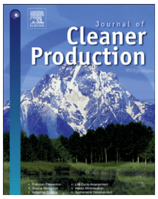
Journal of Cleaner Production 94 (2015) 321–329

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro



Single and multiple goal optimization of structural steel face milling process considering different methods of cooling/lubricating

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A R T I C L E I N F O

Article history:
Received 16 July 2014
Received in revised form
4 February 2015
Accepted 5 February 2015
Available online 14 February 2015

Keywords:
Cooling/lubricating
Face milling
Structural steel
Surface roughness
Optimization

A B S T R A C T

With the main aim of studying the reduced use of cooling/lubricating fluid and thereby contributing to cleaner manufacturing and environmental protection, the present study investigates the influence of four input variables, namely methods of cooling/lubricating (dry cutting conditions, cooling/lubricating through the tool and flood cooling/lubricating), depth of cut, number of revolutions and feed rate, on the surface roughness of face-milled structural steel. Through response surface methodology, the optimal machining parameters for obtaining the least surface roughness and the optimal parameters for two objective functions, namely minimum surface roughness and minimum standard deviation of the variability in the response transmitted from the factors, i.e., the propagation of error, were determined. The robustness study revealed that the obtained optimal parameters (depth of cut, 1.04 mm; feed rate, 100 mm/min; number of revolutions, 800 rev/min; and dry machining) will yield a minimum roughness of 0.62 μm with a minimum variability in the response transmitted from the factors. This study also demonstrated that nearly the same surface roughness of machined area was achieved for dry machining and cooling/lubricating through the tool, while the surface roughness higher values were obtained for flood cooling/lubricating. Due to the short machining time (small surface), the tool heating did not occur in dry machining while in cooling/lubricating through the tool, positive influence of high pressure was emphasized due to suppressing the formed chips from the tool and protecting the tool edge. Therefore, in both processes better quality of surface was obtained than in low pressure flood cooling/lubricating in which suppressing chips on the tool edge occurs as well as vibrations and increase of surface roughness.

1. Introduction

Not long ago, the investigations of machinability and surface roughness were mostly based on studying the influence of machining parameters to obtain the best possible quality of the surface with lower costs and reduced tool wear and energy consumption. However, one of the most important aims of investigations conducted today is cleaner production, i.e., application of “environmentally friendlier” technologies. As a result, a number of different approaches and tools have recently been developed aimed at the prevention of environmental pollution, at the possibility of products being recycled and reused, at saving of energy consumption and at the responsibility to future generations. Thus, for example, the approach Life Cycle Engineering – Assessment and Analysis, or shorter Life Cycle Assessment, LCA, developed in the 1990s, points to the need to save material and energy by using more recycled materials and to the development and application of alternative (sustainable) machining technologies and sustainable production (Pusavec et al., 2010a, 2010b). All of the above approaches contribute to sustainable development through improvement of environmental performances.

The previously mentioned approaches point to the fact that in machining, the principles of sustainable development and sustainable environment need to be applied and fulfilled. To achieve this, one of the goals of greater importance is to use lower quantities of cutting fluid (and of other fluids as well) and alternative methods of cooling/lubricating while machining, as this reduces environment pollution. Along with reduced quantities, the aim is also to use bio-degradable fluids and thus contribute to environment protection. The influence of cutting fluids on human health (toxicity) must not be neglected either. Therefore, one of the important factors to be varied is also the method, way or strategy of

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http://dx.doi.org/10.1016/j.jclepro.2015.02.015
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cooling/lubricating. The type of cutting fluid and the method of cooling/lubricating in terms of the pollution of environment, the effect on human health, the heating and wear of tool, as well as the economic issues, is therefore discussed in many studies.

It can be noticed that different ways of wet or MQL cooling/lubricating are applied. These include cryogenic cooling, high-velocity and high pressure of cutting fluid, narrow, pulsed jet, micro-closed loop recirculation of coolant through the tool holder – indirect cooling, micro-flood technology, micropooled lubricating, and cooling/lubricating through the tool (in the present paper). In the paper of Aggarwal et al. (2008a) it is demonstrated that the cryogenic environment exerts the strongest influence on reducing power consumption, followed by the cutting speed and the depth of cut while feed rate and nose radius showed to be non significant in CNC turning of AISI P-20 tool steel. Those authors, but in Aggarwal et al. (2008b) studied the same material by varying cutting speed, feed rate, depth of cut and nose radius in CNC turning under cryogenic cutting environment. Thepsonthi et al. (2009) pointed out considerable advantages of high-velocity, narrow, pulsed jet of cutting fluid in high-speed milling of hardened steel (reduced tool wear, reduced forces, reduced quantity of coolant, improved roughness). As economical, this method is applied in Pusavec et al. (2010a, 2010b) as well and compared with conventional and cryogenic machining by the application of the LCA approach. These authors have concluded that the two alternative cooling/lubricating methods can be successfully applied at lower speeds of machining and that they are superior at high machining speeds, compared with conventional machining (flood cooling/lubricating). Minton et al. (2013) dealing with the machining of titanium proved that the heat resulting from friction during machining was successfully taken away by a specially designed, diamond coated insert via closed loop recirculation of coolant, through the tool holder (indirect cooling).

