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Tribological and Morphological Study of AISI 316L Stainless Steel during Turning under Different Lubrication Conditions

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Abstract: Due to growing environmental concerns and economical and social problems in manufacturing sectors, there is a huge demand for the substitution of existing cutting fluids. Further, the cutting fluids selected are expected to reduce the cutting force, improve the surface roughness and also minimize the tool wear during machining operations. Hence, this paper discusses the tribological and morphological behaviour of AISI 316L stainless steel while turning under minimum quantity lubrication (MQL) such as oil–water emulsion, mineral oil, simarouba oil, pongam oil and neem oil based on Taguchi L_{25} orthogonal array. From the extensive experimentation, it was observed that neem oil MQL with cutting speed of (140, 140, 60 m/min), feed of (0.30, 0.20, 0.10 mm/rev) and depth of cut of (1.0, 1.0, 1.0 mm) resulted in the lowest surface roughness (0.36 µm),cutting force (235.34 N) and tool wear (100.32 microns), respectively. Further, main effects plots and analysis of variance (ANOVA)can be successfully used to identify the optimum process input parameters and their percentage of contribution (P%) on the output parameters during turning of AISI 316L steel under MQL applications. The results clearly indicate that from both an ecological and economical standpoint, neem oil is the most effective lubricant in reducing cutting forces, tool wear and surface roughness during turning of AISI 316L stainless steel under MQL.

Keywords: AISI 316L stainless steel; cutting force; surface roughness; tool wear; TDOE; ANOVA

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1. Introduction

Today among various types of engineering materials, AISI 316L stainless steel is one such material which is used as an industrial structural material, viz., in automobiles, atmospheric distillation structures, aircraft and marine structures due to its excellent properties such as modulus of elasticity, toughness, corrosion resistance, durability, malleability, yield strength, shear modulus, weldability and thermal expansion [1–3]. However, while machining metals and alloys, the extreme heat and forces generated, result in maximum surface roughness and an increased risk of tool wear [4–6]. Weinert et al. [7] concluded that cutting fluids are the most popular method in the mechanical sector for controlling tool–workpiece friction and temperature during the machining of metals and alloys. Further, they also suggested that the use of cutting fluids resulted in a negative impact on both the environment and human health. Due to environmental concerns, the metal cutting industries are in search of a technology that reduces the use of lubricants during the process of the machining of metals, reducing water pollution, land pollution, waste management, harmful air emissions, and natural resources and raw material depletion [8,9]. Tawakoli et al. [10] suggested that an efficient system of cutting fluid supply on to the chip–tool interface to reduce the cutting fluid consumption and increase the productivity is very much essential. They also suggested that MQL emerges as a viable alternative that may be thoroughly considered to achieve the desirable and optimal results. It was discovered that concerns regarding the environment, health, safety and cost of cutting fluids during metal machining resulted in the increase in manufacturing cost [11]. Hadad et al. [12] concluded that during machining operation, minimal quantity lubricant (MQL) can be the alternative for dry machining. Sadeghi et al. [13] suggested that the application of cutting fluids while cutting difficult-to-cut materials results in increased tool life and better surface characteristics. K. M. Li [14] suggested that minimum quantity lubrication is an appealing option as it combines cooling functionality with exceptionally low fluid consumption. Sharma et al. [15] reported that in many circumstances, small amounts of oil are sufficient to reduce tool friction and avoid material adhesion. Further, they also suggested that during MQL application, lubricant flow ranging from 5 to 500 mL/h at pressures ranging from 2 to 8 bar and nozzle position at the chip–tool interface zone had a significant impact on process output parameters. Attanasio et al. [16] concluded that when the nozzle was projected on the rake face of the cutting tool, there was no evidence of cutting fluid on the machining zone; however, when the nozzle was projected on the flank faces of the tool, there was better cutting fluid penetration. Obikawa et al. [17] concluded that 45° nozzle orientation on both the horizontal and vertical planes was the optimum choice for decreasing tool–work friction. Karthik et al. [18] concluded that lubrication pressure at 0.4 to 0.6 MPa lowered tool life and improved surface finish under MQL application."Mineral based lubricants are considered pollutants because they emit significant amounts of particulate matter (PM), carbon monoxide (CO), and sulphur dioxide (SO_2), all of which have a negative impact on air quality" [19–25]. Abadalla et al. [26] carried out turning of stainless steel 316L using MQL. They suggested that MQL application resulted in less residual stresses compared to flood cooling. Various authors [27–29] reported the reduction in the coefficient of friction on the tool rake face and chip thickness ratio during machining of AISI 316 stainless steel under MQL application. Hossain et al. [30] concluded that the application of MQL had optimized and reduced surface roughness significantly compared to flood lubrication using both conventional and non-conventional cutting fluids in turning operation. Ibrahim et al. [31] suggested that the addition of zinc oxide (ZnO) nanoparticles with vegetable oil (rice bran oil) has been found to reduce cutting forces by about 10.68–18.48%, tool wear by about 9.33–51.96% and surface roughness by 3.86–12.84%. Javid et al. [32] concluded that SiO_2 nanofluids-based minimum quantity lubrication (NF-MQL) improves surface roughness by 28.34% and MRR (material removal rate) by 5.09% over conventional MQL. Nareshbabu et al. [33] concluded that the addition of silver nanofluids in MQL reduced cutting forces, wear and surface roughness while turning SKD 11 steel. Arsene et al. [34] found that a strong anti-wear and anti-friction film was formed in the interface when corn oil is used as lubricant in MQL turning of AISI D2 steel. This improved surface roughness and tool life by 15–20%. The research on cutting force, tool wear and surface roughness has been the easiest way of understanding the machinability characteristics of alloys under MQL [35]. Taguchi's Design of Experiments is an important statistical tool used for optimization of multiple input parameters in experimentation. These techniques use three or more levels of fractional factorial designs to conduct the experiments. However, Taguchi has presented a number of significant new methods of the conceptualizing of an experiment that have proven to be incredibly beneficial, particularly in the fields of product development and industrial engineering [36–38]. However, there has been no effort conducted to measure the surface characteristics, cutting forces, tool wear and microstructural changes during turning of AISI 316 stainless steel under MQL comparing using five different lubricants. Hence, this paper deals with the tribological and morphological study for optimization and microscopic analysis of the machined surface during turning of AISI 316 stainless steel under MQL application using five different lubricants.

2. Methodology

The experiments were carried out using a PSG A141 lathe (2.2 kW) using Cubic Boron Nitride inserts (KB-90)under MQL condition (Figure 1) having principal rake angle (0°), nose radius (0.4 mm),approach angle (91°) and clearance angle (7°) while turning AISI 316L stainless steel. During MQL application, the various lubricants (Figure 2) (oil–water, mineral oil, simarouba oil, pongam oil and neem oil) are supplied on to the chip–tool interface zone by a specially developed MQL setup at a constant flow rate of 10 mL/min, pressure of 5 Bar and 5 mm nozzle stand of distance. The properties of the lubricants are presented in Table 1.

