Article:

Race, A., Zwierzak, I., Secker, J. orcid.org/0000-0001-9545-9970 et al. (4 more authors) (2020) Environmentally sustainable cooling strategies in milling of SA516 : effects on surface integrity of dry, flood and MQL machining. Journal of Cleaner Production, 288. 125580. ISSN 0959-6526

https://doi.org/10.1016/j.jclepro.2020.125580

Environmentally sustainable cooling strategies in milling of SA516: effects on surface integrity of dry, flood and MQL machining.

Adam Race[a], Iwona Zwierzak[a], Jack Secker[b,c], Jonathan Walsh[b,d], Julia Carrell[d], Tom Slatter[d], Agostino Maurotto[a*]

[a]*Nuclear AMRC,The University of Sheffield, Advanced Manufacturing Park, Rotherham, U.K. S60 5WG*
[b]*EPSRC IDC in Machining Science, The University of Sheffield, Mappin Street, Sheffield, U.K. S1 3JD*
[c]*Department of Chemical Engineering, The University of Sheffield, Mappin Street, Sheffield, U.K. S1 3JD*
[d]*Department of Mechanical Engineering, The University of Sheffield, Mappin Street, Sheffield, U.K. S1 3JD*

* Corresponding author. Tel.: +44-0114-2158013; *E-mail address:* a.maurotto@sheffield.ac.uk

Abstract

The recent move towards 'Environmentally Sustainable Manufacturing' (ESM) is leading heavy industries (e.g. oil & gas, nuclear) to explore low-impact manufacturing strategies. In machining, however, most processes are still performed using traditional cooling method using flood or high pressure lubricant emulsions. These emulsions are expensive in their maintenance and disposal, and present a significant environmental concern. This novel study combines evaluations of the performance of low-impact cooling strategies, such as dry milling or minimum quantity lubrication (MQL), in the manufacture of an industrially important pressure vessel carbon steel (SA516) using coated carbide inserts. Tool wear, surface roughness, residual stress and energy consumption were measured during metal cutting trials for each strategy and then compared. Likely tool wear performance when using candidate lubricants was screened prior to machining trials using standard tribological high frequency reciprocating tests. Significant improvements in surface integrity and tool wear were observed when machining with dry and MQL when compared with traditional flood coolant. Measured energy footprints for dry and MQL were also lower when compared to flood coolant machining providing cost savings and environmental advantages in manufacturing using ESM approaches.

Keywords: milling; residual stress; surface integrity; MQL; energy footprint; environmentally sustainable manufacturing

Nomenclature

a_p	depth of cut
f_z	feed per tooth
V_c	cutting speed
XRD	X-ray diffraction
Ra	arithmetic mean surface roughness
SSC	stress corrosion cracking

1. Introduction

Demands associated with global population growth will compel transformation in the manufacture and disposal of industrial and consumer products, with stricter regulations being imposed on manufacturers to reduce the environmental impact of their operations and product [1]. In key industrial sectors, such as oil & gas and nuclear, pressure vessel steels such as SA516 and SA508 are widely used in applications where a high structural integrity is required, due to their desirable mechanical properties. Their high strength and toughness, however, result in high cutting forces and consequently a noticeable friction heat output is generated during cutting operations. Removal or reduction of this heat is necessary as it negatively affects tool life and causes undesirable dimensional inaccuracies. This cooling is conventionally achieved by external flood coolant impinging onto the work-piece or high pressure coolant emulsion being sprayed directly at the work-piece cutting edge interface through the tool. It is widely understood by practitioners that the use of a coolant can reduce machining-induced surface damage and extend the cutting tool life [2], both desirable but are achieved with high environmental and economic cost.

Coolants are responsible for a significant proportion of these costs. Large coolant emulsion reservoirs are expensive to maintain and require constant monitoring to prevent contamination and bacterial growth. Spent coolant is also expensive to dispose of, environmentally harmful and poses a significant health hazard, particularly to the machine operators [3].

In order to achieve this, several alternatives to conventional coolants are currently being investigated, including cryogenic cooling, yet only a few are mature enough to be considered for mainstream production. One such alternative is minimum quantity lubrication (MQL). This technique is a robust and mature candidate, principally used in the automotive and aerospace industries [4][5]. MQL employs a lubricant aerosol delivered in proximity of the cutting zone to reduce the friction between the cutting tool and the work-piece [6]. This reduces heat generation allowing machining with a minimum quantity of lubricant without significant detrimental effects on tool life [7]. As MQL uses less oil and water compared to conventional flood cooling methods, it has a lower energy footprint thus reducing operational process costs.

Most research performed on MQL has focused on milling and turning processes both at a fundamental tribological level and at a machining level. In a study by Uysal et al. [8] tool wear and surface roughness were investigated in milling AISI 420 martensitic steel under; dry conditions, MQL using a vegetable oil cutting fluid, and MQL using a "nano" fluid. They showed that the MQL method could decrease the tool wear and surface roughness. Furthermore, due to the lubrication effect the addition of "nano" fluid resulted in minimum tool wear and surface roughness. A study by Dhar et al. [9] showed significant reduction in tool wear rate and surface roughness by turning with MQL mainly through reduction in the cutting zone temperature and favourable change in the chip-tool and work-tool interaction.

A review of MQL on difficult to machine alloys by Dureja et al. [10] observed improvements in surface finish when machining using MQL compared to dry machining. Tool life was improved without a noticeable increase in power consumption and there was a lower environmental impact i.e. less waste was produced in comparison to flood coolant. The review analysed the effects of MQL in machining of Inconel and other steels. In milling with MQL, improvements in tool life and suppression of burr formation was observed which also foresees potential increases in material removal rate (MRR). The observed reduction of cutting forces resulted in an extension of tool life thus less waste, moreover since only small quantities of oil were deployed to the cutting zone, less environmentally harmful waste had to be disposed of.

When considering the negative effects of the MQL process, Dureja et al. observed a difficulty in keeping a consistent flow rate, MQL did not readily remove cut material from the cutting zone and after the tool engaged with the work-piece it was difficult for additional fluids to enter the tool-work piece interface. Their review concluded that many oil additives commonly used in MQL fluids can be very reactive both under pressure and in the presence of moisture, and MQL fluid left on parts, cut material or machine tools could cause mild to moderate corrosion or staining. These negative effects should be prudently kept into account as they could affect surface finish and contaminate critical components in the absence of a clear strategy to address them. As an example, critical components in the nuclear industry like heat exchangers and control rods would need special attention to be protected from these issues therefore further work into this area is required to enable the implementation of MQL in heavy manufacturing.