Many authors have studied machining under dry, minimal quantity lubrication (MQL) or near dry machining (NDM) and wet conditions. In nearly all investigations, it has been concluded that MQL is a good alternative to wet machining, regarding the tool wear, costs, health and environment protection. A number of authors have concluded that in wet or MQL conditions, better surface roughness can be achieved due to lower friction. However, reduced consumption of fluid is marked at NDM but also dangerous to health because of the application of atomized mist or spray at micro-flood technology (Marksberry, 2007). Turning of AA5083-O wrought aluminum alloy with a high Mg content (4.5%) in dry and wet machining conditions by the use of coated carbide tool is investigated by Davoodi and Tazehkandi (2014). It is concluded that the investigated Al alloy can be machined in dry conditions with high cutting speeds. In Sarikaya and Gullu (2014) Taguchi design and response surface methodology in CNC turning of AISI 1050 steel (the same material is investigated by Yalcin et al., 2009) are carried out to study the effect of cooling condition (dry, wet and MQL), cutting speed, feed rate and depth of cut on surface roughness. A conclusion is made on effectiveness of MQL and increasing the quality of cutting operations. In Tosun and Pihtili (2010), optimization was performed, but in that case by the application of gray relational analysis while examining the face milling process of 7075 aluminum alloy, by varying spindle speed, feed rate, cooling technique, and cutting tool material, by measuring surface roughness and material removal rate. Lower values of surface roughness were obtained for air cooling than for dry procedure, but higher than for fluid cooling, in investigating surface roughness and tool wear in CNC milling of annealed AISI 1050 steel as demonstrated in Yalcin et al. (2009).

Vegetable, mineral and synthetic oils as cutting fluids have been compared and used. The effect of vegetable based oil emulsions and cutting speed, depth of cut and feed rate on specific energy, tool life and surface roughness during end milling of AISI 304 stainless steel was investigated in Kuram et al. (2013). They concluded that the machining performance could be improved by the use of vegetable based oil emulsions (sunflower and canola) which could be considered as an alternative to semi synthetic coolants/lubricants. A similar subject was investigated by Cetin et al. (2011) and similar conclusions were also made but at examining turning AISI 304L stainless steel by the application of the Taguchi method. Lawal et al. (2014) also evaluated vegetable oil-in-water emulsion cutting fluids (as in Cetin et al., 2011; Kuram et al., 2013) and mineral oil-in-water emulsion in turning AISI 4340 steel with coated carbide tools. A conclusion was drawn that vegetable oil-in-water emulsion (palm kernel and cottonseed) could be considered as an alternative to mineral oil. At end milling of Inconel 718, Zhang et al. (2012) combined the afore-mentioned vegetable based oil emulsions and cryogenic environment (they used cryogenic compressed air of -30 °C), and called it minimum quantity cooling lubrication-MQCL.

Nano-cutting fluids have also been used, and their properties have been studied. Sayuti et al. (2014) applied the Taguchi method for optimization of cooling/lubricating technique in turning of hardened steel AISI4140 by the application of nanofluid (a mixture of SiO_2 nanoparticles with an average size of 5–15 nm in the mineral oil and pressured air is used). The following parameters were studied: nanoparticles concentration, nozzle angle and air carrier pressure and their influence on surface roughness and tool wear.

It can be noticed that many investigators have used design and analysis of experiment (DOE) methodology, i.e., statistical methods to model and optimize the machining process. Response surface methodology and appropriate experimental designs, mostly central composite design and Taguchi method is frequently used by many authors. Factorial (full or fractional) and D – optimal design has also been found.

Apart from the design of experiment methodology, application of the methods of artificial intelligence in surface roughness investigation has become more and more common. Using the neural network and genetic algorithm to predict minimum surface roughness in end-milling molded parts is presented in Oktem et al. (2006). Neural networks are used in Simunovic et al. (2013) to predict surface roughness of face-milled aluminum alloy, while in Saric et al. (2013) this method of artificial intelligence is used to predict and simulate the surface roughness of S235JRG2 structural steel.

Finite element method (FEM) is applied to predict the stress of tools with microholes (Lei et al., 2009). These authors used solid lubricant (tungsten disulfide).

Also applied is the LCA approach in which the effect of cooling/lubricating method is analyzed more extensively, in a broader way. In Fratila (2010), workpiece material, scrap processing, use of lubrication, and energy consumption are considered. Energy, water and land use, acidification, solid waste and global warming potential in cutting fluid production are studied in Pusavec et al. (2010a, 2010b), taking into consideration usage amounts, consumption rate and machine tool usage.

Based on the references to the reviewed literature published in different journals, it can be concluded that this subject can be approached from different standpoints, i.e., in a multidisciplinary way, while not disregarding sustainable development. However, in this case, an excellent synergy is needed between educational and research institutions and industry or government. It is noticed that the field of sustainable development has to be introduced into the universities (Lozano et al., 2013).

In view of the ever-increasing possibility of different machining centers to also use cooling/lubricating through the tool in addition