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Green lubrication technique for sustainable machining of AISI 4340 alloy steel

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ABSTRACT

Machining with AISI 4340 usually involves an excessive consumption of cutting oil to ensure a good surface finish and to extend the tool life. Accordingly, three highly sustainable and green cooling techniques that consume zero or a minute amount of cutting fluid, namely, dry cutting, minimum quantity lubrication and cryogenic machining, have been explored in the literature. This paper comprehensively reviews the machinability of AISI 4340 steel by using these sustainable machining techniques. Results show that compared with conventional cooling methods, the aforementioned techniques can enhance the machinability of AISI 4340 with respect to tool wear, cutting force, surface roughness and chips formation. Machining under green conditions also improves the economic aspect of metal cutting in terms of material removal rate. Each process constraint when machining with AISI 4340 has been identified in this article. As such, hybrid green machining can be seen as a solution to the limitations of standalone coolant techniques.

1.0 INTRODUCTION

Modern societies have become increasingly concerned about environmental sustainability given the shortage in natural resources driven by the continuous increase in the global population. In manufacturing, sustainability is considered a crucial aspect of a product lifecycle. Sustainable manufacturing is achieved when the manufacturing of products consumes a minimal amount of

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resources and is supported by the necessary technologies and knowledge for fulfilling environmental, economic and societal objectives (Garetti and Taisch 2012). Machining is a manufacturing approach where a material is sheared down to its final desired shape. Metal cutting industries are known for their large consumption and wastage of energy (Yoon *et al.,* 2015). To ensure a sustainable machining process, Gupta and Laubscher had proposed some machining strategies that govern all pillars of sustainable manufacturing practices (Gupta and Laubscher 2017). With an aim to contribute to an effective implementation of sustainable manufacturing, this paper comprehensively reviews the machinability of AISI 4340 alloy steel when using green machining lubrication techniques.

1.1 Green Lubrication for Sustainable Machining

According to Gupta, one key strategy to achieving sustainability is adopting a green lubrication method in machining. The use of green lubrication techniques ensures a sustainable machining process that benefits the environment, the industry and its workers. The flooding method has been extensively utilised as a lubrication technique in the machining process given its ability to dissipate cutting temperature and ensure a smooth machining process, an extended tool life and an improved surface finish. Meanwhile, most types of tool damage, such as thermal cracking, adhesion and diffusion, are triggered by the presence of high temperatures at the cutting interface. Moreover, using the flooding method consumes a large amount of metalworking fluid (MWF). According to Nune and Chaganti (2019), the flooding method consumes approximately USD1100 million of MWF, which is estimated to grow to USD1500 million by 2020.

The high consumption of cutting fluid can also increase the overall production costs, some of which are used for purchasing, maintaining and disposing working fluid. As mentioned by Lawal, 8% to 16% of the total production costs are due to wastage associated with MWF. Mineral and synthetic oils have been widely used as MWFs in flood cooling because of their lower market price compared with other types of oils, such as vegetable and animal oils (Lawal et al., 2012). However, these conventional cutting fluids are known to cause environmental and health hazards to workers (Pervaiz et al., 2018), thereby prompting some researchers to explore the effects of WMF on workers (Lawal et al., 2012, Park 2012, Debnath et al., 2014, Chia et al., 2019). Accordingly, some alternative approaches that can replace the use of conventional cutting fluids have been proposed. These approaches, also known as green machining methods include dry machining, minimum quantity lubrication (MQL) and cryogenic machining, all of which consume zero or minimal amounts of oil and have minimal impact to the environment (Boubekri et al., 2010, Yap 2019, Nguyen et al., 2020) yet achieve an excellent machining performance; these methods have also been compared with traditional flood cooling methods due to their advantages (Da Silva et al., 2011, Selvam and Sivaram 2018, Gajrani et al., 2019, Masoudi et al., 2019).

1.2. Industrial Application of AISI 4340

Alloy steel is a versatile material that has been widely used in many industries, such as automotive, aerospace, heavy equipment, mould and die and pipeline industries, just to name a few. Alloy steels, such as AISI 4340, AISI 4140 and AISI 4150, are manufactured by combining carbon steel with other alloying elements with an aim to improve their characteristics, including their hardenability, corrosion resistance and hardness, and satisfy product requirements (Ashby and Jones 2013).

AISI 4340 is a heat-treatable low-alloy medium carbon steel that is widely used in applications that require high strength and wear resistance. The high carbon content of AISI 4340 leads to the formation of martensite when rapidly cooled, especially in milling operations. As a result, some changes on the surface or sub-surface of the machined part are observed due to the alteration in the microstructure and residual stresses during machining (Pereira et al., 2017). These materials are commonly used in automotive and aerospace applications, such as crankshafts, cam shafts, landing gears and high tensile screws (Summer et al., 2015, Citti et al., 2018). These grades of alloy steel are also suitable for mould and die applications, specifically cold extrusion rams and dies and moulds for plastic injection moulding (Hassanpour et al., 2016, Senevirathne and Punchihewa 2017) in fabricating bumpers and dashboards (Firrao et al., 2013). The chemical composition of workpiece materials by percentage of weight is given in Table 1. AISI 4340 is usually machined in a hardened state, which accelerates the tool wear and affects the surface quality of the material. For instance, when machining the cavities of mould and die, huge amounts of coolants are consumed throughout the material removal process to prevent excessive heat, but doing so also leads to rapid tool wear and poor surface quality. This paper reviews the literature on AISI 4340 steel machining via sustainable cooling techniques, namely, dry machining, MQL and cryogenic machining, which diverge in their machining performance in terms of tool wear, cutting force, surface integrity and chips formation.

