Journal of Cleaner Production 67 (2014) 265–276

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Novel uses of SiO_2 nano-lubrication system in hard turning process of hardened steel AISI4140 for less tool wear, surface roughness and oil consumption

Mohd Sayuti [a,1], Ahmed A.D. Sarhan [a,b,*,1,2], Faheem Salem [a]

[a] Centre of Advanced Manufacturing and Materials Processing, Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia

[b] Department of Mechanical Engineering, Faculty of Engineering, Assiut University, Assiut 71516, Egypt

ARTICLE INFO

Article history:
Received 29 June 2013
Received in revised form 16 December 2013
Accepted 18 December 2013
Available online 28 December 2013

Keywords:
Hard turning
Taguchi method
Nano-lubrication system
Tool wear
Surface roughness
Oil consumption
Hardened steel AISI4140

ABSTRACT

Hardened steel AISI 4140 material is commonly used to produce automotive parts such as shafts, gears and bearings. Machining this material significantly increases the temperature in the cutting zone and is critical in deciding workpiece quality. Though cutting fluids are widely employed to dissipate the heat in machining, they threaten the ecology and health of workers. Hence, there arises a need to identify eco-friendly and user-friendly alternatives to conventional cutting fluids. Modern tribology has facilitated the use of a nano-lubrication system. For this purpose, a novel uses of nano-lubricants in minimum quantity lubrication (MQL) system were studied. In the present work, a mist of SiO_2 nano-lubrication was used and applied by air pressure in turning of hardened steel AISI4140. In this research work, the optimum SiO_2 nano-lubrication parameters to achieve correct lubrication conditions for the lowest tool wear and best surface quality were investigated. These parameters include nano-lubricant concentration, nozzle angle and air carrier pressure. The Taguchi optimization method is used with standard orthogonal array $L_{16}(4)3$. This research is investigating on the new and novel uses of SiO_2 nano-lubricant by conducting analysis on tool wear and surface roughness using fuzzy logic and response analysis to determine which process parameters are statistically significant. Besides, these analyses were conducted in order to prove the effectiveness of nano-lubricant. Finally, confirmation tests were carried out to investigate optimization improvements.

1. Introduction

Hardened steel material is generally used to produce critical parts in the automotive industry due to its mechanical properties of hardness, toughness and weldability. For example, hardened steel AISI 4140 is used to produce automotive parts such as shafts, gears and bearings. Machining of hardened steel, particularly in hard turning, experiences high temperatures due to high friction between the tool and workpiece, thus affecting product quality (Li et al., 2009). Machining temperatures can be controlled by introducing an effective lubrication system to reduce the friction at the tool–chip interfaces (Kuram et al., 2013). A common lubrication system employed in machining is conventional flooding techniques to act as both lubricant and coolant (Sayuti et al., 2013a, b, c). However, the application of conventional flooding techniques has become a huge liability since it can cause several adverse effects such as environmental pollution, dermatitis to operators, water pollution, and soil contamination during disposal (Shaji and Radhakrishnan, 2003). In economic terms, it has been reported that the cost related to lubrication and cutting fluid is 17% of the total production cost is normally higher than that of cutting tool equipment, which incurs only 7.5% of the total cost (Klocke and Eisenblätter, 1997).

At present, many efforts are being undertaken to develop advanced machining processes using less lubricant. Researchers are striving to achieve eco-friendly, sustainable manufacturing due to tight regulations and environmental aspects set by governmental pollution-preventing initiatives (Tai et al., 2011). Hence, as an alternative to cutting fluids, researchers are investigating dry machining, coated tools, cryogenic cooling, minimum quantity

* Corresponding author. Centre of Advanced Manufacturing and Materials Processing, Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia. Tel.: +60 603 79674593; fax: +60 603 79677669.

E-mail addresses: mdsayuti@siswa.um.edu.my (M. Sayuti), ah_sarhan@yahoo.com, ah_sarhan@um.edu.my (A.A.D. Sarhan), salemfaheem@yahoo.com (F. Salem).

[1] Tel.: +60 603 79674489; fax: +60 603 79677633.

[2] Tel./fax: +20 882335572.

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http://dx.doi.org/10.1016/j.jclepro.2013.12.052

Table 1
Control factors and experimental condition levels.

Factor	A	B	C
Level (i)	Nanoparticles concentration (wt%)	Air pressure (Bar)	Nozzle orientation (Degree °)
Level 1 ($i = 1$)	0%	1	15
Level 2 ($i = 2$)	0.2%	2	30
Level 3 ($i = 3$)	0.5%	3	45
Level 4 ($i = 4$)	1.0%	4	60

Table 3
Mechanical properties of AISI4140 steel.

Properties		Conditions	
		T (°C)	Treatment
Density (× 1000 kg/m^3)	7.7–8.03	25	
Poisson's ratio	0.27–0.30	25	
Elastic modulus (GPa)	190–210	25	
Tensile strength (MPa)	655.0	25	Annealed at 815 °C more
Yield strength (MPa)	417.1		
Elongation (%)	25.7		
Reduction in area (%)	56.9		

lubrication (MQL), and solid lubricants. MQL is one of the promising techniques adopted by researchers (Sayuti etal., 2013a, b, c). The encouraging results include significant reduction in tool wear and surface roughness by MQL obtained as a result of lowered temperature in the cutting zone and favorable changes in the chip–tool and work–tool interactions (Díaz et al., 2010).