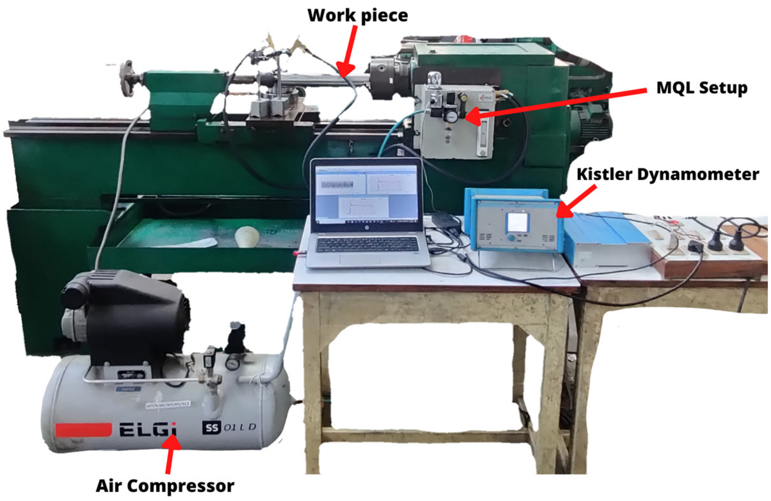


Figure 1. MQL Experimental set up.

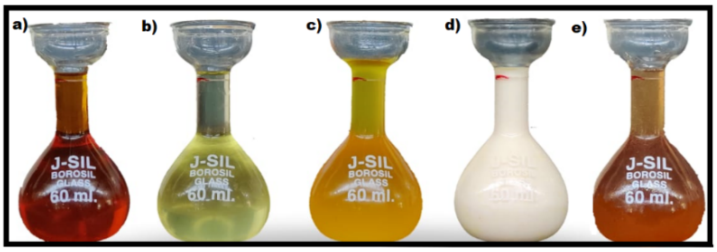


Figure 2. Cutting Fluids. (**a**) Neem Oil (NO); (**b**) Simarouba Oil (SO); (**c**) Pongam Oil (PO); (**d**) Oil –Water (OW); (**e**) Mineral Oil (MO).

Table 1. Physical properties of the lubricants used.

Properties	Neem Oil (NO)	Simarouba Oil (SO)	Pongam Oil (PO)	Oil–Water (OW)	Mineral Oil (MO)
Viscosity (≅40 °C) Pa s (Pascal second)	0.0245–0.028	0.0274–0.03107	0.0369–0.0415	0.027–0.0324	0.0826–0.087
% of Oxygen	0.2–0.5%	1.2–1.5%	0.5–0.8%	20.5–21%	1.5–2%
Density (g/cm^3)	0.875	0.914	0.924	0.900	0.870
Flash point	218 °C	178 °C	225 °C	NA	135 °C

Figure 2 presents the different lubricants used under MQL. Dynamic viscosity of the lubricants was measured using a Systonic S-9251 Viscometer and the range of results is presented. The dissolved oxygen percentage of oils was measured using the diaphragm electrode method. Density of the lubricants was measured by volume and mass relation. Flash point of the lubricants was measured using ABELS flash point tester apparatus. The AISI 316L stainless steel workpiece in the form of round bars of 50 mm diameter had been procured from Dhanalakshmi Steel Distributors, Mumbai. Physical and mechanical properties of the workpiece as provided by the vendor is mentioned in Tables 2 and 3.

Table 2. Mechanical properties of AISI 316L stainless steel.

Property	Typical Value
Hardness, Rockwell B	95
Ultimate Tensile Strength (MPa)	485
Yield Tensile Strength (MPa)	170
Modulus of Elasticity (GPa)	200
Poisson's Ratio	0.3
Density(g/cm^3)	7.90
Elongation (%)	40
Fatigue Strength (MPa)	146

Table 3. Chemical composition of AISI 316L stainless steel.

Element	C	Mn	Si	P	S	Cr	Mo	Ni	N
Wt (%)	0.03	2	0.75	0.05	0.03	18	3	14	0.10

During turning of AISI 316L stainless steel, the cutting forces generated were measured by a 9257BA KISTLER Dynamometer. Talysurf Surtronic 3+ surface roughness measuring equipment was used to measure roughness of the cylindrical specimen, which follows the principle where surface irregularities are traced by the probe/stylus and its subsequent motion is converted into fluctuations in the electric current. For each run, a fresh KB-90 insert was used and was weighed both before and after machining to measure wear. A total of 25 tools were used for the whole operation where each tool was passed one time (250 mm length) while turning. OLYMPUS BX53M System Optical microscope has been used to observe the surface microstructure of the workpiece. The workpiece was etched using a reagent aqua regia (1:3 molar ratio) of hydrochloric acid and nitric acid.

The Taguchi L_{25} orthogonal array was obtained by using MINITAB software (Version 15). Analysis of L_{25} orthogonal array was conducted to find out the design parameters majorly affecting the characteristics quality and to identify percentage contribution of each input process parameter. The turning test parameters and levels chosen are mentioned in Table 4. Experiments were carried out using an L_{25} orthogonal array (Table 5).

Table 4. Factors and Levels used in this Experimentation.

Trial No	Lubrication Conditions (A)	Cutting Speed (m/min) (B)	Feed (mm/rev) (C)	Depth of Cut (mm) (D)
1	Oil–Water	60	0.10	0.20
2	Mineral Oil	80	0.15	0.40
3	Pongam Oil	100	0.20	0.60
4	Simarouba Oil	120	0.25	0.80
5	Neem Oil	140	0.30	1.00

Table 5. L_{25} Orthogonal Array.

Trial No	Lubrication Conditions (A)	Cutting Speed (m/min) (B)	Feed (mm/rev) (C)	Depth of Cut (mm) (D)
1	Oil–Water	60	0.10	0.2
2	Oil–Water	80	0.15	0.4
3	Oil–Water	100	0.20	0.6
4	Oil–Water	120	0.25	0.8
5	Oil–Water	140	0.30	1.0
6	Mineral Oil	60	0.15	0.6
7	Mineral Oil	80	0.20	0.8
8	Mineral Oil	100	0.25	1.0
9	Mineral Oil	120	0.30	0.2
10	Mineral Oil	140	0.10	0.4
11	Pongam Oil	60	0.20	1.0
12	Pongam Oil	80	0.25	0.2
13	Pongam Oil	100	0.30	0.4
14	Pongam Oil	120	0.10	0.6
15	Pongam Oil	140	0.15	0.8
16	Simarouba Oil	60	0.25	0.4
17	Simarouba Oil	80	0.30	0.6
18	Simarouba Oil	100	0.10	0.8
19	Simarouba Oil	120	0.15	1.0
20	Simarouba Oil	140	0.20	0.2
21	Neem Oil	60	0.30	0.8
22	Neem Oil	80	0.10	1.0
23	Neem Oil	100	0.15	0.2
24	Neem Oil	120	0.20	0.4
25	Neem Oil	140	0.25	0.6

3. Results and Discussions

AISI 316L stainless steel is a widely used structural material in various industries such as construction, automobile and marine applications. Study on the machining characteristics of AISI 316L stainless steel while turning under various MQL conditions provides a better way of understanding their tribological and morphological behaviour. Thus, the impact of process input parameters on surface roughness, cutting forces and tool wear using an L_{25} orthogonal array has been discussed in the subsequent sections.