Table 1: Chemical composition of AISI 4340 steel (Pereira et al., 2017).

Ni	Mn	S	Si	Cr	P	C	Fe
1.8	0.70	0.04	0.25	0.8	0.035	0.41	Balance

2.0 ALTERNATIVE TO CONVENTIONAL CUTTING FLUIDS FOR SUSTAINABLE MACHINING

2.1 Dry Machining

Dry machining eliminates the usage of cutting fluids during the cutting process. To this end, most problems associated with the application of cutting fluids can be avoided. The implementation of dry machining can also reduce the costs for manufacturers by eliminating the use of coolants. Moreover, a minimised exposure to harmful cutting fluids creates a safe working environment, thereby improving the job satisfaction of workers and increasing their productivity. Dry machining also has a positive impact on the environment and complies with the relevant labour and environmental laws. With these benefits and positive impacts, enterprises can establish a good rapport with the society and leave a good corporate impression on others.

In dry cutting, increasing the feed rate and depth of cut can also increase the contact area and cutting temperature in the cutting region, thereby accelerating tool wear and degrading the workpiece surface quality (Sampath et al., 2016). Excessive thermal and mechanical loading during machining may also place stress upon the workpiece surface and subsequently induce high fatigue stress on the product (Sarnobat and Raval 2019). Therefore, the production steps are usually followed by heat treatment and finishing processes to improve the surface integrity of the product and to address some imperfections, including microcracks, dimensional inaccuracies or residual stresses that result from previous processes (Jomaa et al., 2016). To overcome these problems, improved tooling materials, such as CBN, PCBN, PCB, cermet, ceramics and different coatings, have been used along with dry machining (Weinert et al., 2004, Goindi and Sarkar 2017). These coating technologies extend tool life by reducing the tool thermal shock and temperature variation at the tool tip especially during milling operations.

Xavior and Sciences (2015) conducted a comparative experiment to determine the machinability of milling AISI 4340 in a dry environment by using coated (titanium nitride (TiN)) and uncoated carbide tools and found that the wear rate of the coated tool is slower than that of the uncoated tool due to the TiN layer used for the coating material, which prevents the adhesion of the work material to the tool edge. A more rapid and severe tool wear rate is observed when using uncoated tools especially at high cutting speeds. The ANOVA results in this work identify cutting speed and feed rate as the main parameters that contribute to tool wear.

Similarly, Li et al., (2019) also conducted an experiment to compare the performance of different cutting tool coatings when dry milling AISI 4340 in HSM. The result shows that lower cutting force and cutting temperature are achieved by using TiN/TiCN/TiAlN multi-coated tool compared to using coated tools with, TiCN + NbC, and AlTiN coating.

In the absence of cutting fluid during machining, a huge amount of heat is generated at the cutting zone due to the friction between the work material and the cutting tool. In this case, cutting fluid is always consumed in the machining process to remove the excess heat and lubrication in the cutting region, to extend tool life and to improve surface quality. To avoid the use of cutting fluid, manufacturers have resorted to green machining processes, such as MQL. This approach, also known as near-dry machining, uses a minute amount of cutting fluid, usually vegetable-based cutting oil (with a consumption of 0.5 mL/h to 500 mL/h as opposed to flood coolant, which has a consumption of 30,000 mL/h to 60,000 mL/h) mixed with pressurised air, to form a mist that is sprayed on the target area of the cutting region. In sum, MQL is a nearly clean process that requires a minimal amount of cutting fluid, thereby reducing production costs by 4% and greenhouse gas emissions by 21% (Ginting et al., 2015). MQL removes heat from the machining process in three ways (Walker 2013):

(a) by cutting fluid vaporisation;
(b) by spraying pressurised air onto the cutting region and
(c) By using the cutting fluid as a lubricant to reduce the friction at the tool–chips interface.

Using vegetable-based cutting fluids, especially palm oil, has been proven to create a highly stable protective oxide layer, thereby extending the tool life (Rahim and Sasahara 2011; Lawal et al., 2014; Shankar et al. 2017; Norfazillah et al., 2018). Using vegetable-based oils can also yield better machining results due to the complex structure of fatty acids contained in these oils, thereby leading to a high oxidation stability, which is crucial in high-temperature machining operations and in maintaining the properties of oil throughout the entire machining process (Lawal et al., 2014; Shankar et al., 2017).

Aside from improving the machinability of the material, vegetable-based cutting oils are also known as safer alternatives for workers and the environment compared with mineral-based cutting fluids. However, at higher cutting speeds, the effect of the protective layer created by vegetable-based cutting oils deteriorates, thereby making these oils ineffective in lubricating the tool–chips interface. Moreover, the plastic deformation of chips at high cutting speeds prevents the oil mist from penetrating the cutting regions. In this case, MQL is not suitable to be used at high cutting speeds. At a certain cutting condition, when the oxide layer is absent, MQL is no longer effective compared with dry or wet machining. To make things worse, straight cutting oils, such as vegetable- and mineral-based oils, have low thermal conductivity, thereby leading to a poor cooling ability. Al-Ghamdi and Iqbal (2015) attempted to identify a suitable cutting speed range for AISI 4340 and found that a high yield strength can rapidly reduce tool life.