The reduction of tool wear, surface roughness and improving dimensional accuracy was successfully conducted using clean machining processes with minimum quantity lubricant (MQL). MQL shows superior performance compared to dry and wet turning. However, the usage of MQL in conjunction with a nano-lubrication system would be a noteworthy advantage to the manufacturing process due to its effect on product quality (Itoigawa et al., 2007). Nowadays, several nano-lubricants have been identified by the advancement in modern technology, making it possible to sustain and provide lubricity over a wide range of temperatures (Nakamura et al., 2000). Nano-lubricant is a novel type of engineering system consisting of nanometer-sized particles dispersed in base oil. It could be an effective method to reduce friction between two contact surfaces depending on working conditions. Lubrication effectiveness depends on the morphology and crystal structure of solid lubricants, as well as the way particles are introduced to the tool–workpiece interface (Sayuti et al., 2013a, b, c).

Beside the nano based lubricants high performance, labor and materials associated with preserving lubricant and equipment integrity will soon be minimized. Health and environmental concerns need to be addressed when dealing with lubricant materials. In addition, productivity in the machining industry could be increased through cost reduction by abandoning cutting fluid, saving the environment and at the same time machining performance would be improved. Physical analysis of nano-lubricants (Peng et al., 2009) shows that dispersed nanoparticles can easily penetrate into the rubbing surfaces and have a great elasto-hydrodynamic lubrication effect. Under a single-thrust bearing tester, researchers reported that the nano-lubricant's coefficient of friction is less than that of pure oil, and the extreme pressure of a nano-lubricant is two times higher than that of pure oil; hence, it can be concluded that nano-lubricant improves lubrication performance by preventing contact between the metal surfaces. Moreover, thermal conductivity of the nano-lubricant increases linearly with concentration, interacting hydro-dynamically to enhance thermal transport capability (Murshed et al., 2009).

Table 2
Standard L16(4)3 Orthogonal array, the sixteen experiments with detail of the combination levels.

Exp. no.	Control factors and levels (i)		
	A	B	C
1	$i = 1$	1	1
2	$i = 1$	2	2
3	$i = 1$	3	3
4	$i = 1$	4	4
5	$i = 2$	1	2
6	$i = 2$	2	1
7	$i = 2$	3	4
8	$i = 2$	4	3
9	$i = 3$	1	3
10	$i = 3$	2	4
11	$i = 3$	3	1
12	$i = 3$	4	2
13	$i = 4$	1	4
14	$i = 4$	2	3
15	$i = 4$	3	2
16	$i = 4$	4	1

Various nanoparticle types have been used as lubricant by researchers in order to investigate its effects on machining performance. It is well documented that silicon dioxide (SiO_2) nanoparticles are hard, cheap and available on the market. This nanoparticle has very good mechanical properties especially in terms of hardness (Vickers hardness – 1000 kgf/mm^{-2}) and is available in very small sizes, ranging from 5 nm up to 100 nm. Accordingly, the SiO_2 solid nanoparticles in mineral oil would act as a combination of rolling and sliding bearings at the tool chip interface. These, in turn, could reduce the coefficient of friction and improve machining performance significantly.

In line with previous research works reviewed above, an investigation of optimum SiO_2 nano-lubrication parameters in hard turning of AISI4140 is needed to effectively improve the machined surface quality by minimizing tool wear. Parameters include nanolubricant concentration, air carrier pressure and nozzle angle (hereafter called control factors). The conventional method to determine the optimal values of these parameters is the "trial and error" approach. However, due to the large number of experiments, the "trial and error" approach is very time consuming. Hence, a reliable systematic approach for parameter optimization is required. The optimization method presented in this study is an experimental process called the Taguchi optimization method.

Taguchi optimization, developed by Dr. Genichi Taguchi, is a set of methodologies in which the inherent variability of materials and manufacturing processes is taken into account at the design stage (Kuram and Ozcelik, 2013). In Taguchi optimization, multiple

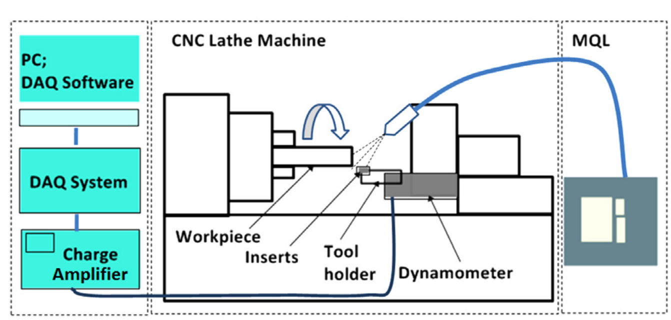

Fig. 1. Experimental set up.