3.1. Surface Roughness

AISI 316L stainless steel is abundantly used as a structural material among various applications. However, the components of AISI 316L stainless steel are frequently coated for improving surface properties;the roughness of the surface plays a key role in the adhesion of the coating material to the surface. Thus, study on surface roughness characteristics of AISI 316L stainless steel during turning under various minimum quantity lubrication conditions is an important way of understanding its tribological behaviour in different machining environments. Figure 3a–c present the comparison of surface roughness under different machining and lubrication conditions such as oil–water, mineral oil, simarouba oil, pongam oil and neem oil. From the extensive experimentation, it is seen that the surface roughness decreasesunder neem oil MQL while compared to oil–water, mineral oil, simarouba oil and pongam oil. This is due tothe higher oiliness and wettability characteristics of neem oil followed by its optimum viscosity (0.0245–0.028 Pa s)compared to other lubricants employed in the experimentation. Further, optimum viscosity facilitates deep penetration of the lubricantinto the tool–chip interface while decreasing the vibration and chatter, and avoidingthe adhering of the chip on the flank face.

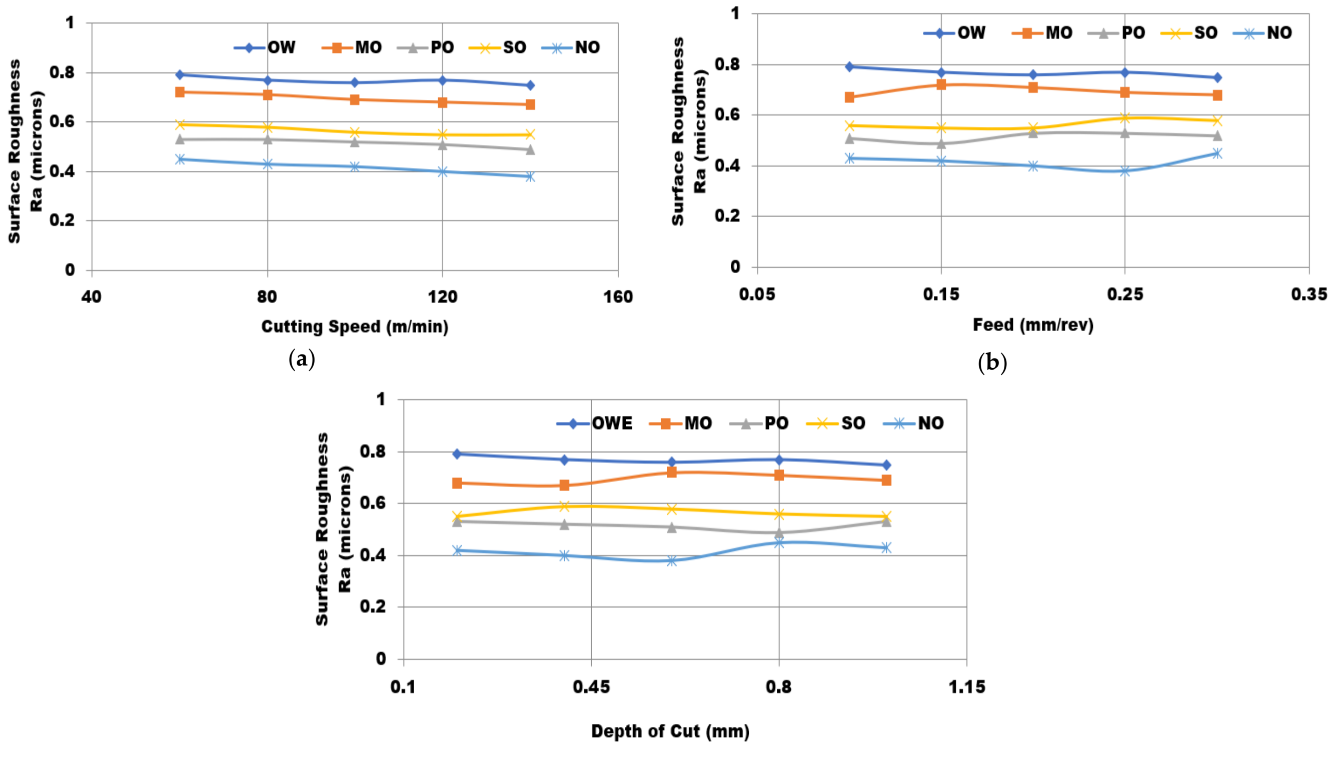


Figure 3. Variation in Surface roughness, Ra (microns) with: (**a**) varying cutting speed, constant feed (0.40 mm/rev) and depth of cut (1.00 mm) for different lubrication conditions; (**b**) varying feed, constant cutting speed (140 m/min) and depth of cut (1.00 mm) under different lubrication conditions; (**c**) varying depth of cut, constant cutting speed (140 m/min) and feed (0.35 mm/rev) for different lubrication conditions.

Figure 4 presents the microscopic images of the machined surface under different lubrication conditions. From Figure 4, it was observed that neem oil as cutting fluid showed better surface roughness with less surface irregularity compared to other cutting fluids. Figure 5 presents the surface roughness profiles of AISI 316L stainless steel under neem oil minimum quantity lubrication conditions.

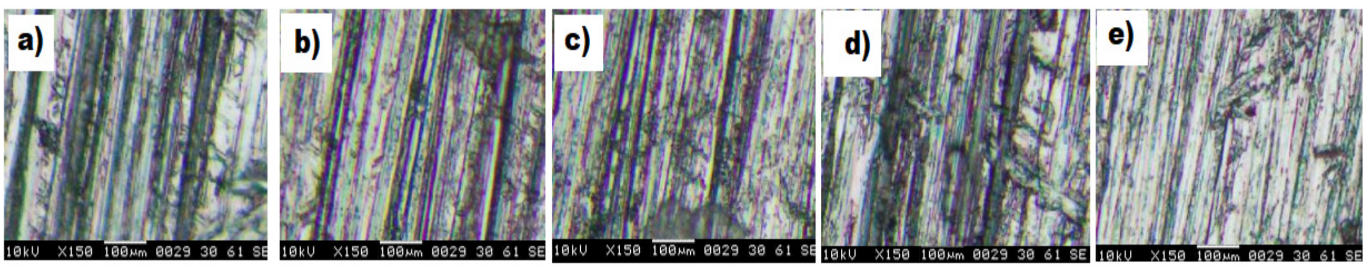


Figure 4. Microscopic images of machined surface under different lubrication conditions. (**a**) Oil –Water Oil; (**b**) Mineral Oil; (**c**) Simarouba Oil; (**d**) Pongam Oil; (**e**) Neem Oil.

On the basis of evaluation of the percentage of contribution (P%) for different factors selected for S/N ratio (Table 6), for surface roughness, it can be seen that lubrication conditions have the highest contribution of about 98.1%; thus, lubrication conditions are an important factor to be taken into consideration while machining AISI 316L stainless steel under MQL. Further, for the selected range of input parameters, the cutting speed (P = 1.74%), feed (P = 0.03%) and depth of cut (P = 0.04%) have minimal effect on surface roughness characteristics.