Hadad and Sadeghi (2013) examined AISI 4140 and proved that MQL can reduce forces and improve surface quality at 100 m/min. However, at much lower (50 m/min) and higher speeds

(150 m/min), zero or minimal reduction in forces are recorded. The same result was reported by Senevirathne and Punchihewa (2017), who showed that MQL does not effectively improve tool life and surface roughness at a cutting speed of 150 m/min when machining AISI P20 and D2.

2.2 Cryogenic Coolant

Cryogenic machining is an eco-friendly method that directly removes the heat source from the cutting zone by using liquefied gas. The cooled gas absorbs and evaporates the heat without leaving any residues that can contaminate the parts, chips, machine tools or operator, thereby eliminating the costs related to oil-based cutting fluids. The cutting is performed at a very low temperature by using liquid nitrogen (LN2; –196 °C) or carbon dioxide (–78.5 °C) (Muhamad *et al.,* 2018). Pusavec *et al.,,* (2009) and Umbrello *et al.,,* (2012) enumerated the following benefits of cryogenic machining:

(a) this machining process is clean, safe and sustainable;
(b) cryogenic machining can improve the material removal rate (MRR), cutting speed and surface roughness whilst retaining the tool life, thereby improving productivity; and
(c) hard machining is achievable by using cryogenic methods.

All these statements have been supported by evidence from related studies. When machining medium carbon steel AISI 1040 under cryogenic and dry conditions, Gupta *et al.,,* (2015) found that cryogenic machining can improve the machinability of steel way better than dry machining. Specifically, cryogenic machining can improve tool wear, surface roughness and cutting force by 55.45%, 125.9% and 61.94%, respectively, at a constant cutting speed of 100 m/min and feed rate of 0.051 mm/rev. The obvious improvement in the measured output can be ascribed to the reduced cutting temperature at each tested feed rate. The reduction in temperature retained the hardness of the part and strengthened the tool material, thereby reducing the effects of crater and flank wear mechanisms. Similarly, Bicek *et al.,*, (2012) used cryogenic coolants to improve tool life during machining, improved MRR by 23%, enhanced surface quality and discovered 300% to 400% higher compressive stresses on and below the machined surface. Umbrello et al., (2012) found that the surface roughness yield of cryogenic hard turning is similar to that of the grinding process. In this case, cooling via cryogenic liquid has three benefits, namely, cooling off the workpiece, reducing the temperature at the tool–chip cutting zone and cooling the cutting tool.

Cryogenic machining has always been associated with altering the cutting tool material. The low temperature condition increases the strength and hardness of tools and subsequently enhances wear resistance, extends tool life (Haron et al., 2019) and improves surface quality (Nazra et al., 2020).

3.0 RESULTS AND DISCUSSION

3.1 Effect of Sustainable Machining on Tool Wear and Tool

Tool wear and life are amongst the most important factors in measuring the machinability of a process as they can increase the production costs and influence the surface quality of products (Yan et al., 2009). When dealing with tool failure, machining needs to be stopped immediately to prepare fresh tools, thereby extending the processing time. A manufacturer can manage his/her productivity by forecasting the rate of tool wear to control the dimensional accuracy and quality of the final product (Yan et al., 2009).

Most studies on dry cutting have examined the effect of the cutting tool material on the tool wear rate. Tool wear is greatly influenced by cutting speed, followed by feed rate and depth of cut.

Increasing the cutting speed and feed rate will accelerate the flank wear rate (Chinchanikar and Choudhury, 2013a; Das et al., 2017). Chinchanikar and Choudhury (2013b) studied the wear mechanism on coated and uncoated tools when dry turning AISI 4340 and found that the uncoated tools suffered from severe crater and flank wears even when machining at low cutting speeds. PVD and CVD have also been used as coated tools to test the machining parameters. The CVD tools outperformed the PVD tools under all tested conditions with adhesion and abrasion as the main causes of wear. The PVD tools also demonstrated poor tool life at high cutting speeds. However, a PVD single-layer tool can produce a goods surface finish with minimum force, but the speed must be limited to 200 m/min to prevent the sudden failure of the tool due to severe crater wear.

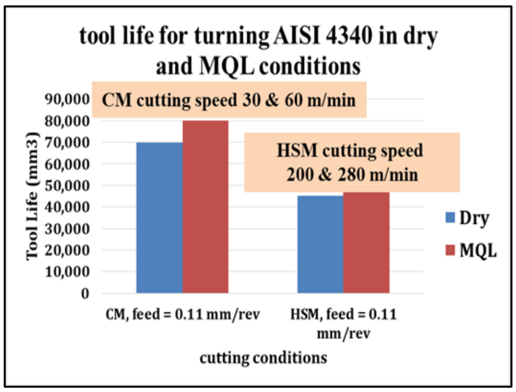
Das et al., (2018) conducted an experiment to compare the machining performance of AISI 4340 (50HRC) under dry and MQL conditions based on tool wear. By using a PVD multilayer coated carbide insert tool, they found that the flank wear value for MQL is lower than that for dry machining at cutting speeds of 100 m/min to 200 m/min and feed rate of 0.04 mm/min. The wear at the flank face was mainly dominated by abrasion and diffusion wear mechanisms. Steadily increasing values of wear were also recorded in both cutting environments when increasing the cutting speed, thereby suggesting that the effect of tool wear is sensitive to cutting speed.