Coolant can generally limit the amount of surface damage that occurs to the work-piece [11]. Since it directly influences corrosion and fatigue resistance, surface integrity is vital in the design of components for the nuclear industry [12]. Defects on the surface resulting from the milling process, such as cracks, are preferential sites for stress corrosion cracking (SSC) and can ultimately lead to the premature failure of the component when coupled with high residual stresses, especially important with the large castings common in these industries [13]. These stresses result from the non-uniform deformation during cutting: the material undergoes compressive deformation in front of the cutting tool and tensile behind it [14]. Leppert and Peng [15] studied machined layer residual stresses using different cooling conditions in turning AISI 316L stainless steel and found that cooling and lubrication had the highest influence on residual stress. Highest values of hoop and axial residual stresses were observed in turning with emulsion and the lowest in dry machining, while their values in cutting with MQL lay in between.

At present MQL is not commonly used, if at all, in the oil & gas and nuclear industries, particularly when compared to the automotive and aerospace sectors where it is widespread. As a result, there is a paucity of published research in this field, especially for the specific types of steels grades commonly used (e.g. SA508, SA516 and 304L), compared to the alloys widely used elsewhere (for example, aluminium alloy grades: 6061, A-390, stainless steel grades: 316L, AISI 4140, and hardened steel grades: AISI 4140, 4340). This study, therefore, evaluates the effects of commercially available synthetic oil and suitable vegetable-based oils (both designed for machining and also more general purposes) in MQL machining of a boiler/pressure vessel carbon steel SA516 gr. 70. The aim of this novel study is to inform practitioners, particularly in these industries, about the specific efficacy of these lubricating strategies, suggest a screening methodology to aid in selection, and assess the potential economic savings.

In this study, tribological tests were used to screen the selected candidate oils before using in MQL. The selected oils were then tested in a design of experiment trial in MQL machining to assess their effect on tool life and surface integrity. The analysis of tool life in terms of tool wear (*VB max*), work-piece average surface roughness (*Ra*), surface residual stress and a comparison of the machining energy footprint for the MQL system and the flood coolant system are presented in the following sections.

2. Materials and methods

2.1. Specimen & workpiece materials

Commercially available carbon steel SA516 Grade 70 plates (Brown McFarlane) of 250 mm (*W*) x 250 mm (*L*) x 70 mm (*H*) were used in the machining tests. The material was used in its 'as received' state, with no further metallurgical processing performed beyond that which is typically performed in the processing of this grade. The metallurgical composition of the plates used in this study is presented in Table 1. Material from the same plates were cut and ground into 70mm (*W*) x 25mm (*L*) x 4mm (*H*) samples for use in the tribometer tests.

Table 1. Chemical composition of SA516 Grade 70 plates.

Element (wt. %)									
C	Si	Mn	P	S	Cr	Ni	N	Co	Fe
0.153	0.38	1.45	0.010	0.0009	0.035	0.075	0.0062	0.226	Bal.

2.2. Lubricants

The investigated MQL lubricating oils are presented in Table 2. Other than a commercially available general purpose biodegradable synthetic oil for machining, all of the oils were vegetable-based. A commercially available vegetable-based oil for machining applications and pure vegetable oils were tested to investigate their efficacy and compared to the synthetic one. As soya bean oil is produced from natural sources it was expected to have compositional differences between harvests. In order to minimise this effect two oil batches were compared, a fresh batch and a 1-year-old batch. The addition of zinc dialkyldithiophosphate (ZDDP) to soya bean oil as an anti-wear additive was performed to assess its ability to improve tool life, as perhaps an equivalent for a general purpose oil to the 'performance additives' present in the commercial vegetable oil. ZDDP has been used in the automotive industry since the 1940s as a bearing corrosion inhibitor and also in high performance automotive lubricants as an anti-wear additive [16]. Soya bean oil and ZDDP (5% wt.) was mixed at 200 rpm for 5 minutes using a torque-limited mixer.

Table 2. Lubricant oils tested.

Oil Name	**Type**
SKF LubriOil	Biodegradable synthetic oil
Wysecut VNX 32	Vegetable oil with performance additives
Soya Bean Oil (Fresh) (SBOf)	Vegetable oil (fresh batch)
Soya Bean Oil (1 year old) (SBOo)	Vegetable oil (1 year old batch)
SBO (Fresh) with ZDDP	Vegetable oil with anti-wear additive

2.3. Tribometer experimental setup

The tribological responses of the selected oils were investigated in a reciprocating sliding contact (under severe contact conditions) with a high frequency reciprocating tribometer (Plint/Phoenix Tribology TE77). The samples were cleaned with acetone to remove excess material and oil and their mass was measured three times with a precision mass measurement scale (± 0.00005 g) and the mean was taken. The specimens were mounted in a 15 ml 'lubricant bath' maintained at 70 °C, ensuring the surface of the sample was completely covered. A 6 mm diameter, AISI 51200 grade chrome steel ball (average surface roughness, Ra = 0.03 µm) was fixed into the holder and lowered onto the surface of the coupon. Experimental set up is shown in Figure 1 [17].

A 40 N load was applied through the ball, providing an initial Hertzian contact pressure of approximately 1.4 GPa. Maximum stroke length was set to 15 mm to achieve a large displacement for film formation. Frequency of reciprocation set to approximately 4.3 Hz and ran for 30 minutes with the friction force data recorded by means of the force transducer positioned normal to the applied load. The oil was drained, system cleaned, fresh oil poured in and the ball replaced. This test was repeated three times, equally spaced on each coupon, creating three parallel scratches on the coupons. The coupon was then removed and system thoroughly cleaned before repeating the tests for all oils.

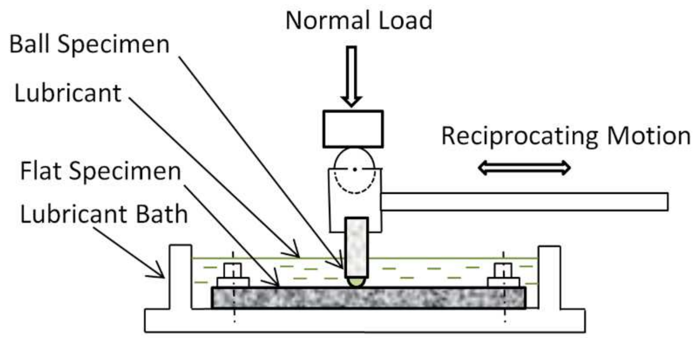

Figure 1 - Reciprocating motion of ball on flat specimen in lubricant.

A 3D non-contact profilometer (Alicona Infinite Focus SL) was used to measure wear scar geometry and internal surface roughness. The surface roughness was taken along the length of the wear scar near the centre (again to remove the issue of the stationary ends).

2.4. Machining experimental set up and cutting conditions

This work is a comparative study between conventional lubricating strategies and MQL and aims to identify the benefits of employing MQL instead of flood coolant as a direct substitute for a particular process. As production processes are relatively codified and significant changes in cutting strategies would warrant for additional costs, it was deemed appropriate and interesting to focus on comparing coolant emulsion and MQL even in non-optimised condition for MQL i.e. for conditions optimised for conventional lubrication strategies. The design of experiment selected aimed to investigate the effects of different oils and flow rates at fixed speed, feed and depth of cut in face-milling. A more complex design of experiments approach with multiple cutting speeds/depths and feeds would have inevitably shifted the topic of this study toward the effects of machining parameters rather than lubricant effects and cost/energy comparison.