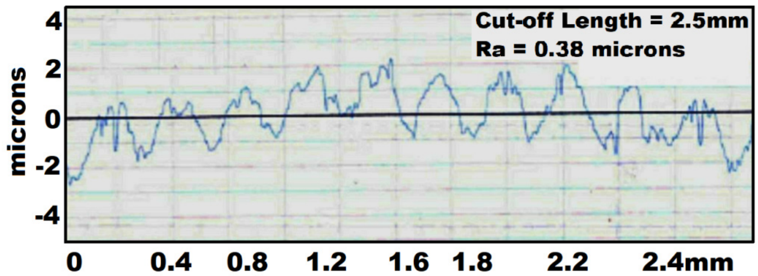


Figure 5. Surface roughness profiles of AISI 316L stainless steel under Neem oil lubrication condition.

Table 6. Analysis of Variance for S/N ratios for Surface roughness (microns).

Source	DF	P	P (%)
Lubrication Conditions (A)	4	0.9810	98.1
Cutting Speed (m/min) (B)	4	0.0174	1.74
Feed(mm/rev) (C)	4	0.0030	0.03
Depth of Cut(mm) (D)	4	0.0040	0.04
Residual Error	8		
Total	24		

From Figure 6, indicating the main effects plot for surface roughness, the selection of neem oil, cutting speed (140 m/min), feed (0.30 mm/rev) and depth of cut (1.0 mm)have resulted in the best combination to get the lowest surface roughness value (0.36 µm) during turning of AISI 316L stainless steel under MQL.

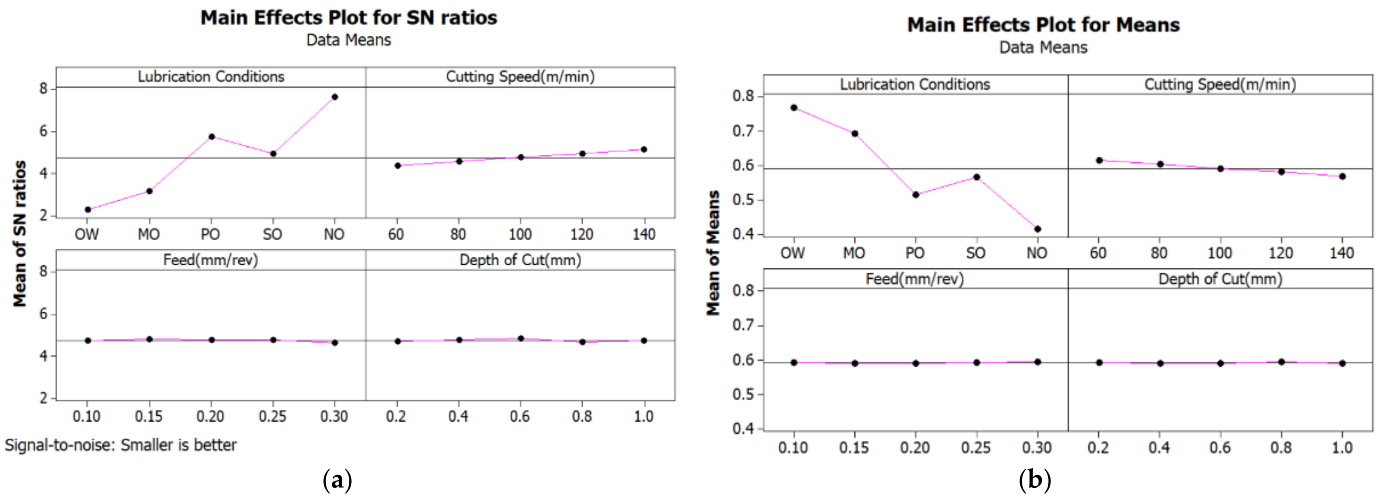


Figure 6. Main effects plot for Surface roughness (microns): (**a**) S/N ratio; (**b**) Means.

3.2. Cutting Force

During machining of any metals and alloys, the cutting force variable is the major component to analyse machinability characteristics. Hence, in this section, the cutting force induced during turning of AISI 316L stainless steel under MQL has been discussed.

Figure 7a–c present the cutting force values generated under different cutting conditions. From the figure, it was observed that the cutting force is lower in the neem oil application compared to oil–water, mineral oil, simarouba oil and pongam oil. In neem oil application, the easy flow of cutting fluid penetrates into the capillaries existing between the tool–chip interfaces. This causes reduction in friction, which in turn reduces the cutting force. Further, when neem oil is used as cutting fluid in MQL, the cutting fluid gets fragmented into tiny globules, the size of which is inversely proportional to the pressure of injection. The velocity varies as a function of the square root of the injection pressure.

This high velocity facilitates better penetration of the neem oil to the underside of the chip resulting in the reduction of friction [37]. Figure 8 presents the cutting force signals during turning of AISI 316L stainless steel under different lubrication conditions.

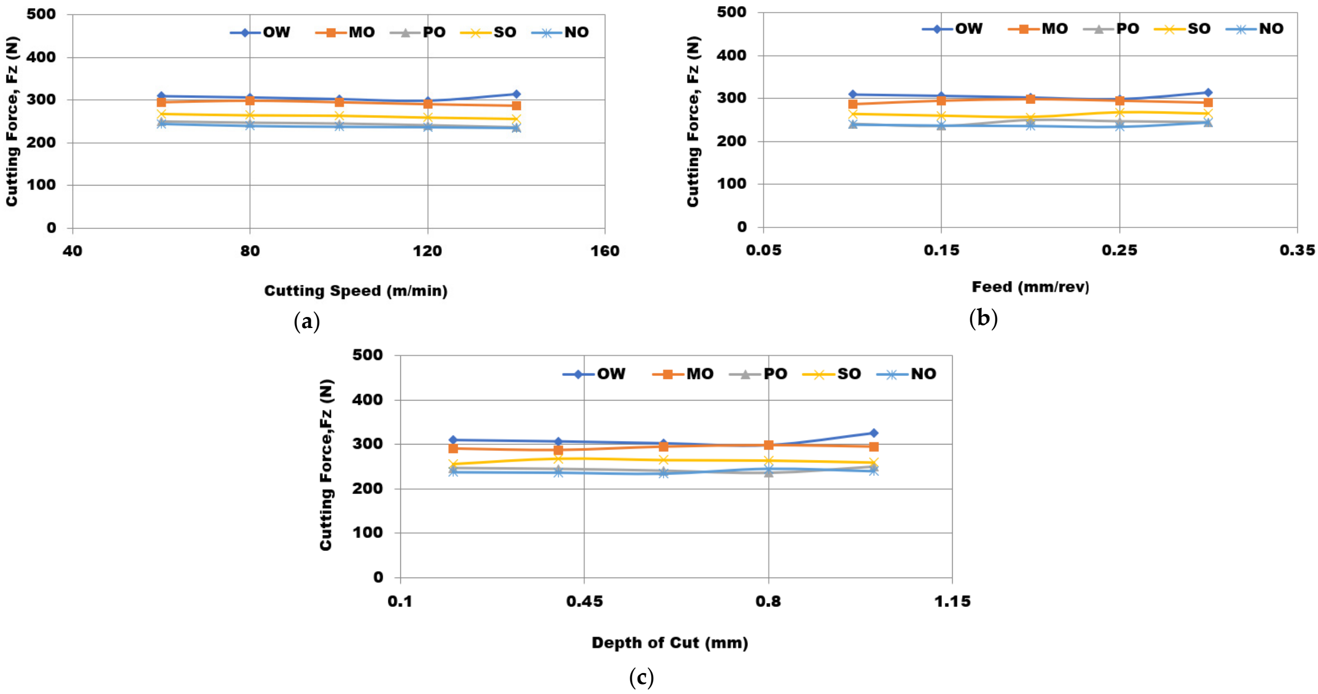


Figure 7. Variation of cutting force, Fz (N) with: (**a**) different cutting speed, constant feed (0.40 mm/rev) and depth of cut (1.00 mm) for different lubrication conditions; (**b**) different feed, constant cutting speed (140 m/min) and depth of cut (1.00 mm) under different lubrication conditions; (**c**) different depth of cut, constant cutting speed (140 m/min) and feed (0.35 mm/rev) for different lubrication conditions.