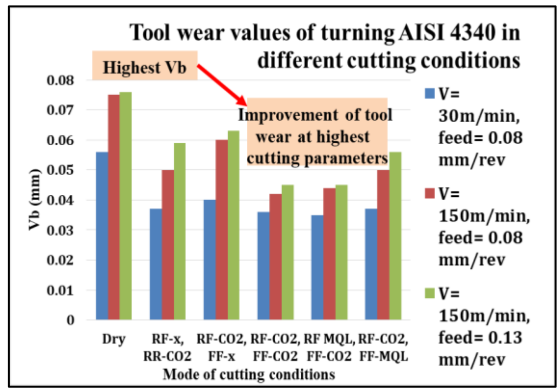
Sohrabpoor et al., (2015) reported similar findings when comparing the effects of tool wear when turning AISI 4340 in MQL, dry and wet conditions. Even when the machining condition was changed from levels 1 to 3 (i.e. finishing regime – semi finishing regime – roughing regime), MQL achieves the lowest tool wear and surface roughness amongst the three investigated conditions. The authors added that MQL can reduce the cutting temperature at the flank face, thereby decelerating the formation of tool wear related to adhesion and diffusion. In sum, an increasing feed rate contributes to 21.14% of tool wear compared with the other parameters. BUE also forms along with an increasing feed rate, which contributes to the wear at the flank face.

Al-Ghamdi and Iqbal (2015) studied the wear mechanism of a tungsten carbide tool when using two yield strength values (900 MPa and 1120 MPa) of AISI 4340 in dry and MQL conditions. The cutting conditions were classified into two speed modes, namely, CM (for cutting speeds 30 m/min and 60 m/min) and HSM (for cutting speeds 200 m/min and 280 m/min). The tool life under the CM mode was twice longer than that under the HSM mode. However, such tool life drastically reduced when machining materials with a high yield strength. In this case, the CM mode is economically preferred over the HSM mode given its long tool life. MQL also improves tool life under the CM mode but does not show any significant effects under the HSM mode (Figure 1(a)). Adhesion and abrasion wear have been identified as the main wear mechanisms that lead to flank wear. The intensity of adhesion significantly increases under the HSM mode, especially for materials with high yield strength, and the presence of MQL does not show any significant effects on the wear mechanism.

To further reduce the tool wear and improve the tool life of the cutting tool, some researcher have proposed a new approached based on hybrid cooling/lubricating by combining more than one of these cooling/lubricating strategies (Sartori et al., 2017). Research in hybrid cooling/lubrication approached have been widely studied in the area of machining hard-to-cut studied material such as Inconel 718 (Pereira et al., 2015, Shokrani and Newman 2018) and Ti-6Al-4V titanium alloy (Mark Benjamin et al., 2018, Shokrani et al., 2019). Both material results in significant improvement of the tool life when machining in hybrid cooling/lubricating environment when compare to the standalone cooling/lubricating method.

Meanwhile, Al-Ghamdi et al., (2015) combined the MQL and cryogenic (CO2) coolant techniques to study the tool wear at extended cutting speeds of 30 m/min to 150 m/min. The nozzles for both the MQL and cryogenic coolants were placed at several positions along the cutting tool, namely, at the flank face (FF), rake face (RF) and both the flank and rake faces. This hybrid coolant technique significantly improved the tool life. Applying CO^2 at the flank face and MQL at the rake face have also been proven as the best combination for improving the machinability of AISI 4340 at a high cutting speed of 150 m/min (see Figure 1(b)).





(a) (b)

Figure 1: (a) Comparison of tool life between conventional machining (CM) and high-speed machining (HSM) under dry and MQL conditions, and (b) tool life across different cutting conditions and machining parameters.

Only few studies have examined the use of AISI 4340 in cryogenic machining. By using a PVD-coated carbide tool, Arun et al., (2018) examined the rate of tool wear of turning AISI 4340 when using an LN2 cryogenic coolant. At a specified cutting speed range and at a constant feed and depth of cut, they found that tool life can be extended much longer under the cryogenic condition than under the flood coolant condition. At 100 m/min, a catastrophic flank wear behaviour was observed under the flood coolant condition as early as 14 min after machining. Meanwhile, in cryogenic machining, a slow flank wear was observed along with a long tool life. However, when the cutting speed increased further from 100 m/min to 200 m/min, the application of cryogenic coolant progressively shortened the tool life.

When machining AISI 4340 under cryogenic and dry environments, Dhar et al., (2001), found that compared with dry cutting, using a cryogenic system can reduce the temperature at the tool tip by 34%, significantly reduce the flank wear and improve both surface finish and dimensional accuracy. This approach can also extend the tool life much longer compared with dry cutting at a cutting speed and feed rate of 103 m/min and 0.2 mm/rev, respectively. Whilst most of the cutting speeds investigated in previous research are lower than 300 m/min under all conditions, Shalaby, Veldhuis and Mandal used alumina-based ceramic tools to cut AISI 4340 at a speeds ranging from 450 m/min to 1000 m/min (Mandal et al., 2011, Shalaby and Veldhuis 2018).