The experimental work was carried out on a 3-axis vertical milling machining centre (Hartford LG500) with a maximum spindle speed of 12,000 rpm and a spindle power of 5.5 kW. The plates used in the experiments were fastened to a vice (Hilma NC 125) fixed horizontally to a tombstone block. Figure 2a shows the experimental setup for face-milling of SA516 carbon steel plates. The machine centre was retrofitted with a single channel MQL system (SKF Digital Super). This system pre-mixes the lubricant and air into an aerosol before sending it through the spindle to the tool. This unit can provide flow rates from 5 ml/h to 200 ml/h but the maximum amount is upper limited by the coolant duct diameter in the tool. In our tests, the 3 mm coolant duct diameter in the tool used for this study restricted the maximum flow rate to 45 - 50 ml/h. In the machining tests, through tool flood coolant was delivered at 900-1080 l/min at 20 bar pressure.

A spiral toolpath with a tool engagement of 60% was used to machine the plates in several passes. This was carried out to reduce the tool damage caused by repeated engagement by limiting the amount of time out of cut. The cutting tool selected was the Ø40 mm Coromill 300 face mill cutter (R300-052C-12M) with a C5-390B555-40-090 holder fitted with a BIG-PLUS MAS-BT to Coromant Capto Adaptor from Sandvik Coromant. This tool allows four cutting indexable inserts. The R300-1240E-PL grade 4240 carbide inserts, coated with Ti(C, N)+Al2O3+TiN were used in the machining trials. The selected cutting conditions were: 2 mm depth of cut, a cutting speed (Vc) of 277 m/min and a feed rate (fz) of 0.268 (mm/tooth).

These particular cutting parameters were selected because they represented those typically recommended for medium and finish cuts on this type of work-piece material. This was considered to be ideal as the surface finish related effects of the lubricant strategy would be left on a large surface of work-piece (and it follows that using conditions used in rough machining would not provide useful indication of the effects on the surface of a finished part). As the focus of the experiments was to compare the lubricant strategies, the cutting conditions were kept constant throughout to minimise the size of the experimental design (as is typical when designing screening tests) and to enable the geometry of the cutting inserts to be kept constant (and therefore optimal). Different tool and insert geometries would be required to perform tests with significantly different cutting parameters and this would render comparison of the results difficult. Furthermore, the combination of cutting parameters used was suitable for all the coolant strategies taken into account without significantly penalizing any.

The aim of the cutting trial was to compare tool life for each strategy without reaching catastrophic failure conditions. The software tool provided by the tooling insert manufacturer (Sandvik Coromant), was used to select a combination of parameters that would warrant a theoretical tool life (and thus tool condition likely to be ‘worn’ but not to have completely ‘failed’) of 28 minutes when using coolant emulsion. Given the possible tool life changes that would result by using MQL it was decided that each cutting test would be set up to run 24 subsequent passes, with no pausing, equivalent to 28 minutes and 24 seconds of machining time. This was deemed sufficient to achieve measurable damage without risking complete failure. The cutting experiments were started with the dry cutting strategy, moved to flood coolant and eventually to MQL with the four selected oils.

Tool life analysis was conducted according to ISO 8688-1:1989. The measurement of the tool wear was performed using a Nikon Shuttlepix P-MFSC camera. Flank wear was measured from the top of the damaged area to the edge of the tool. A continuation of the edge line based on the geometry of a new tool was used as a guide. Figure 2b (an unworn tool edge) and 2c (a worn tool edge) illustrate this approach.

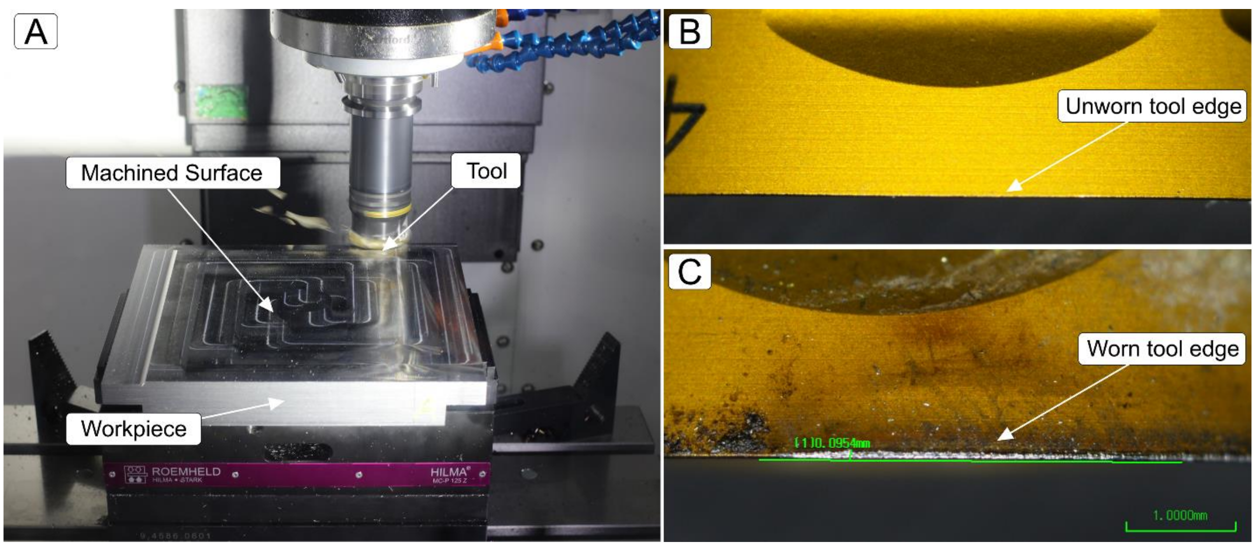

Figure 2 - Typical experimental setup for the machining trials (a), unworn tool edge (b), and worn tool edge (c).

Surface roughness measurements were carried out in accordance with ISO 4287-1997 Surface texture: Profile method [18]. To measure the surface roughness on the machined surfaces, a Mitutoyo stylus surface roughness tester (SJ-410 / standard ISO4287:1997) was used. Measurements for mean roughness (*Ra*) were taken at five different locations across the surface of the plate as shown in Figure 3, it should be noted that these measurement areas were selected to follow the spiral toolpath and when averaged minimise the noise of the measurement. The residual stresses were determined using a laboratory based x-ray diffraction (LXRD) residual stress measurement system supplied by Proto Manufacturing. A mono-chromatic Cr K-alpha radiation was used with an accelerating voltage of 25 kV a current of 25 mA and an aperture of 1 mm diameter. The stress analysis was carried out based on the sin2ψ method. The residual stresses were measured in the transverse (φ=0°) and the longitudinal (φ=90°) directions. Data for each sample were collected at four locations each separated by 20 mm, along a line that was coincident with the path of the centre of the milling tool.

