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Application of compressed cold air cooling: achieving multiple performance characteristics in end milling process

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ABSTRACT

This paper applies Taguchi's design of experiment methodology and grey relational analysis for multi objective optimization of process parameters and cutting environments during machining operation. In addition to the machining using cutting fluid, this research includes machining with compressed cold air cooling and dry machining. These environment-friendly cutting techniques are considered to be two practical ways to the cleaner manufacturing in the context of the sustainable production since the reduction of environmental harmful impact is an important topic in sustainable production. Experiments were performed based on L18 standard orthogonal array design by five input process parameters, namely cutting speed, feed per tooth, radial depth of cut, cutting time and cutting environment. Cutting environment is considered as machining using cutting fluid, machining with compressed cold air cooling and dry machining. The objective of process parameters optimization is to achieve at the same time the maximum volume of removed material and minimum surface roughness, minimum flank wear and minimum cutting force components. Based on grey relational analysis, the optimal setting of process parameters were identified and analysis of variance indicated that cutting time, feed per tooth and cutting environment are the most influential parameters on machining performances.
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1. Introduction

The most of metal parts which are embedded in different machines and devices get their final form by different processing techniques such as machining processes. Machining processes make about 60 %–80 % of the total manufacturing and represent the most often used metal processing in manufacturing. Moreover, machining is in single and small serial production irreplaceable and it represents the only possible economically viable way of production. Out of the three principal machining processes such as turning, drilling and milling, milling still remains the most important operation because of its efficiency and its possibility of creating complex geometrical shapes. Milling is also commonly used as a secondary process to add or refine features on parts that were manufactured using some other process such as casting or forging. Most of the articles published in the field of the cutting parameters optimization are mainly based on technological and economic considerations without the environmental dimension, (Kant and Sangwan, 2014; Oektem et al., 2006; Reddy and Rao, 2006). Today, the intention is to improve production while alleviating the manufacturing impact on the environment. The correct choice of cutting environment as well as the suitable machining technique are decisive factors for obtaining better performance characteristics. Cutting fluids are used in metal machining for a variety of reasons such as improving tool life, reducing workpiece thermal deformation, improving surface finish and flushing away chips from the cutting zone. Identification of oil-based cooling/lubrication fluids (CLF) as a main non-sustainable element of the machining has invited environmental concerns on calling for the reduction of cutting fluids in industry and finding alternative types of cooling. Most out of the large number of research conducted in the area of machining is focused on its activities and improvement of the process itself. Some of these improvements, such as optimisation of machining, minimizing use of cutting fluids and reduction of energy consumption necessary to remove the material from workpiece, have important positive consequences for the environment. For example, usage of cutting fluids which causes serious health and environmental problems arising from their application often opens new research fields for the purpose of solving the above mentioned problems. Strict regulations on use

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and disposal and higher purchase price, costs of cutting fluids which in the 80's of the last century made about 3% of machining costs now reach the level of 17% (Weinert et al., 2004). For the sake of comparison, costs of purchase and replacement of tools represent a share of 2 %–4 % of production costs. Also some studies showed that out of the total power consumption necessary for machining, almost 60% was used for procurement and supply of cutting fluids, which made a serious problem considering the trend of permanent growth of energy resources in the previous decade (King et al., 2001; Rahäuser et al., 2011). Consequently, rapid tool wear and achieving a certain quality of the machined surface do not exclusively represent the most significant obstacle in economic sustainability of machining, but it is also important to take into consideration the aspect of application of cutting fluids. Previously mentioned cost and a series of negative effects on humans and the environment explain why modern production industry gives more and more attention to the careful selection of socially and environmentally acceptable coolants. The results of research on negative effects of cutting fluids as well as multiplication of these effects in recent times bring into question the sustainability of such an approach of cooling applications in machining. The use of inappropriate type, quantity and technique of cutting fluids application which is not in proportion with a particular machining process brings to the reduction in efficiency of positive function of cutting fluids, reduction of tool life, increase the surface roughness and consequently to the decline in process productivity. Many contemporary researches in the field of cutting fluid application in machining suggest the abandoning of the use of conventional and transfer to the use of alternative cooling techniques and eventually dry machining. The best approach to reduce the usage and costs of using cutting fluids is not to use them at all (Sreejith and Ngoi, 2000).