3.2 Effect of Sustainable Machining on Cutting Forces

Cutting force is another research topic that has received much attention from scholars. Information on cutting forces is essential in estimating the power requirements when choosing the optimal machine components, such as tool holders or fixtures, to minimise vibration and distortion (Kalpakjian & Schmid, 2013; Trent & Wright, 2000). Therefore, a proper selection of machine components based on cutting force ensures an optimum tool life, good surface finish and excellent dimensional accuracy (Bai et al., 2011). High cutting forces can represent heavy cutting conditions by means of the large contact area between the tool and work material. Higher power requirements for shearing off the metal correspond to a higher temperature generated at the cutting edge.

When machining AISI 4340 with different cutting modes (CM and HSM), Al-Ghamdi and Iqbal (2015) observed that the force yield during machining in the HSM mode is twice larger than that in the CM mode under dry and MQL conditions. The serration chips produced during machining indicate that a higher force is required when cutting in the HSM mode. Al-Ghamdi et al., (2015) examined the cutting force requirements when cutting AISI 4340 under dry and MQL+CO^2 conditions. The nozzles for MQL and CO^2 were placed at different positions of the rake and flank faces of the tool. As a result, the combination of MQL at the rake face and CO^2 at the flank face obtains the lowest force.

Saini et al., (2014) changed machining parameters, such as cutting speed and feed rate, to examine their effects on cutting force when machining AISI 4340 (39 HRC). They performed their work under dry and MQL conditions by using CVD and PVD coated carbide inserts. The MQL parameters were kept constant, whereas the pressure, flow rate and nozzle distance were set to 4 bars, 300 ml/h and 35 mm, respectively. They found that force decreased along with an increasing cutting speed. A similar phenomenon was observed in dry cutting, where speed increased the cutting energy and stress, which subsequently increased the temperature. Meanwhile, high temperatures resulted in the thermal softening of the material, thereby reducing the overall cutting force. The values of temperature and cutting force under the MQL condition were much lower than those under the dry cutting condition. The temperature was further reduced under the capillary action and re-binder effects (Astakhov, 2009). The small droplets that penetrated the cutting region also reduced the friction and cutting energy and subsequently resulted in the curling of chips, thereby reducing the chip–tool contact length, cutting force and temperature at the cutting region. PVD (TiCN/TiN)-coated inserts also outperformed CVD-coated (TiCN/Al2O3) inserts in terms of their cutting forces and tool-tip temperature. Under the MQL condition, as the cutting speed increased from 40 m/min to 140 m/min, the force slightly increased as the temperature continued to increase in large increments. In this case, MQL is not suitable for high cutting speed applications given its lack of cooling ability. This finding was supported by Boswell, Islam, Davies, Ginting and Ong (2017). Meanwhile, the reductions in cutting forces have been ascribed to the presence of a lubrication oil at the cutting region under the MQL condition.

Arun Kumar et al., (2018) examined the effect of cutting forces on the cryogenic coolant conditions and found that cryogenic machining can reduce the friction at the tool–chip interface much better compared with flood machining. As the cutting speed increased to 100, 150 and 200 m/min, the cutting forces were significantly lower across all the cryogenic coolant conditions compared with the flood coolant conditions (18.1%, 14.03% and 11.45%, respectively). In addition, the power consumption of cryogenic machining was lower compared with that of flood machining. Although power consumption was directly proportional to the increasing cutting speed, their values remained lower compared with flood machining at all cutting speeds.

Natasha et al., (2016) and (Muhamad et al. 2019) obtained similar findings, where the cutting force under cryogenic machining is lower than that produced under dry machining in both the cutting force (fx) and feed force (fy) directions. The chips produced by cryogenic machining had a sawtooth-like appearance and tended to curl more, thereby suggesting that cryogenic cooling can lead to embrittlement and increase chip hardness. In this case, less energy is required to shear off the metal, thereby reducing the cutting force.

3.3 Effect of Sustainable Machining on Surface Integrity

Surface integrity needs to be examined to determine the quality of a product (Werda et al., 2016) because the surface integrity of a product can significantly affect its dimensional accuracy and service life in terms of fatigue and corrosion behaviour (Sarnobat and Raval 2019). Residual stresses, work hardening, microstructure alterations and surface roughness are other problems that have been extensively studied in surface integrity research.

In dry cutting, feed rate, cutting speed and depth of cut are the most significant contributors to surface roughness (Chinchanikar and Choudhury 2013b, Das et al., 2013, Xavior and Sciences 2015). Increasing the cutting speed can produce finer finished surfaces. However, the surface quality deteriorates along with an increasing feed rate. Apart from comparing MQL with dry cutting, Das et al., (2018) investigated the effects of these machining parameters on surface roughness. At feed rates ranging from 0.04 mm/rev 0.16 mm/rev, they found that the surface roughness values increased under both dry and MQL conditions. Machining under MQL with the same parameters yields finer surface roughness compared with dry machining. In sum, the surface roughness values are sensitive to an increasing feed rate.

Sohrabpoor et al., (2015) obtained similar results and confirmed that feed rate contributes to 30.48% of the significant factors. Specifically, feed rate greatly influences the formation of flank wear, which in turn directly affects the quality of surface roughness. Three conditions were examined in this work, namely, the finishing, semi-finishing and roughing regimes. In these regimes, MQL lubrication obtains the lowest surface roughness compared with dry, wet and air-cooled conditions. Meanwhile, the finishing and roughing regimes achieved the lowest and highest surface roughness values, respectively. The finest surface roughness was reported at the highest cutting speed (1000 rpm). The temperature builds up at high cutting speeds eliminated the welded BUE at the cutting edge, thereby improving the surface finish. MQL also obtained the lowest surface roughness compared with the dry and wet conditions when using aerospace materials for machining (Gupta and Sood 2017).