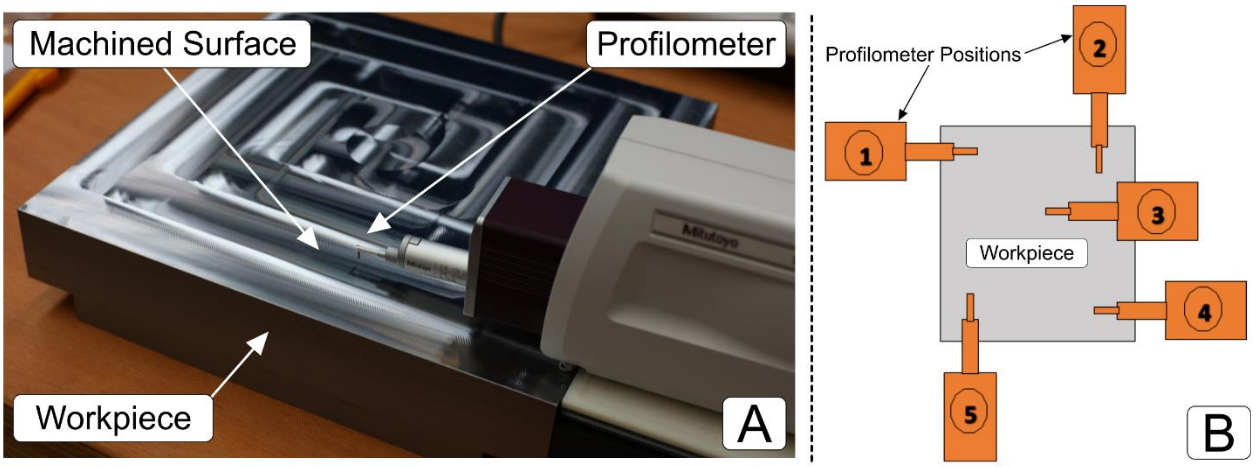

Figure 3 - Surface measurement setup (a) and measurement locations (b).

The energy measurements were performed online during cutting using a Fluke 1730 Three-Phase Energy Logger. The device was connected to the Hartford LG500 milling machine three phase service cable to measure the electric power usage.

3. Results and discussion

3.1. Reciprocating wear tests

From the mass loss data, it is difficult to see significant difference in performance between the lubricants apart from a slight increase in the mass loss when using the commercially available vegetable oil based machining oil (0.00296 g). This would suggest the generation of the wear scar is mainly from a ploughing action where material is moved plastically away from the contact zone, but remains part of the specimen, rather than completely removed as wear debris.

The ploughing action can be seen in the surface scans of the wear scars as material was pushed to the edges, leaving a raised border (thin line surrounding grooves in Figure 4). The wavy pattern throughout the length of the scar has been seen in previous studies by the authors and is particularly likely in the higher contact pressures and lubrication states seen in these tests, resulting in plastic ratcheting and shakedown [17], [18]. Both fresh/new and 1-year-old batches of SBO were similar in appearance, and, when combined with ZDDP, SBO performed similarly to the commercially available synthetic machining oil, so are not included in Figure 4.

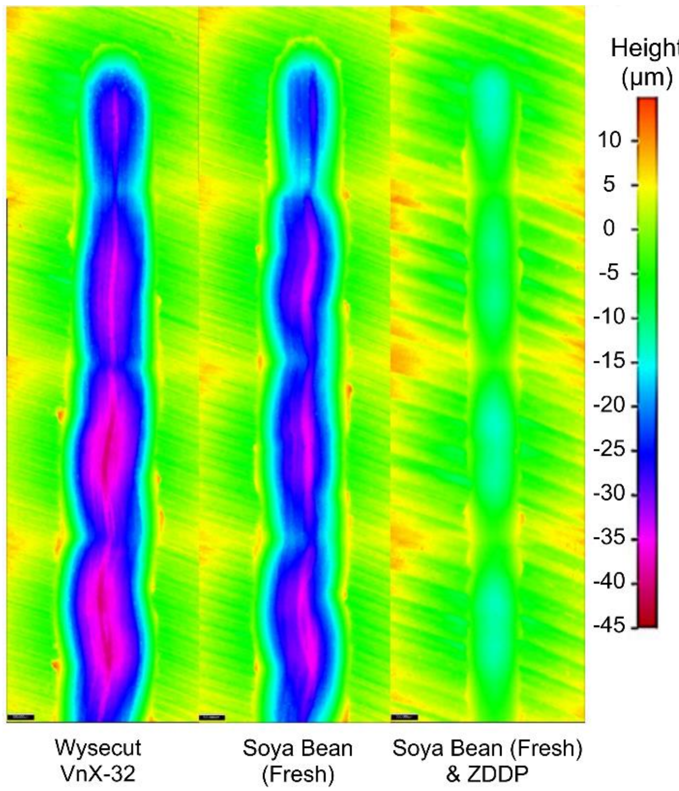

Figure 4 - Example wear scars from non-contact profilometer analysis.

Both batches of soya bean oil (SBO) performed similarly, producing almost identical wear scars, indicating little sensitivity of wear mechanism to the aging of the oil or any potential difference in feedstock source. Further chemical analyses would be required to formally characterize any formulaic difference. The addition of ZDDP reduced the size of the scar, indicating improved tribofilm formation. Wysecut VNX-32 produced the largest wear scar, both in depth and width. This in accordance with the mass data where lubrication by Wysecut VNX-32 oil led to a higher material removal. Measurement data for the surface roughness of the resulting scar is shown in Figure 5. In machining, surface roughness is usually used to gauge the quality of the cut as under harsh cutting conditions (high temperature and non uniform pressure) the surface quality tends to decrease. However, from the previous data the high surface roughness indicates tribofilm formation allowing separation of asperities and therefore less smoothing due to ploughing. It is also interesting to note, that surface roughness appears to be more sensitive to the batch of the soya bean oil compared to senstivity of wear mechanism. Caution should be taken, however as there are issues with this measurement technique: small surface artifacts on the tested metal samples can have a large effect on scar results (thus the large difference between SBO batches).

This data was then used as a method of screening the performance of the lubricants to then further test a subset with the machining trials.