The concept of dry machining has many advantages, such as non-pollution of the atmosphere or water, no residue or the swarf resulting in the reduction of disposal and cleaning cost, no danger to health, such as skin rupture or allergy. The elimination of coolant also imposes the loss of its positive effects, namely lubrication, cooling and chip flushing. Consequently, the mechanical and thermal loads of the cutting tool are increased, (Jianxin et al., 2005; Schulz et al., 2001). To analyse the cutting process in a dry machining operation, Haddag and Nouari (2013) developed multisteps of 3D finite elements modelling including prediction of tool wear and heat transfer in the tool. Zhong et al. (2010) presented a comparative study on dry milling and a newly proposed method called little quantity lubrication in milling. Their study is based on vibration signals that are dependent on the use of cutting fluid. In order to reduce vibration and cutting fluid usage, process parameters should be considered while deciding whether and how to apply cutting fluid. Fratila and Caizar (2011) used Taguchi optimization methodology to optimize the cutting parameters in face milling in order to get the best surface roughness and the minimum power consumption. Their investigation includes conventional flood lubrication, minimal quantity lubrication and dry milling.

Sun et al. (2010) developed a new cooling approach with cryogenic compressed air in order to cool the cutting tool edge during turning of Ti–6Al–4V alloy. The cutting forces, chip morphology and chip temperature were measured and compared with those measured during machining with compressed air cooling and in dry cutting conditions. They observed flank wear and results showed that application of both compressed air and cryogenic compressed air reduced flank wear.

Liew (2010) investigated the performance of TiAlN/AlCrN nanomultilayer coated, TiAlN single-layer coated and uncoated carbide tools in low-speed milling of stainless steel under flood and mist lubrication. Observed from the view point of tool wear and surface quality, the best cutting conditions are nano-coated tool and small quantity of oil sprayed in a mist form as a lubricant. Da Silva et al. (2011) presented a comparative study of the influence of two machining environments (dry and wet) in tool wear and surface quality during end milling of AISI 1047 steel with carbide tools. Fluids were directed to the cutting zone by three different techniques: flooding, reduced flow rate and minimum quantity of lubrication (MQL). The results showed that longer machined length values and higher material machining removal volume were obtained when machining was performed by means of reduced flow rate system.

Rahman et al. (2003) investigated how different types of cooling affect the machining performances of end milling operation of mould steel using uncoated tungsten carbide inserts. They applied chilled air, conventional overhead flood coolant and dry cutting. The relative performance of these modes is assessed in terms of surface finish, tool wear, cutting force and quality of the chips. Cold air is more favourable in terms of tool wear when cutting parameters have lower values. Cold air is also more favourable in terms of surface roughness if the cutting conditions are set to the higher values. Cutting forces are lower in many cases when using chilled air, than when using flood coolant.

Environmentally conscious machining of difficult-to-machine materials was reported by Shokrani et al. (2012). Different types of coolant/lubricants currently in use in machining industries were reviewed and the drawbacks of using conventional cutting fluids were defined. The major drawbacks were the environmental and health impacts with the costs associated with their use, maintenance and disposal. Due to the difficulties in machining difficult-to-machine materials, there were no techniques that were found to be a complete alternative for cutting fluids. As a result, further research on cooling techniques, cutting tool materials, cutting parameters and tool geometries was identified as essential and had potential to provide significant advantages.

Analysis of single performance characteristics of machining processes has been carried out by many researchers. However, single objective approaches constitute only adequate simplifications of the real problem. Machining processes are complex in nature and require often optimizing of various different and conflicting objectives. The Taguchi method together with grey relational analysis (GRA) has been used in dealing with optimization of multi-objective criteria (Siddique et al., 2010; Balasubramanian and Ganapathy, 2011; Sadasiva et al., 2012). Taguchi's parameter design offers a simple and systematic approach to optimizing design for performance, quality and cost of production (Camposeco-Negrete, 2013; Rama Rao and Padmanabhan, 2012). Sreenivasulu and Srinivasa (2012) have used GRA to find optimal cutting parameters for the drilling process in order to minimize surface roughness and roundness error.

Literature clearly indicates that comprehensive investigations have to be performed in order to obtain more effective and environment-friendly machining conditions. Therefore, this paper deals with multi-objective optimization problem of the cutting parameters and cutting environments (dry, wet and air-cooled) during end milling process. Surface roughness, flank wear, cutting force components in X and Y direction, Fx and Fy, and volume of removed material were considered as response variables. Cutting force component in Z direction, has not been used into consideration because of the negligible small value of the Fz in comparison to components in X and Y direction. The Taguchi design approach is utilized for experimental planning during end milling with coated carbide inserts. Additionally, GRA was used to find the optimal machining parameters satisfying the multiple characteristics of the process, i.e. lower values of surface roughness, flank wear, cutting force and higher value of the volume of removed material. Finally,

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