Cryogenic machining is capable of achieving a finer surface roughness compared with other types of machining. Arun Kumar et al., (2018) compared the surface roughness achieved by the cryogenic, dry and flood machining of turning hardened AISI 4340. At cutting speed, feed rate and depth of cut of 100 m/min, 0.1 mm/rev and 0.5 mm, respectively, a low Ra value (0.432 μm) was observed during cryogenic machining, which was equal to the surface roughness value produced by the grinding processes. Using dry machining also has no significant benefits over flood in terms of surface roughness. The surface roughness values reported in dry and flood machining were 1.089 μm and 0.979 μm, respectively. The poor surface roughness yield was attributed to the completely chipped off tool at the interface of the rake and flank area under flood cooling.

Natasha et al., (2018) examined the effect of cryogenic machining on the surface quality of AISI 4340 by performing machining tests in dry and cryogenic conditions at cutting speeds of 160, 200 and 240 m/min and by using a multilayer coated carbide tool. The feed rate varied between 0.3 mm/rev and 0.4 mm/rev, whereas the depth of cut was maintained at 1.0 mm. The experiment results show that the surface roughness value was more sensitive to the change in feed rate than in cutting speed. The increasing value of surface roughness was directly proportional to the increasing value of feed rate. Cryogenic cutting also improved the machine surface roughness except at a cutting speed of 240 m/min. Natasha et al., (2016) examined the effects of cutting temperature at the tool tip surface on the surface quality produced in machining AISI 4340 under cryogenic and cutting conditions and observed an 11% improvement in surface roughness when machining under the cryogenic condition. They ascribed the poor surface quality to the high temperature that is generated during cutting, which produces adhesive effects at the workpiece–tool interface. Such high cutting temperature has also been associated with the flank wear and build-up edge that is formed at the tool tip of the insert. Given that cryogenic effects can effectively reduce the cutting temperature, the tools can withstand a long cutting time before they are worn off.

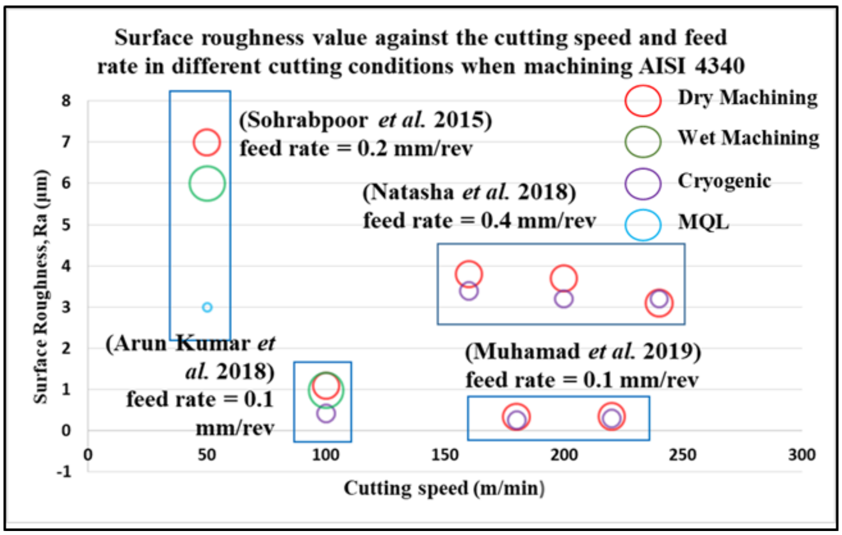


Figure 2: Surface roughness values against cutting speed and feed rate across different cutting conditions.

Muhamad et al., (2019) reported better surface finishes in their comparison of the dry and cryogenic milling of AISI 4340. A 24% improvement in surface finish was observed at a cutting speed, feed rate and depth of cut of 180 m/min, 0.1 mm/tooth and 0.3 mm, respectively. However, as the cutting speed increased, the improvement in surface finish was reduced to 14%. Figure 2 summarises the relationship of feed rate and cutting speed with the yield value of surface roughness. Ghani et al., (2016) examined the effect of machining under the cryogenic condition on the formation of the hardness subsurface layer of AISI 4340. They analysed samples from the machined part by using a Merlin Compact Zeiss field emission scanning electron microscope to check for changes in the microstructure approximately 7 µm deep into the subsurface layer of the sample. The result indicates that, up to 7 µm beneath the machined surface, the microstructure was more compressed than the bulk material. The hardness of the sample can be tested to understand the magnitude of the microstructure changes. In this work, maximum hardness which could be obtained was 8,500 N/mm^2 Marten's hardness. The authors claimed that such hardness is equivalent to the hardness of the case hardening steel, which is usually obtained by using conventional induction hardening methods that are applied to improve the hardness properties of the material.

3.4 Effect of Sustainable Machining on Formation of Chips

The formation of chips during the cutting process must be explored to understand the quality of the surface being machined (Suresh et al., 2012). For example, continuous long tubular chips indicate that an effective plastic deformation has occurred during the shearing of the work material, thereby leading to a good surface finish (Basavarajappa et al., 2014). However, these types of chips present a challenge in machining given the dangers they pose to operators and their tendency to stick to the machine, thereby damaging the tool tips. Discontinuous chips are produced along with chip breakage resulting from the high friction and adhesion between the tool and chips (Werda et al., 2016).