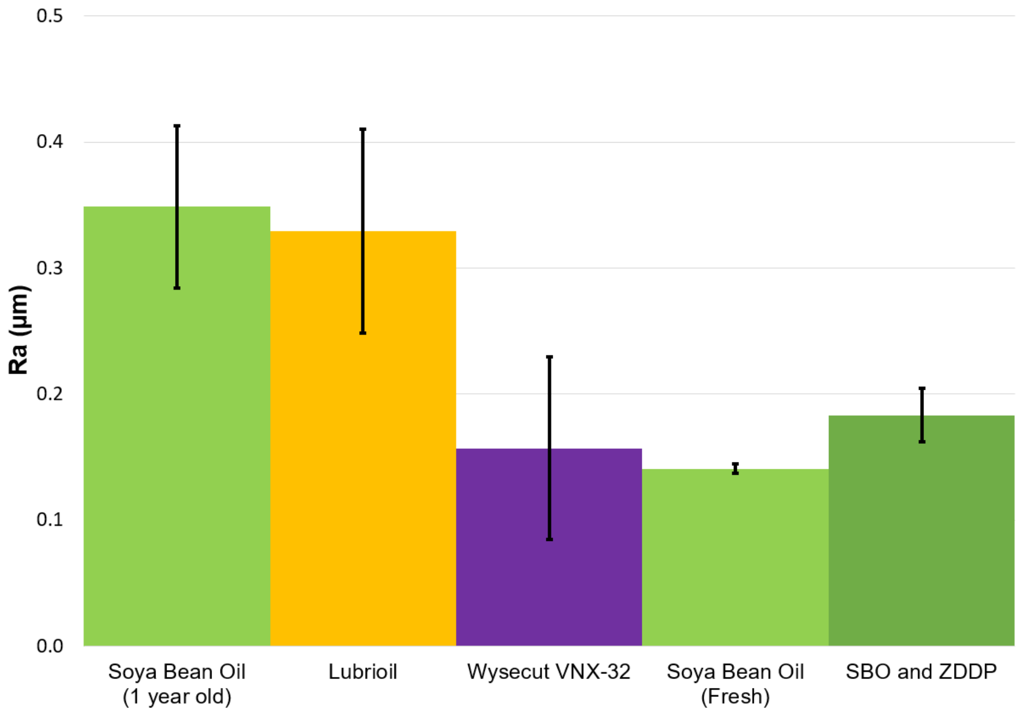

Figure 5 - Average surface roughness in the reciprocating wear scars.

3.2. Tool wear trials

Figure 6 collates the tool wear measurements under dry, flood coolant and MQL (using the four different oils detailed in Table 2). The average flank wear (VB_{max}) across all four inserts was measured using 300 µm as a tool failure criterion as it is the value generally accepted for finishing operations.

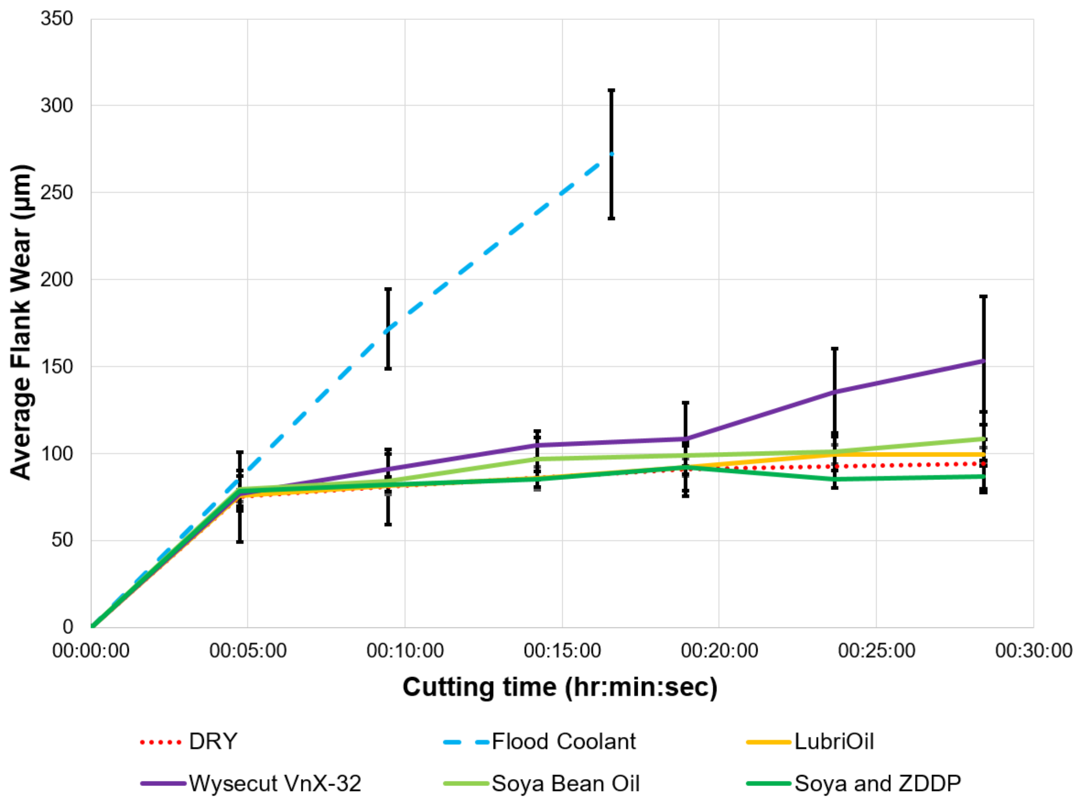

Figure 6 - Tool wear progression under dry, flood and MQL conditions.

As stated previously, the depth of cut, tool engagement, feed rate and cutting speed were constant for the whole trial. It is possible, therefore, to easily and directly compare the effect of the different oils on tool wear. In Figure 6 it is shown how flank wear was noticeably greater with through tool flood coolant than MQL and dry machining. The flood coolant machining tests had to be stopped due to inserts prematurely reaching the failure criteria at 16 minutes and 34 seconds. These inserts are shown in Figure 7 . This was deemed a result of thermal cracking due to the quenching effects of the flood coolant. Thermally induced cracks are common in milling operations as the inserts are subject to strongly alternating thermal stresses and are aggravated by the use of coolant.

Flank wear observed using Wysecut VNX-32 as an MQL oil started to diverge from those observed with the other MQL oils after 18 minutes of cutting time. Measured flank wear increased relatively slowly for the other MQL oils and for dry machining, there was also no observable statistical difference between them. However, in the final run soya bean oil with ZDDP was best performing, producing a 20% decrease in tool wear compared to pure soya bean oil. Wysecut VNX-32 resulted in a final flank wear of 153.43 µm which was 29% higher than the second worst performing oil (soya bean oil). This matched the increased wear when using Wysecut VNX-32 and the positive influence of ZDDP found in the previous reciprocating wear results.