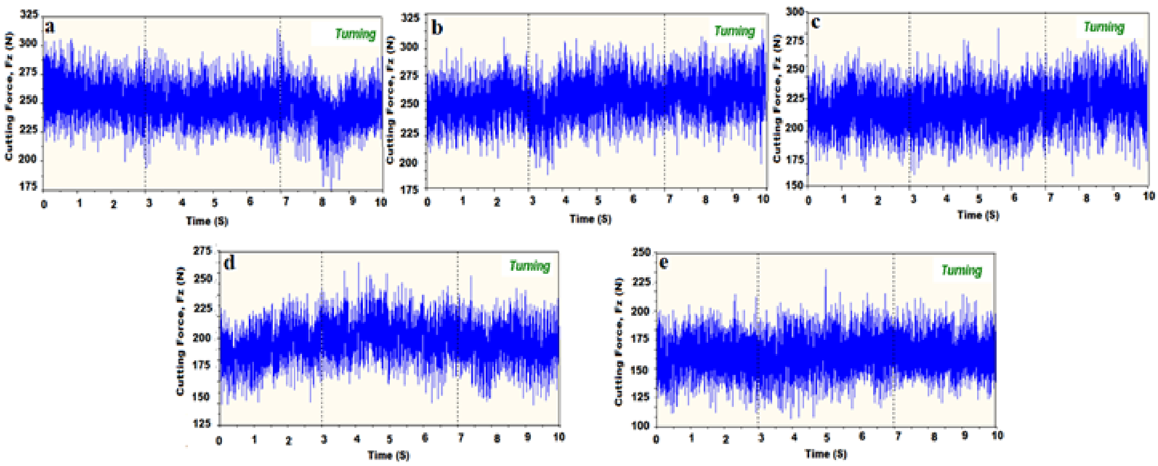


Figure 8. Cutting force signals during turning of AISI 316L stainless steel under different lubrication conditions. (**a**) Oil–Water Oil; (**b**) Mineral Oil; (**c**) Simarouba Oil; (**d**) Pongam Oil; (**e**) Neem Oil.

While evaluating the percentage of contribution (P%) for different factors selected for S/N ratio and means (Table 7), for cutting force, it is evident that lubrication conditions have the highest contribution of about 91.9%; thus, lubrication conditions are prominent factors to be taken into consideration while machining AISI 316L stainless steel under MQL. Further, cutting speed (P = 4.25%), feed (P = 2.86%) and depth of cut (P = 0.99%) have lesser statistical and physical significance on cutting force for the range of input parameters selected.

Table 7. Analysis of Variance for S/N ratios for Cutting Force, Fz(N).

Source	DF	P	P(%)
Lubrication Conditions	4	0.919	91.9
Cutting Speed (m/min)	4	0.0425	4.25
Feed(mm/rev)	4	0.0286	2.86
Depth of Cut(mm)	4	0.0099	0.99
Residual Error	8		
Total	24		

Figure 9, indicating the main effects plot for cutting force, suggests the selection of neem oil, cutting speed (140 m/min), feed (0.20 mm/rev) and depth of cut (1.0 mm) result in the best combination to get the lowest cutting forcevalue (235.34 N) during turning of AISI 316L stainless steel under MQL.

