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Ultrasonic assisted grinding process with minimum quantity lubrication using oil-based nanofluids

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ABSTRACT

Optimization of grinding process from the viewpoint of surface integrity and production cost is of the primary interest in grinding technology. Previous studies have shown that ultrasonic vibration assisted grinding (UAG) improves the grinding performance. These improvements are attributed to the change of the nature of the cutting process in UAG. On the other hand, minimum quantity lubrication (MQL) method has also been shown to increase the effect of lubrication characteristics of cutting fluid, and to minimize consumption of cutting fluid and reduce its environmental impact. Furthermore, it is perceived that adding nanoparticles to the cutting fluid, will improve its effectiveness.

This paper reports an experimental investigation of the vibration assisted grinding process combined with MQL using oil-based nanofluids with MoS_2 nanoparticles. Results are presented in terms of normal and tangential forces, force ratio and ground surface roughness. The results show that imposed horizontal ultrasonic vibration significantly decreases the grinding normal force. Also, MQL using nanofluid significantly decreases the grinding tangential force. Finally, simultaneous application of both techniques reduced forces by around 60%, which is very substantial. It also improved the surface quality.

1. Introduction

During grinding process, many of the grinding wheel grains come into contact with the workpiece surface every moment, but only a relatively small portion of these grains actually cuts. The other grains rub on the surface and generate heat by plowing and sliding in the contact zone (Tawakoli et al., 2009). As a result, the efficiency of the grinding process is much lower, and its specific energy is much higher than other material removal processes such as milling or turning. Therefore, a great portion of consumed energy in grinding process is wasted and converted to heat, raising the temperature of the cutting zone, and reducing the dimensional accuracy and surface integrity of the ground surface (Marinescu et al., 2007; Tawakoli et al., 2007).

A possible strategy to increase the engagement of contacting grains in the grinding zone is to impose a high frequency (>16 kHz) and low amplitude (2–30 μm) vibration on the grinding process. This process is called ultrasonic assisted grinding (UAG). The use of ultrasonic vibration in material removal, first time showed by A.L. Loomis and R.W. Wood in a paper in 1927, and the first patent granted to L. Balamuth in 1945 (Bhaduri et al., 2012). The most of researches on ultrasonic assisted grinding process show a reduction in workpiece surface finish and improvement in thermal damage/grinding burn, as well as notable reductions in grinding forces (~30–70%) (Tawakoli and Azarhoushang, 2008b). It is used for machining of both ductile and brittle materials. Significant improvements in quality of surface finish, tool wear, temperature and heat generation, material removal rate, noise reduction, burr size, machining forces and increasing in the number of active grains in grinding zone through the use of ultrasonic vibration have been reported (Bhaduri et al., 2012; Tawakoli and Azarhoushang, 2008b; Nik et al., 2012; Kadivar et al., 2014; Azarhoushang and Tawakoli, 2011; Gao et al., 2009; Nomura et al., 2007).

On the other hand, high volume of grinding fluid is commonly needed to reduce damages to the workpiece surface due to excessive heat generation. Cooling, flushing away the swarf, minimizing the corrosion, cleaning of the grinding wheel and chemo-mechanical lubrication are the main purposes of using a grinding fluid. Besides the high cost of these fluids and their subsequent filtration and disposal, these fluids cause environmental pollution and have health hazards to operators too. Furthermore, flooding grinding fluids cannot effectively penetrate into the grinding

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contact zone and provide good lubrication (Tawakoli et al., 2009). Although new techniques such as dry cutting are proposed to decrease the negative impacts of the cutting fluids (Marinescu et al., 2007; Tawakoli et al., 2009; Tawakoli and Azarhoushang, 2008b; Tawakoli and Azarhoushang, 2008a), without sufficient cooling and lubrication, thermal damage on the workpiece surface and dimension integrity is expected in grinding (Uhlmann and Sammler, 2010). Minimum quantity lubrication (MQL) seems to be a good alternative for effective cooling during machining process (Hadad and Sadeghi, 2013; Fratila and Caizar, 2011; Tawakoli et al., 2011; Sarıkaya and Güllü, 2014).

In MQL grinding, compressed air and oil mixture, i.e. an aerosol, is applied into the wheel–material contact region. However, effective application of MQL technique for processes with high frictional impacts such as grinding needs lubricants with improved tribological characteristics to facilitate large thermo-mechanical effect on the process.