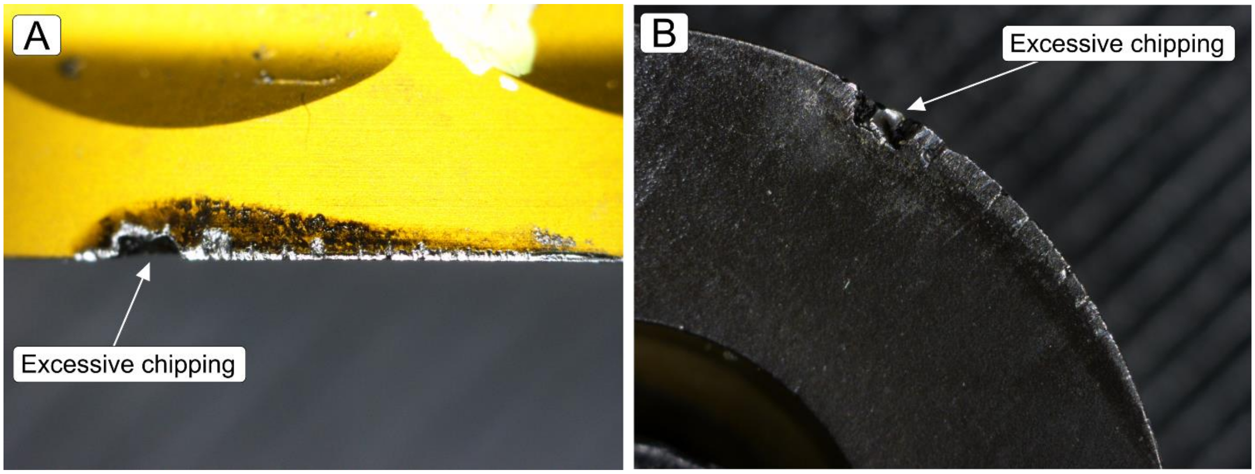

Figure 7 - Excessive chipping of flank (a) and rake (b) wear observed while using flood coolant (Insert C).

Surface roughness measurements are shown in Figure 8 (obtained midway during machining at 14 minutes and 12 seconds) and Figure 9 (obtained at end of machining at 28 minutes 24 seconds). In Figure 8 it is important to remember that the through tool flood coolant trial was stopped at 16 minutes and 34 seconds due to severe flank and rake wear. The surface roughness results showed that dry machining had slightly higher average roughness compared to through tool flood coolant and MQL. The lowest roughness was achieved with Wysecut VNX-32 in MQL. The lowest roughness at the end of machining was achieved with soya bean oil with 2% ZDDP in MQL. Results were similar to those seen in the reciprocating wear tests. Further work would be required to fully ascertain the validity of using surface roughness measurements in this way to screen candidate oils given the change in ranking as testing progressed. This may be as a result of the changing contact geometry, and thus its interaction with the lubricant, as tool wear evolves.

At the end of each trial the temperature of a dry machined plate was empirically observed to be higher than these of plates machined with flood or MQL. MQL plates were slightly warm to touch and through tool flood coolant plates were cold.

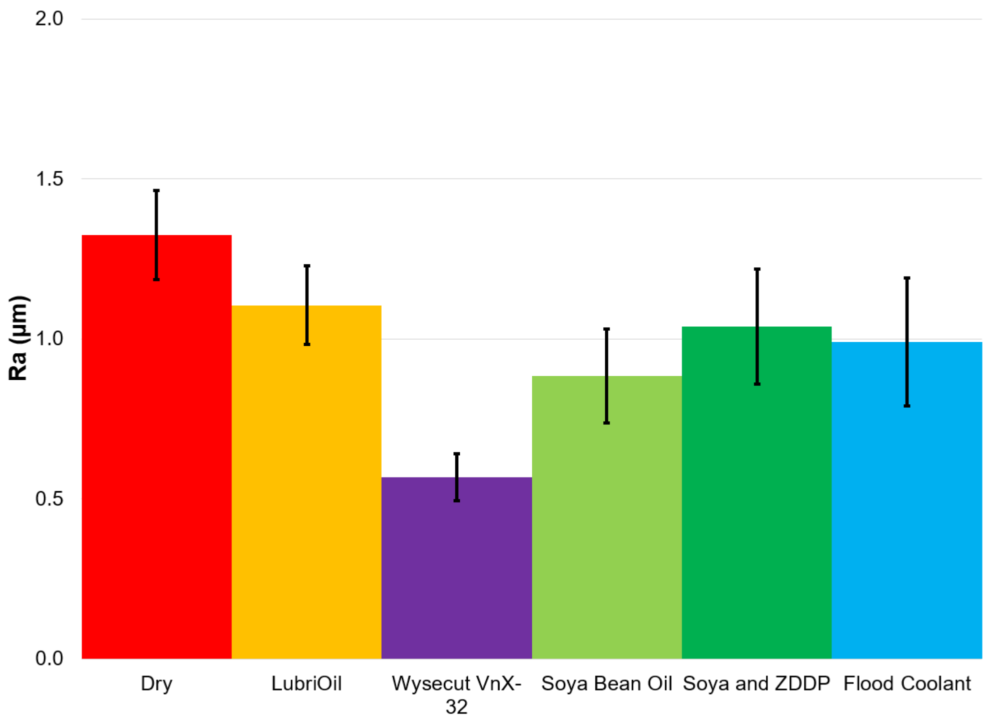

Figure 8 - Surface roughness of plates midway the machining tests.

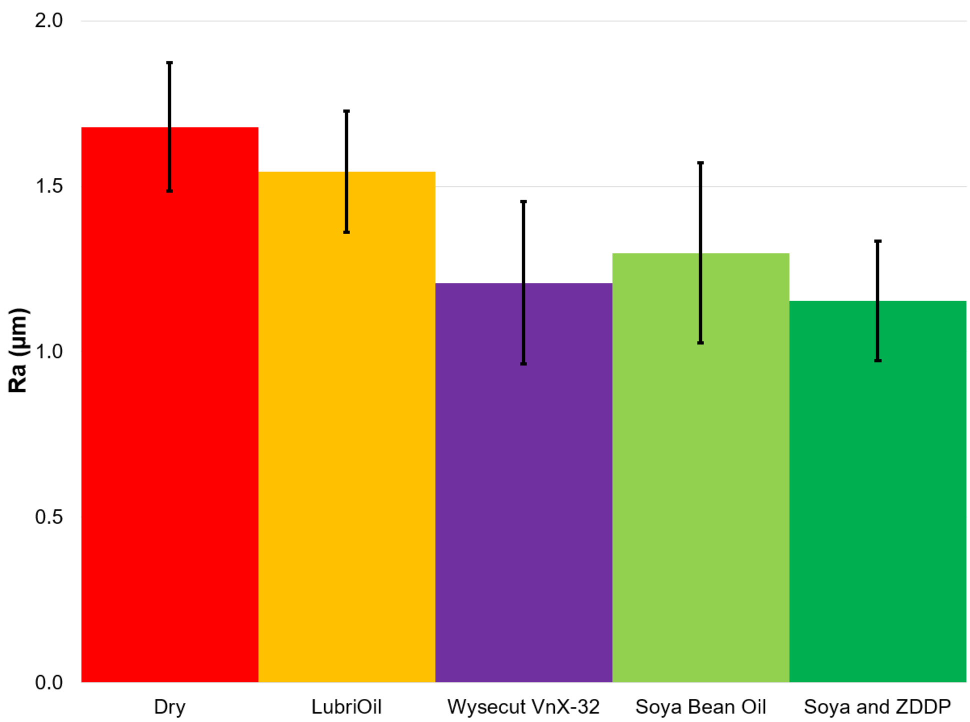

Figure 9 - Surface roughness plates at the end of machining tests.