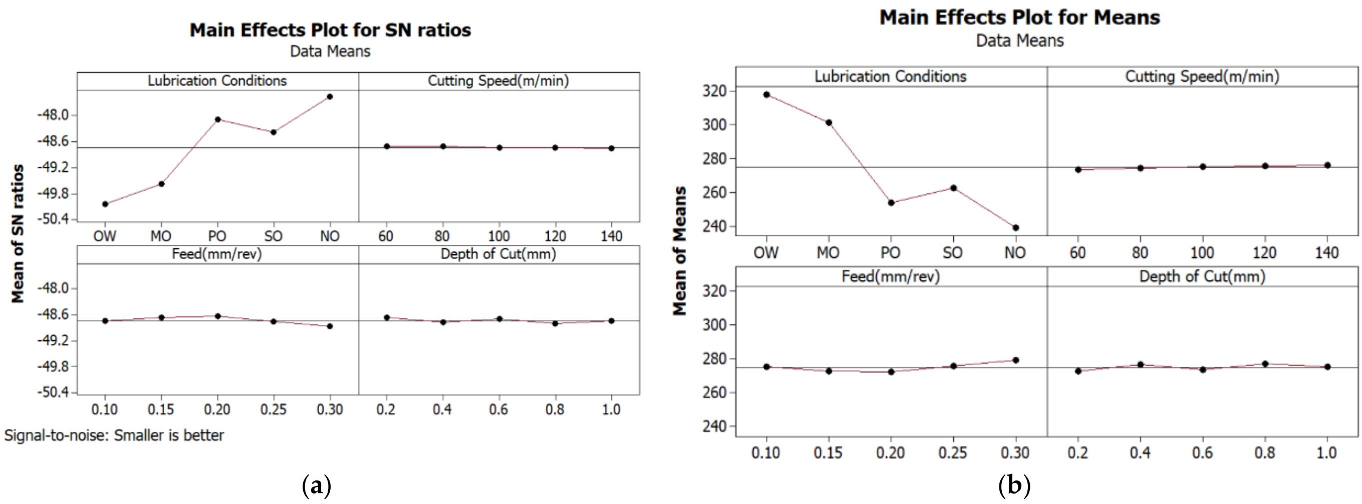


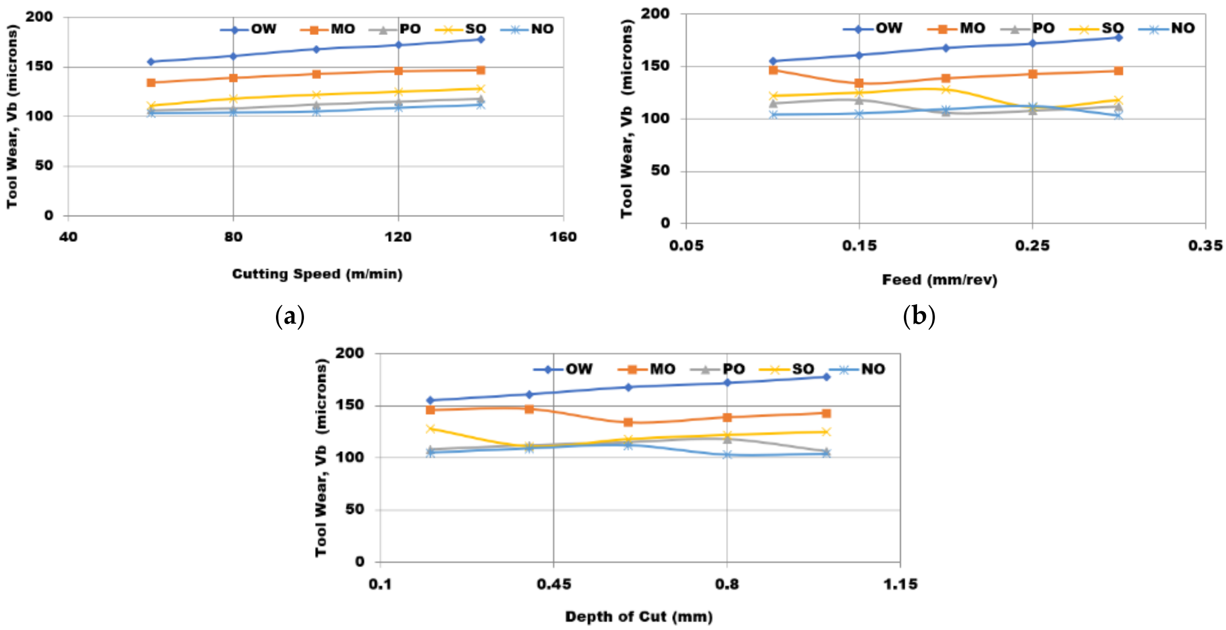
Figure 9. Main effects plot for cutting force (N): (**a**) S/N ratio; (**b**) Means.

3.3. Tool Wear

During machining, the study related to tool wear plays a major role in terms of machining cost and product quality. Hence, in this section, optimum input parameters for tool wear minimization will be discussed. From Figure 10a–c, it is very much clear that tool wear is lesser under neem oil application compared to oil–water, mineral oil, simarouba oil and pongam oil application. This is because the neem oil penetrates easily on to chip–tool interface resulting in minimum tool wear compared to other cutting fluids.

Further, as the cutting speed, feed and depth of cut increases the temperature induced, thermal softening of AISI 316L stainless steel results in increase of tool wear. Figure 11 presents the microscopic images of cutting tools after turning of AISI 316L stainless steel under different lubrication conditions. From Figure 11, we can observe that higher cutting speeds, feed and depth of cut results in built-up edge formation, flank wear progression and flaking under different machining conditions.

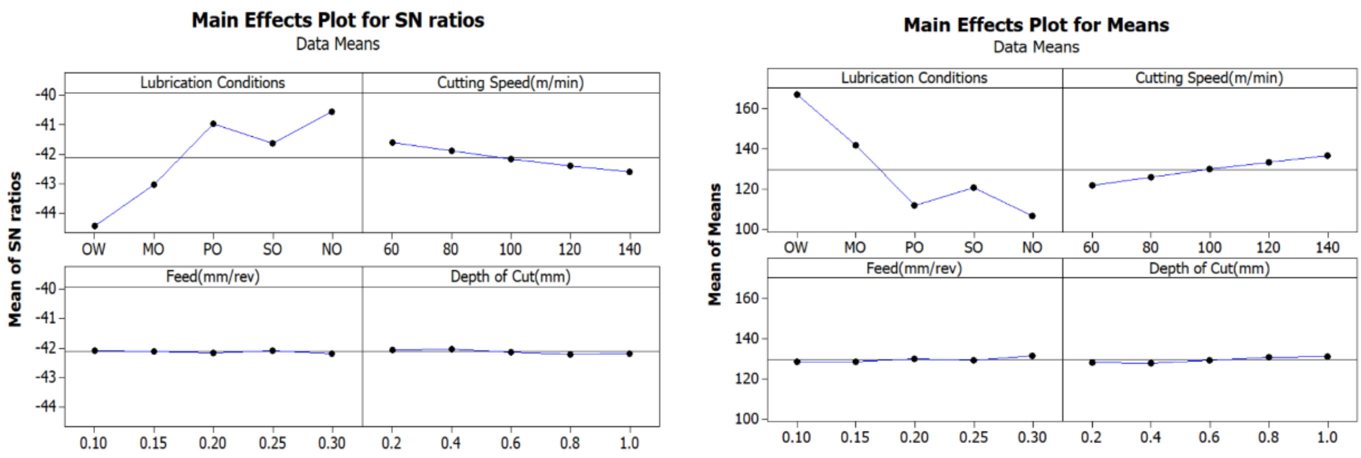
While evaluating the percentage of contribution (P%) for different factors selected for S/N ratio and means (Table 8), for tool wear, it can be seen that lubrication conditions have the highest contribution of about 84.1%; thus, lubrication conditions are an important factor to be taken into consideration while machining AISI 316L stainless steel under MQL. Further, cutting speed (P = 7.46%), feed (P = 3.46%) and depth of cut (P = 4.98%) have a minimal statistical and physical significance on tool wear for the selected range of input parameters.



(**a**) (**b**)

(**c**)

Figure 10. Variation of Tool Wear, Vb (microns) with: (**a**) different cutting speed, constant feed (0.40 mm/rev) and depth of cut (1.00 mm) for different lubrication conditions; (**b**) different feed, constant cutting speed (140 m/min) and depth of cut (1.00 mm) under different lubrication conditions; (**c**) different depth of cut, constant cutting speed (140 m/min) and feed (0.35 mm/rev) for different lubrication conditions.



(**a**) (**b**)

Figure 11. Main effect plots for cutting force (N): (**a**) S/N ratio; (**b**) Means.

Table 8. Analysis of Variance for S/N ratios for Cutting Force, Fz (N).

Source	DF	P	P (%)
Lubrication Conditions	4	0.8410	84.1
Cutting Speed (m/min)	4	0.0746	7.46
Feed (mm/rev)	4	0.0346	3.46
Depth of Cut (mm)	4	0.0498	4.98
Residual Error	8		
Total	24		

Figure 11, indicating the main effects plot for cutting force, suggests that the selection of neem oil, cutting speed (60 m/min), feed (0.10 mm/rev) and depth of cut (0.2 mm) result in the best combination to get the lowest tool wear value (100.32 microns) during turning of AISI 316L stainless steel under MQL. Figure 12 provides the microscopic images during turning of AISI 316L stainless steel under Oil–Water, Mineral Oil, Simarouba Oil, Pongam Oil, Neem Oil lubrication conditions.

