and equipment have been developed for fluid maintenance and waste disposal, more research is warranted towards machining with elimination of cutting fluids.

Solid lubricant assisted machining is one attempt to avoid the use of cutting fluids [10–12]. Graphite and molybdenum disulphide (MoS_2) are the predominant materials used as solid lubricant. These materials are effective lubricant additives due to their lamellar structure. Other components that are useful solid lubricants include boron nitride, polytetrafluorethylene (PTFE), talc, calcium fluoride, cerium fluoride and tungsten disulphides. It is observed that rate of flank wear is less with solid lubricant assisted machining compared to wet and dry machining [13]. During the machining of thoroughly hardened AISI 52100 steel with ceramic inserts by using solid lubricants, it was observed that at high cutting speed range, the solid lubricants were more effective [14]. During the turning of EN8 steel workpiece with cemented carbide tool in the presence of solid lubricants (a mixture of graphite and boric acid with SAE 40 oil), cutting forces were measured to assess the lubricating properties of solid lubricants [15]. Among the lubricants, 20% boric acid in SAE 40 oil provided better performance for the selected tool–work combination and cutting conditions. But not much change was observed beyond 20%. This can be attributed to the fact that high viscosity of the solid lubricant decreases their sliding nature. The lubricant effectiveness in minimizing the frictional effects at the tool and workpiece interaction, in case of solid lubricant assisted machining, is evident from the reduced cutting forces compared to dry and wet machining. This performance of solid lubricants is due to its lattice layer structure that allows it to act as an effective solid lubricant. In an another study it was shown that the friction coefficient at the tool–chip interface in dry cutting of hardened steel and cast iron with $Al_2O_3/TiC/CaF_2$ ceramic tool was reduced compared with that of Al_2O_3/TiC tool without CaF_2 solid lubricant [16]. In addition to the morphology and crystal structure of the solid lubricant particles, the effective method of supplying solid lubricant at the workpiece–wheel interface, and their size and quantity also play a dominant role in the lubrication achieved during the grinding process. One approach is to add the solid lubricant in powder form directly to the machining zone using an automated feeder [17]. Use of solid lubricant in machining process has reported considerable improvement in the process performance as compared to that of machining with cutting fluid in terms of cutting forces, surface quality and specific energy [18]. Towards finding out an improved method of application of solid lubricant, attempts on development of solid lubricant moulded grinding wheels with various bonding and lubricants have been reported [19]. Such wheels with resin bonding were successfully made and improved process results were obtained. Investigations carried out on using graphite as a lubricating medium to reduce the heat generated at the grinding zone [20]. An experimental setup has been developed and a detailed comparison has been done with dry and coolant flooded grinding in terms of forces, specific energy, temperature and surface finish. Results show that grinding force, energy and temperature are reduced and resultant surface finish depends on workpiece material.

The above mentioned studies indicate the great potential of using solid lubricant for low cost and eco-friendly machining. The summary of the literature also suggests that the results can be further fine tuned with the proper application method of solid lubricant. Hence, in the present research work an electrostatic solid lubrication experimental setup has been developed to supply solid lubricant at constant flow rate to the machining zone and enhance the process efficiency of drilling operation under solid lubricant assisted machining conditions by considering thrust force, tool wear, chip thickness, hole diameter and surface finish of machined workpiece as performance indices.

3. Experimentation

Experiments have been conducted under wet, dry and solid lubricant conditions to study the machining parameters in drilling AISI 4340 steel material. The experiments were carried out on a high speed CNC milling machine; the machine spindle had a power of 2.6 kW and a maximum speed of 30,000 rpm. Number of