3.3. Surface residual stress

The residual stresses measured in both the longitudinal and transverse directions are presented in Figure 10 and Figure 11. It should be minded that the flood coolant trial was stopped at 16 minutes and 34 seconds due to severe flank and rake wear. Wysecut VNX-32 and Soya bean oil with ZDDP were ruled out of the residual stress measurements due to time constraints.

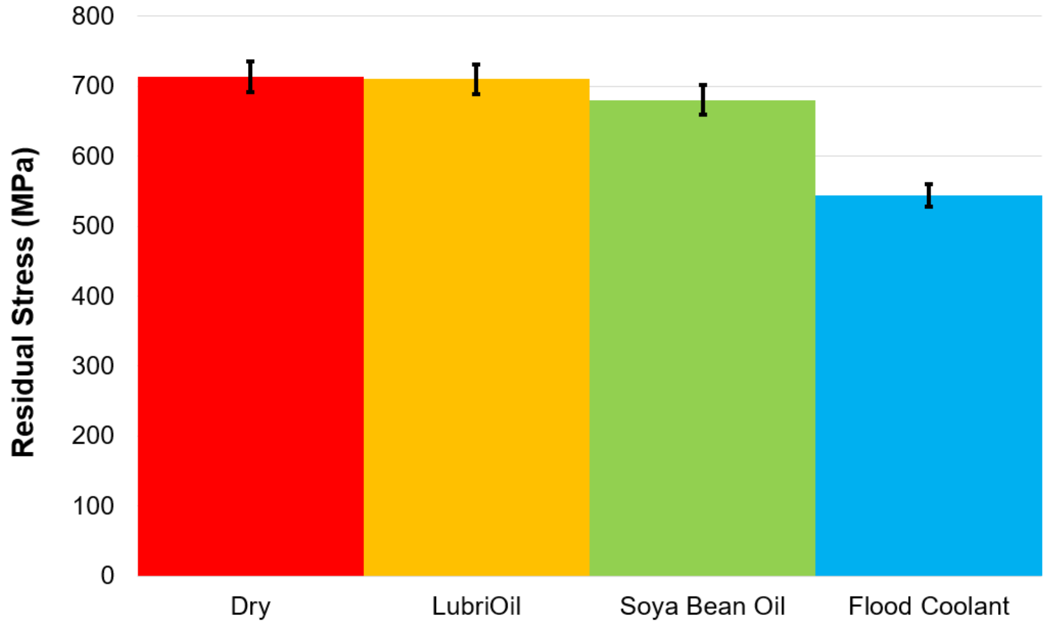

Figure 10 - Longitudinal residual stress in milling with different machining strategies.

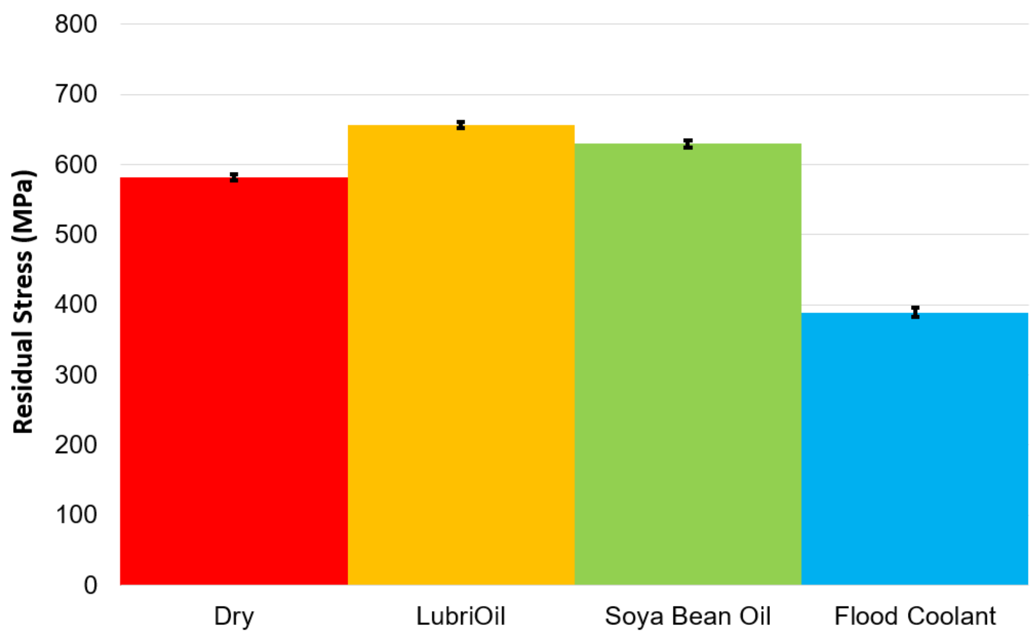

Figure 11 - Transverse residual stress in milling with different machining strategies.

The measured residual stresses were all tensile as it is commonly observed in steel cutting, however their magnitude varied, depending on the lubricant used. The spread of longitudinal stress were smaller, ranging from 544 to 714 MPa (a difference of 170 MPa), than those of transverse stresses, varying from 389 to 656 MPa (a difference of 267 MPa). Elimination or type of cooling fluid in the milling process resulted in changes in the magnitude of residual stresses both in the longitudinal and transverse directions. The lower magnitude of the surface residual stressed observed with flood coolant could be explained by the reduced thermal load on the machining surface, resulting in mechanical effects dominating over thermal ones, ultimately reducing the tensile stress on the surface. Further research into residual stresses of deeper layers could offer a better understanding of the effects of lubrication.

3.4. Energy footprint comparison

Energy saving was noticeable when using MQL, reducing the machining energy footprint by one fifth. An electrical energy logging device (Fluke 1730) recorded in energy consumption data continuously throughout this work. The average peak power for four machining runs was 6.98 kW for flood coolant and 5.51 kW for MQL. There was a statistically significant (two-tailed P=0.02) 1.5kW difference between MQL and flood coolant which was attributed to the coolant recycling and circulatory pumps. These pumps were switched off as they were not necessary while running the dry or MQL machining. With MQL the significant environmental concern generated by the need of a safe disposal of the spent coolant was also eliminated as well as the need to employ biocides and chemical stabilisers to keep the coolant in good working conditions. In this study, MQL appeared to be a valuable low-impact machining technique offering both cost saving and environmental advantages.

3.5. Cost comparison of coolants

A simple annual cost comparison between conventional flood coolant and MQL was calculated to quantify the cost benefits by employing the latter. Running costs for one year were calculated for a medium-sized conventional machining centre, commonly used in manufacturing, with an annual utilisation of 352 hours of machine time. Table 3 highlights the key annual costs calculated for through tool flood coolant and MQL.