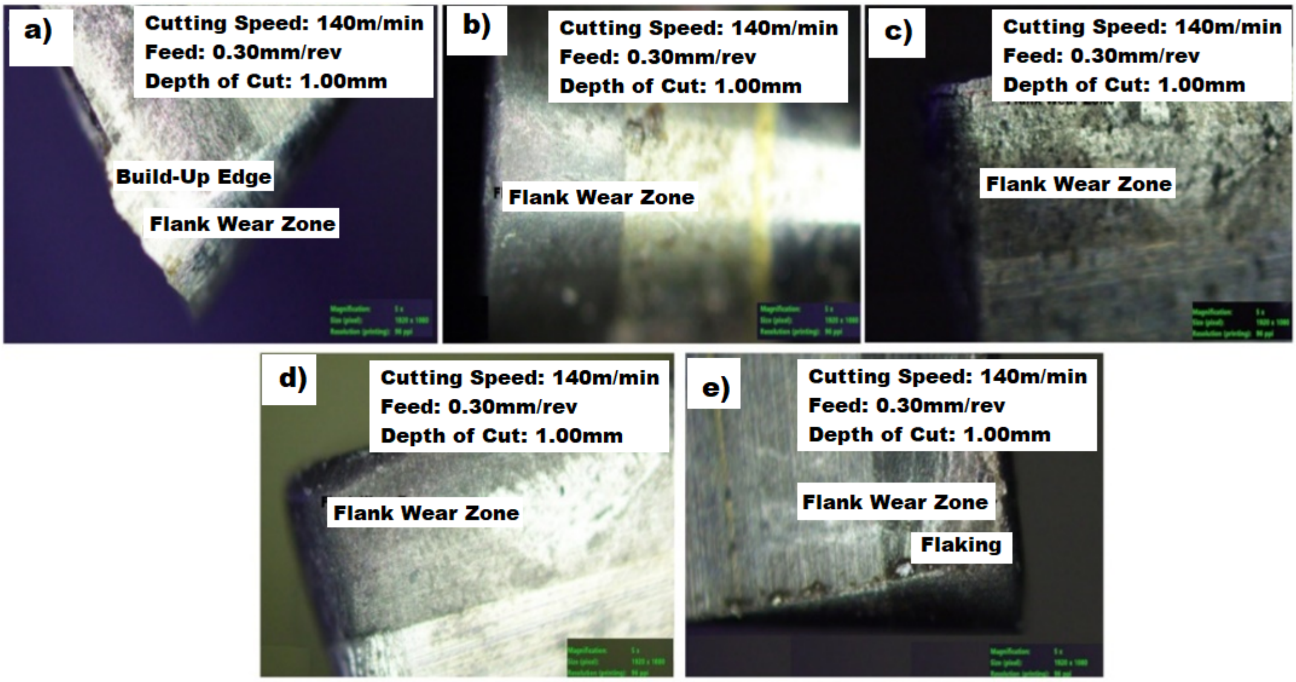


Figure 12. Microscopic images during turning of AISI 316L stainless steel under different lubrication conditions. (**a**) Oil–Water Oil; (**b**) Mineral Oil; (**c**) Simarouba Oil; (**d**) Pongam Oil; (**e**) Neem Oil.

4. Conclusions

During turning of AISI 316L stainless steel under MQL using L_{25} orthogonal array for optimization of process output variables of machining, such as surface roughness, cutting force and tool wear, the following conclusion can be drawn:

- The surface roughness value was found to be minimal under neem oil application compared to other lubricants because of the optimum viscosity, penetrability and high flash point of the neem oil. From the examination of the percentage of contribution (P%) for the selected range of input parameters, it can be seen that lubrication conditions have the highest contribution of about 98.1% compared to cutting speed (P = 1.74%), feed (P = 0.03%) and depth of cut (P = 0.04%). Further, the selection of neem oil as lubricant with cutting speed (140 m/min), feed (0.30 mm/rev) and depth of cut (1.0 mm) has resulted in the best combination among the selected range of input parameters to obtain the lowest surface roughness value of 0.36μm.
- A similar observation was found for cutting force. As neem oil flows easily, it reduces frictional forces by deeply penetrating into the capillaries existing between the tool–chip interfaces. From the examination of the percentage of contribution (P%) for the selected range of input process parameters, lubrication condition had the highest contribution of 91.9% compared to cutting speed (P = 4.25%), feed (P = 2.86%) and depth of cut (P = 0.99%). Further, the selection of neem oil as lubricant with cutting speed (140 m/min), feed (0.20 mm/rev) and depth of cut (1.0 mm) resulted in the best combination to get the lowest cutting force value (235.34 N).
- Tool wear was lesser under neem oil application because neem oil penetrates easily on to chip–tool interface and creates a fine film resulting in minimum friction and

tool wear compared to other cutting fluids. From the evaluation of the contribution percentage (P%), it can be seen that lubrication conditions have the highest contribution of about 84.1%, while cutting speed (P = 7.46%), feed (P = 3.46%) and depth of cut (P = 4.98%) have a minimal statistical and physical significance on tool wear for the selected range of input parameters. Further, the selection of neem oil as lubricant with cutting speed (60 m/min), feed (0.10 mm/rev) and depth of cut (0.2 mm) resulted in the best combination to get the lowest tool wear value (100.32 microns).

Concluding from the above findings, neem oil is found to have performed better than other lubricants employed in the study. Because of the lowest viscosity, density and oxygen percentage, neem oil is able to positively lubricate in MQL conditions compared to conventional cutting fluids. As neem oil is non-toxic and biodegradable in nature, it offers better sustainability under MQL. Further, the developed L_{25} orthogonal array can be effectively used to obtain optimum process input parameters for better surface roughness, cutting force and tool wear.

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Nomenclature and Abbreviations:

AISI	American Iron and Steel Institute
MQL	Minimum Quantity Lubrication
ANOVA	Analysis of Variance
S/N Ratio	Signal to Noise Ratio
F_z	Cutting Force
V_b	Tool Wear
R_a	Roughness Average
OW	Oil–Water
MO	Mineral Oil
PO	Pongam Oil
SO	Simarouba Oil
NO	Neem Oil
DF	Degrees of Freedom

References

1. Tesler, A.B.; Kim, P.; Kolle, S.; Howell, C.; Ahanotu, O.; Aizenberg, J. Extremely durable biofouling-resistant metallic surfaces based on electrodeposited nanoporoustungstite films on steel. *Nat. Commun.* **2015**, *6*, 1–10. [CrossRef] [PubMed]
2. Bharsai, N.S.; Kannan, S. Microstructure, Corossion and mechanical properties characterization of AISI type 316L(N) stainless steel and modified 9Cr-1Mo steel after 40,000 h of dynamic sodium exposure at 525 °C. *J. Nucl. Mater.* **2019**, *516*, 84–89. [CrossRef]
3. Suleiman, I.Y.; Sani, A.M.; Ogheneblorhie, C. Characterisation and corrosion behaviours of AISI 316 in hydrochloric environment at various concentrations. *Zast. Materrijala* **2020**, *61*, 220–228.
4. Mia, M.; Dhar, N.R. Effects of duplex jets high pressure coolant on machining temperature and machinability of Ti-6Al-4V superalloy. *J. Mater. Process. Technol.* **2018**, *252*, 688–696. [CrossRef]
5. Masoudi, S.; Esfahani, M.J.; Jafarian, F.; Mirsoleimani, S.A. Comparison the effect of MQL, wet and dry turning on surface topography, cylindricity tolerance and sustainability. *Int. J. Precis. Eng. Manuf. Green Technol.* **2019**. [CrossRef]