Li et al., (2019) studied the chip morphology when dry milling AISI 4340 using HSM. All chips produced are characterised by the serrated shape, results from the effect of cutting force and material's softening due to the high cutting temperature. However, the serration degree are varied through different types of coating material used for the cutting tool.

Das et al., (2018) studied chip formation when cutting AISI 4340 under MQL and dry environments. When cutting with a lubricant at a high cutting feed and speed (f = 0.16 mm/rev and 150 m/min), the chip colour remained metallic while, whereas the lubricant colour changed from metallic blue to burnt blue. These changes reflect the ability of MQL to reduce the temperature at the cutting region during machining and suggest that a high cutting temperature is generated in the absence of cutting fluid. Helical-shaped chips are produced when using MQL, whereas helical and ribbon-shaped chips are produced during dry cutting.

Naigade et al., (2013) examined the effect of different cutting environments (dry, wet and MQL environments) on chips formation when hard turning AISI 4340 and found that similar chips were formed when cutting under the wet and MQL conditions. Short-curled chips were formed, and no chip entanglements were reported at the cutting tool. Continuous and tightly-coiled-shaped chips were also observed during dry machining. These chips cannot be easily handled and clogged both the cutting edge and machined surface. The burnt blue colour of these chips may indicate the presence of a high cutting temperature, whilst yellowish brown chips were detected under the wet and MQL machining conditions.

Berlin et al., (2015) investigated the effect of MQL and dry cutting conditions on chip thickness and tool–chip contact length. During machining, MQL produced thinner chips compared with dry machining due to the low cutting temperature. Less friction and adhesion were also observed at the tool tip, thereby explaining why the chip thicknesses under MQL are 3% to 9% thinner than those observed under dry cutting conditions. These thicker, longer chips indicate the presence of a heavy cutting process that results in high cutting forces and power consumption.

Cryogenic cooling is a well-known method that can effectively reduce the cutting temperature at the cutting zone. Reducing the cutting temperature under the cryogenic condition can lead to the embrittlement of the chips. Therefore, the contact time between the tool and chip can be reduced, thereby improving the chip breakability during machining. Natasha et al., (2016) related chip formation with the temperature at the tool tip during the cryogenic and dry machining of AISI 4340. In their simulation, the highest temperature distribution was recorded at the rake face of the secondary shear cutting zone under both dry and cryogenic conditions. The predicted temperature during cryogenic machining was 350 °C, which could be ascribed to the difficulty for the liquid LN to penetrate the tool–chip zone, thereby localising heat in this region. Fortunately, the primary and tertiary cutting zones are effectively cooled down by LN, thereby facilitating the dispersal of the accumulative heat transferred to the tool.

Based on the results of the actual experiment, the cryogenic coolant can reduce the cutting temperature by 32% to 33% compared with dry cutting. The chip samples from both types of machining were collected and compared and chips that produced by cryogenic cooling had more curls compared with those produced by dry cutting. The curls started to form when a temperature difference is observed between the upper and undersides of the chip. A larger temperature difference corresponds to a curlier chip. A higher degree of curl also indicates a shorter contact length between the chips and tool face. A shorter contact length is preferable as it reduces the occurrence of crater wear and facilitates the entrapment of LN within the primary shear zone. The simulation results show that the contact lengths of the chips during deformation are 0.567 mm and 0.614 mm during cryogenic and dry cutting, respectively. Moreover, the chips produced during cryogenic turning had a highly apparent serrated-sawtooth-like appearance, which is indicative of an increased hardness of the chip material affected by the cryogenic condition.

4.0 ECONOMIC REVIEW OF SUSTAINABLE MACHINING FOR AISI 4340

This section discusses how green lubrication affects the machining sustainability of AISI 4340 in relation to the economics of machining. Productivity is one parameter used for measuring economics of production (Bhanot et al., 2015). In metal cutting, productivity is largely determined by the effectiveness of machining and tooling strategies in removing excess material within the shortest period. Along with an increasing feed rate and a proper selection of cutting speed and depth of cut, an increased amount of metals can be removed at a low energy cost. However, the amount of tool wear in high contact areas during machining presents a problem. Therefore, if tooling cost is not significant to the producer, then the metal removing process can be completed by using higher-level of parameters to achieve increased productivity (Iqbal et al., 2015) .

By contrast, if the cutting tool poses a concern in measuring production cost, then an appropriate selection of cutting tools is vital to improve the overall machining performance. According to Gidi, (2015), an appropriate selection of cutting tools can reduce production costs by 15% and improve productivity by 20%. Ginting et al., (2018) compared the productivity of dry machining for two types of coated tools, namely, PVD and CVD. Machining in a dry environment is very challenging given the excessive temperature and tool wear. However, avoiding the use of cutting fluid can be a rewarding point that can motivate the application of dry machining. To compute productivity, the volume of material removal (VMR) and material removal rate (MRR) should be considered. These parameters can be computed as:

$$VMR = MRR \times T = (v.f.a) \times T \tag{1}$$

VMR	=	Volume of material removal (cm^3)
MRR	=	material removal rate (cm^3 / min)
V, f, a	=	Cutting speed (m/min), feed rate (mm/rev), depth of cut (mm)
T	=	Tool life (min)

Results show that the CVD-coated tool removes 78% to 125% more materials compared with the PVD-coated tool. However, the PVD-coated carbide tool has a longer machining time and tool life compared with the CVD-coated carbide tool. Therefore, to achieve a rapid material removal, the CVD cutting tool should be used. Meanwhile, using the PVD-coated carbide tool, which is suitable for light or finishing cuts, is preferred in scenarios where the user aims for a longer tool life and lower surface finish.