By physical analysis of a nanolubricant – lubricant containing nanoparticles, Peng et al. (2009) stated that nanoparticles can easily penetrate into the contacting surfaces and show notable elastohydrodynamic lubrication action. Also, Lee et al. (2009) stated that nanoparticles penetrate between rubbing surfaces and improve the lubricating performance by increasing the viscosity and forming a tribofilm that reduces direct metal to metal contact. Also Simulations by Wenlong et al. (2011) showed tool wear rate is significantly reduced when adhesion strength between surfaces is reduced. Murshed et al. (2009) discussed that the thermal conductivity of nanofluid is enhanced by increasing the concentration of nanoparticles, due to increasing hydrodynamic interplays and thermal transport coefficient.

Assorted types of nanoparticles have been used to investigate machining performance, such as molybdenum disulfide, silicon dioxide, graphite, aluminum oxide, diamond, CNT (carbon nanotube), etc. Among them, molybdenum disulfide and graphite are widely used in lubricants, because they show excellent lubrication properties due to their layered morphology and crystal structure. Their poor Van der Waals force provides easy sliding among S–Mo–S layers. MoS_2 nanoparticles usually have better tribological properties compared with bulk MoS_2 (Hu et al., 2011).

The successful use of MoS_2 nanoparticles in cutting fluids in MQL experiments on various machining processes is reported by previous researches (Zhang et al., 2015; Rahmati et al., 2014; Kalita et al., 2010). Application of MoS_2 nanolubricant in MQL grinding demonstrated an excellent grinding performance by reducing the specific grinding energy and by creating high grinding ratio as compared to flood cooling using a water based grinding fluid and MQL of pure base oils without nanoparticle (Shen et al., 2008; Verma et al., 2008).

It is observed that the positive effects of both minimum quantity lubrication using nanofluids and ultrasonic vibration in the grinding process are well documented. Both achieved notable improvement of grinding performance. However, combined use of both techniques is not reported so far. As there seems to be no interference in their respective influence mechanisms, further improvement of grinding process through this combination is expected.

This work presents an experimental investigation of the individual and combined effects of minimum quantity lubrication of ultrasonic assisted grinding. MQL was applied using oil-based nanofluids. These effects are evaluated in terms of the normal and tangential grinding forces, force ratio and workpiece surface roughness.

2. Experimental procedures

2.1. Ultrasonic vibration system

An experimental setup for UAG is designed to apply high frequency oscillation at low amplitude to the workpiece. The horn and booster are used to enhance and transmit the vibrations generated by the transducer. The flexible structure is composed of the main plane, flexible joints and a fixed base. Flexible hinges are designed in a way that allow the system to maintain its stiffness and stability under machining forces while providing the required flexibility for the system in the direction of vibration, here, longitudinal direction. The result of the finite element analysis of the ultrasonic head is shown in Fig. 1. The proposed setup, shown in Fig. 2, that is composed of a transducer, a horn, a booster and a flexible structure.

Grinding experiments were carried out with and without ultrasonic vibration. Ultrasonic vibration was generated by a signal generator and a transducer (Master sonic MSG 2000) and was applied on the workpiece in the feed direction. High frequency vibration at 21.900 kHz was generated from the electric current at about 50 Hz through an ultrasonic generator. The proposed setup facilitates the vibration at a resonance frequency at 21.900 kHz with the highest magnification ratio. Because of its good acoustical

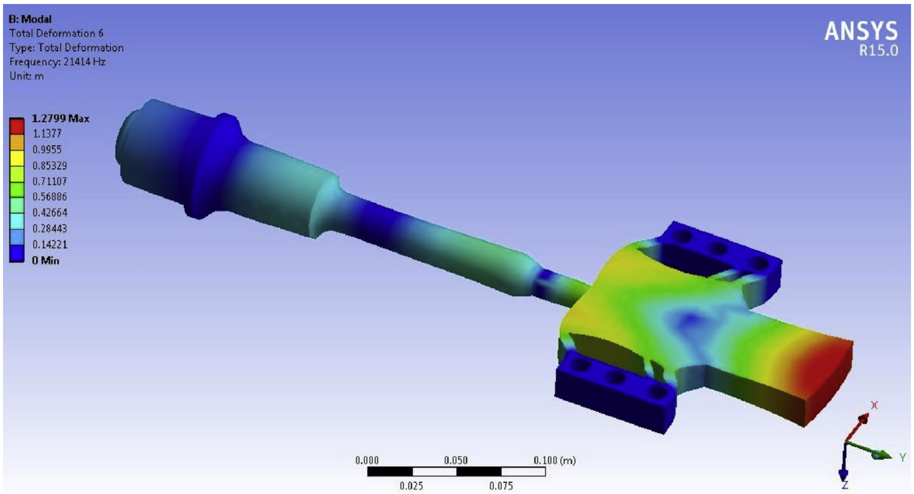

Fig. 1. Longitudinal displacement diagram of ultrasonic head obtained by FEM.