The energy cost was calculated using the measured total power consumption for each coolant strategy over an average year of operation and by multiplying it by the specific cost of electricity (0.133 £/kWh) as supplied from the UK's grid. The maintenance costs were calculated in a similar fashion: the time required for maintenance activities was based on the number of components used for each system and subsequently multiplied by the basic cost rate for a maintenance engineer (80 £/h). The cost calculation for the coolant emulsion was based on a 12% concentration of Hocut 795N for the 237 litres of coolant required to fill the machine as recommended by its manufacturer. A coolant life of 6 months was assumed (typical for this machine type and usage) thus it was costed as being completely replaced once (i.e. two complete disposals per year, the cost of which was calculated as part of a multi-machine disposal process). The oil cost for MQL was based on the basic cost of Wysecut VNX-32 multiplied by the annual consumption (based on the set flow rate of 50 ml/hr and 352 hours of machining time), it is understood that further savings could be achievable by using pure vegetable oils. Given the savings calculated for this machine centre (approximately 50%), the MQL system's capital and installation costs would be fully recovered in 1345 hours of machining.

The cost model did not include the standby of the machine, overnight power costs and cost of water for coolant emulsion (as it was negligible). It also did not include the productivity improvement cost reductions due to tool wear extension which would further push the advantage toward MQL (Table 3).

Table 3. Cost comparison of through tool flood coolant vs MQL.

Through tool flood coolant	**Cost (£/h)**	**Minimum quantity lubrication (MQL)**	**Cost (£/h)**
Power: for cooling units/pumps. 28900 kWh / year (pumps, high pressure coolant skids, etc.)	10.92	Power: for CNC machine and MQL system. 25800 kWh / year (coolant pumps not in use)	9.75
Time required: 30 hours per year filling / topping off / inspection / maintenance / set-up time	11.08	Time required: 4 hours per year filling / topping off / maintenance	1.25
Fluid medium oil: (7 litres per year)	0.71	Fluid medium oil: 17.6 litres per year	0.54
Waste coolant disposal: (2x year)	0.52		
Total	23.23		11.54

4. Conclusions

From the work presented here, the following main conclusions can be drawn:

1) Adding ZDDP to soya bean oil, regardless of the batch of oil used, improved its performance as a lubricating oil when machining with MQL.
2) Tool wear under dry and MQL machining was significantly lower than when using flood coolant. The presence of ZDDP improved the reduction of tool wear when using soya bean oil by a further 20%.
3) Surface roughness appeared to be little influenced by the lubricating properties of the oils tested.
4) Residual stress was lower for flood coolant than for the other lubricating strategies used.
5) Statistically significant ($P = 0.02$) energy saving in excess of 20% was observed in machining with MQL.
6) Per-hour operation costs with MQL were calculated to be approximately 50% of those when using flood coolant in this cutting configuration.

Acknowledgements

The authors would like to acknowledge financial support from the U.K. High Value Manufacturing Catapult (HVMC), EPSRC (EP/L016257/1) and tooling support from Sandvik Coromant.

References

[1] M. Tennant, "Sustainability and Manufacturing," *Foresight, Gov. Off. Sci.*, 2013.

[2] F. Jiang, J. Li, L. Yan, J. Sun, and S. Zhang, "Optimizing end-milling parameters for surface roughness under different cooling/lubrication conditions," *Int. J. Adv. Manuf. Technol.*, vol. 51, no. 9–12, pp. 841–851, 2010.

[3] M. Soković and K. Mijanović, "Ecological aspects of the cutting fluids and its influence on quantifiable parameters of the cutting processes," *J. Mater. Process. Technol.*, 2001.

[4] B. L. Tai, D. A. Stephenson, R. J. Furness, and A. J. Shih, "Minimum Quantity Lubrication (MQL) in Automotive Powertrain Machining," *Procedia CIRP*, vol. 14, pp. 523–528, Jan. 2014.

[5] K.-H. Nguyen, T., Nguyen, D., Howes, P., Kwon, P., Park, "Minimum quantity lubrication (MQL) using vegetable oil with nano-platelet solid lubricant in milling titanium alloy," p. 20159466, 2018.

[6] A. Filipovic and D. A. Stephenson, "Minimum quantity lubrication (MQL) applications in automotive power-train machining," *Mach. Sci. Technol.*, vol. 10, no. 1, pp. 3–22, 2006.

[7] V. N. Gaitonde, R. S. Karnik, and J. P. Davim, "Minimum Quantity Lubrication in Machining," *Sustain. Manuf.*, no. November, pp. 79–110, 2013.

[8] A. Uysal, F. Demiren, and E. Altan, "Applying Minimum Quantity Lubrication (MQL) Method on Milling of Martensitic Stainless Steel by Using Nano Mos2 Reinforced Vegetable Cutting Fluid," *Procedia - Soc. Behav. Sci.*, vol. 195, pp. 2742–2747, 2015.

[9] N. R. Dhar, M. Kamruzzaman, and M. Ahmed, "Effect of minimum quantity lubrication (MQL) on tool wear and surface roughness in turning AISI-4340 steel," *J. Mater. Process. Technol.*, vol. 172, no. 2, pp. 299–304, 2006.

[10] J. S. Dureja, M. Dogra, H. Singh, and M. Bhatti, "A review of near dry machining / minimum quantity lubrication machining of difficult to machine alloys," no. August, 2016.

[11] A. Maurotto, D. Tsivoulas, and M. G. Burke, "Surface integrity in dry milling of 304L steel: A parametric study," in *Procedia CIRP*, 2014.

[12] S. Ghosh and V. Kain, "Microstructural changes in AISI 304L stainless steel due to surface machining: Effect on its susceptibility to chloride stress corrosion cracking," *J. Nucl. Mater.*, 2010.

[13] W. Li, Y. Guo, and C. Guo, "Superior surface integrity by sustainable dry hard milling and impact on fatigue," *CIRP Ann. - Manuf. Technol.*, 2013.

[14] F. Klocke, E. Brinksmeier, and K. Weinert, "Capability profile of hard cutting and grinding processes," *CIRP Ann. - Manuf. Technol.*, 2005.

[15] T. Leppert and R. L. Peng, "Residual stresses in surface layer after dry and MQL turning of AISI 316L steel," *Prod. Eng.*, vol. 6, no. 4, pp. 367–374, Sep. 2012.

[16] D. Johnson, "The Tribology and Chemistry of Phosphorus- Containing Lubricant Additives," 2016.

[17] A. Bahari, R. Lewis, and T. Slatter, "Friction and Wear Phenomena of Vegetable Oil–Based Lubricants with Additives at Severe Sliding Wear Conditions," vol. 2004, 2018.

[18] ISO 4287, "Geometrical Product Specifications (GPS) -- Surface texture: Profile method -- Terms, definitions and surface texture parameters," *Int. Organ. Stand.*, p. 25, 1997.