Al-Ghamdi et al., (2015) tested the AISI 4340 productivity (MRR) and specific energy in different machining environments. They calculated MRR by using the above formula and obtained the specific energy by dividing the average cutting force recorded in the experiments by the calculated MRR. By using fuzzy logic as their optimisation technique and 'minimise VB and minimise specific energy' as one of their objectives, Al-Ghamdi et al., found that the combination of MQL and CO^2 at the rake and flank faces shows the optimum value for the chosen objective. These findings prove that the combination of green cutting environment can be a suitable alternative for improving machining productivity compared with wet, dry and standalone coolant techniques.

5.0 SUGGESTIONS FOR FURTHER WORK

The best sustainable machining practice is yet to be identified as each process has its own pros and cons. The following recommendations for future studies are proposed based on the gaps identified in the literature:

(a) Compared with wet and dry conditions, MQL has been proven to yield better results in terms of tool wear, surface finish and cutting force. However, one major drawback of MQL is its inability to remove the heat generated at extreme parameters. Cryogenic cooling outperforms MQL, dry, and wet conditions in removing heat from the machining zone. Numbers of research have been published that demonstrate the effectiveness of combining these green machining methods especially MQL and Cryogenic techniques in improving the machinability of Inconel 718 and Titanium Alloy. Therefore, a hybrid green machining technique should be employed to address the inherent limitations of standalone coolant techniques. It, should improve the lubricating and cooling effects during the metal cutting process whilst simultaneously ensure a green machining environment that is in line with the pillars of sustainable machining. The cutting parameters can also be increased further to improve productivity by removing more metals within a short period without jeopardising the surface quality of the product.

(b) Only few studies have examined the machinability of hybrid coolant strategies in sustainable machining by using AISI 4340. Most studies have focused on the machinability of hard-to-cut materials, such as nickel alloy and titanium, in automotive and aerospace applications.

(c) Alloy steels, such as AISI 4340, are widely used in die and mould applications. The process of manufacturing mould and die starts with a rough machining of the pre-hardened work material. Afterwards, case hardening treatment is applied to improve wear resistance and to achieve sufficient hardness and toughness at the outer layer of the workpiece. With proper machining parameters, tooling and coolant strategies, the microstructure of AISI 4340 during machining can be altered, thereby allowing the formation of martensite to harden the subsurface layer of the alloy steel. Through this method, the conventional heat treatment can be excluded, thereby reducing the processing steps and cost.

6.0 CONCLUSIONS

The effectiveness of the sustainable machining of alloy steel AISI 4340 in green environments through dry, MQL and cryogenic cooling has been evaluated in this review paper based on the latest available literature. Sustainable machining is an alternative to conventional machining where zero or minimal cutting fluid is used to preserve the environment and reduce production costs. Each green cutting method is unique and should be properly chosen to achieve the desired objectives:

(a) Dry cutting - Based on the reviewed literature, a major advantage of dry cutting is that this approach is a very clean process. One consequence of not using cutting fluid is the high temperature build up at the cutting region resulting from the excessive friction during the shearing process, which tends to cause severe tool wear and premature tool failure that, in turn, affect product surface quality. To address the tool wear during dry cutting, many studies have examined the role of tooling strategies in improving the machinability of the entire process. WC-based cutting tools used for machining AISI 4340 can sustain machining at not more than 200 m/min. Meanwhile, alumina-based ceramic tools can withstand tougher cutting parameters but at a higher price in the form of tool cost. Therefore, some processes, especially in critical applications, continue to utilise cutting fluids to facilitate the manufacturing process.

(b) MQL - MQL, also known as near-dry cutting environment, uses a mixture of cutting fluid and delivers MWF directly to the cutting zone. In this way, MQL effectively lubricates the cutting surface and subsequently reduces the overall cutting force, improves the surface finish and extends the cutting tool life. However, at high cutting speeds, this protective layer no longer effectively lubricates the tool–chips interface. Moreover, the plastic deformation of the chips at high cutting speeds prevents the oil mist from penetrating the cutting regions. When the lubrication effect grows weak at high cutting speeds, the temperature at the cutting edge rises. Given these factors, the MQL cutting environment is not suitable for high cutting speeds. Under certain cutting conditions, when the oxide layer is absent, MQL becomes ineffective compared with dry or wet machining.

(c) Cryogenic - A cryogenic agent is applied in a machining process to reduce the cutting temperature at the tool–chips interface and to improve the wear properties of the cutting tool. With a reduced tool-tip temperature, applying cryogenic coolant in machining can effectively improve the surface integrity of AISI 4340, enhance the surface finish and reduce the geometrical deviations. The sub-surface layer of the machined surface also shows a fine grain structure, which suggests that the desired compressive residual stress can be induced during cryogenic machining. The microhardness value of the sub-surface is equivalent to the hardness of the case hardening steel and can therefore be used to improve the hardenability of a product. Another positive effect of temperature reduction is its potential to reduce the cutting force, thereby extending the tool life, reducing the tool wear and preventing catastrophic tool failure during machining.

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