6. Shokrani, A.; Dhokia, V.; Newman, S.T. Environmentally conscious machining of difficult-to-machine materials with regard to cutting fluids. *Int. J. Mach. Tools Manuf.* **2012**, *57*, 83–101. [CrossRef]
7. Weinert, K.; Inasaki, I.; Sutherland, J.; Wakabayashi, T. Dry machining and minimum quantity lubrication. *CIRP Ann. Manuf. Technol.* **2004**, *53*, 511–537. [CrossRef]
8. Inasaki, I. Towards symbiotic machining processes. *Int. J. Precis. Eng. Manuf.* **2012**, *13*, 1053–1057. [CrossRef]
9. Goldberg, M. Improving productivity by using innovative metal cutting solutions with an emphasis on green machining. *Int. J. Mach. Mach. Mater.* **2012**, *12*, 17–125. [CrossRef]
10. Tawakoli, T.; Hadad, M.; Sadeghi, M.; Daneshi, A.; Stöckert, S.; Rasifard, A. An experimental investigation of the effects of workpiece and grinding parameters on minimum quantity lubrication-MQL grinding. *Int. J. Mach. Tools Manuf.* **2009**, *49*, 924–932. [CrossRef]
11. Jegatheesan, V.; Liow, J.L.; Shu, L.; Visvanathan, C. The need for global coordination in sustainable development. *J. Clean. Prod.* **2009**, *17*, 637–643. [CrossRef]
12. Hadad, M.J.; Sadeghi, B. Thermal analysis of minimum quantity lubrication- MQL grinding process. *Int. J. Mach. Tools Manuf.* **2012**, *63*, 1–15. [CrossRef]
13. Sadeghi, M.H.; Haddad, M.J.; Tawakoli, T.; Emami, M. Minimal quantity lubrication-MQL in grinding of Ti-6Al-4V titanium alloy. *Int. J. Adv. Manuf. Technol.* **2009**, *44*, 487–500. [CrossRef]
14. Li, K.M. Predictive Modeling of Near Dry Machining: Mechanical Performance and Environmental Impact. Ph.D. Thesis, Georgia Institute of Technology, Atlanta, GA, USA, 2006.
15. Sharma, V.S.; Dogra, M.; Suri, N.M. Cooling techniques for improved productivity in turning. *Int. J. Mach. Tools Manuf.* **2009**, *49*, 435–453. [CrossRef]
16. Attanasio, A.; Gelfi, M.; Giardini, C.; Remino, C. Minimal quantity lubrication in turning: Effect on tool wear. *Wear* **2006**, *260*, 333–338. [CrossRef]
17. Obikawa, T.; Kamata, Y.; Asano, Y.; Nakayama, K.; Otieno, A.W. Micro-liter lubrication machining of Inconel 718. *Int. J. Mach. Tools Manuf.* **2008**, *48*, 1605–1612. [CrossRef]
18. Karthik, S.R.; Londe, N.; Shetty, R.; Nayak, R.; Hegde, A. Optimization and prediction of hardness, wear and surface roughness on age hardened Stellite 6 alloys. *Manuf. Rev.* **2022**, *9*, 10.
19. Shetty, R.; Sanjeev Kumar, C.R.; Ravindra, M.R. RSM based expert system development for cutting force prediction during machining of Ti-6Al-4V under minimum quantity lubrication. *Int. J. Syst. Assur. Manag.* **2021**, in press. [CrossRef]
20. Shetty, R. L16 Orthogonal Array Based Three Dimensional Finite Element Modelling for Cutting force and chip formation analysis during Dry Machining of Ti-6Al-4V. *J. Adv. Manuf. Syst. World Sci.* **2021**, *20*, 123–134. [CrossRef]
21. Kamata, Y.; Obikawa, T. High speed MQL finishturning of Inconel 718 with different coated tools. *J. Mater. Process. Technol.* **2007**, *192–193*, 281–286. [CrossRef]
22. Mannekotte, J.; Kailas, S.V.; Kathyayini, N. Environmentally Friendly Functional Fluids from Renewable and Sustainable sources. *J. Renew. Sustain. Energy* **2017**, *81*, 1787–1801. [CrossRef]
23. Shashidhara, Y.M.; Jayaram, S.R. Vegetable oils as potential cutting fluids an evolution. *Tribol. Int.* **2010**, *43*, 1073–1081. [CrossRef]
24. Rahim, E.A.; Sasahara, H. A study of the effect of palm oil as MQL Lubricant of high-speed titanium alloys. *J. Tribol. Int.* **2011**, *44*, 309–317. [CrossRef]
25. Ozcelik, B.; Kuram, E.; Cetin, M.H.; Demirbas, E. Experimental investigations of vegetable based cutting fluids with extreme pressure during turning of Aisi 304l. *Tribol. Int.* **2011**, *44*, 1864–1871. [CrossRef]
26. Abdalla, H.S.; Baines, W.; McIntyre, G.; Slade, C. Development of novel sustainable neat-oil metal working fluids for stainless steel and titanium Alloy machining. Part 1. Formulation development. *Int. J. Adv. Manuf. Technol.* **2007**, *34*, 21. [CrossRef]
27. Nagendramma, P.; Kaul, S. Development of eco-friendly/biodegradable lubricants: An overview. *Renew. Sustain. Energy Rev.* **2012**, *16*, 764–774. [CrossRef]
28. Leppert, T.; Peng, R.L. Residual stresses in surface layer after dry and MQL turning of AISI 316L steel. *Prod. Eng.* **2012**, *6*, 367–374. [CrossRef]
29. Maruda, R.W.; Krolczyk, G.M.; Niesłony, P.; Krolczyk, J.B.; Legutko, S. Chip formation zone analysis during the turning of austenitic stainless steel 316L under MQCL cooling condition. *Proc. Eng.* **2016**, *149*, 297–304. [CrossRef]
30. Hossain, S.; Abedin, M.Z. Effect of Minimum Quantity Lubrication System for Improving Surface Roughness in Turning Operation. *Int. J. Eng. Mater. Manuf.* **2021**, *6*, 50–59. [CrossRef]
31. Ibrahim, A.M.M.; Omer, M.A.E.; Das, S.R.; Li, W.; Alsoufi, M.S.; Elsheikh, A. Evaluating the effect of minimum quantity lubrication during hard turning of AISI D3 steel using vegetable oil enriched with nano-additives. *Alex. Eng. J.* **2022**, *61*, 10925–10938. [CrossRef]
32. Javid, H.; Jahanzaib, M.; Jawad, M.; Asad Ali, M.; Umar Farooq, M.; Pruncu, C.I.; Hussain, S. Parametric analysis of turning HSLA steel under minimum quantity lubrication (MQL) and nanofluids-based minimum quantity lubrication (NF-MQL): A concept of one-step sustainable machining. *Int. J. Adv. Manuf. Technol.* **2021**, *117*, 1915–1934. [CrossRef]
33. NareshBabu, M.; Anandan, V. Turning SKD 11 Steel Using Silver Nanofluids With Minimum Quantity Lubrication. *Int. J. Manuf. Mater. Mech. Eng.* **2021**, *11*, 74–95.
34. Arsene, B.; Gheorghe, C.; Sarbu, F.A.; Barbu, M.; Cioca, L.-I.; Calefariu, G. MQL-Assisted Hard Turning of AISI D2 Steel with Corn Oil: Analysis of Surface Roughness, Tool Wear, and Manufacturing Costs. *Metals* **2021**, *11*, 2058. [CrossRef]

35. Shetty, R.; Pai, R.B.; Rao, S.S.; Nayak, R. Taguchi's technique in machining of metal matrix composites. *J. Braz. Soc. Mech. Sci. Eng.* **2009**, *31*, 12–20. [CrossRef]
36. Jayashree, P.K.; Sharma, S.S.; Shetty, R.; Mahato, A.; Gowrishankar, M.C. Optimization of TIG welding parameters for 6061Al alloy using Taguchi's design of experiments. *Mater. Today: Proc.* **2018**, *5*, 23648–23655. [CrossRef]
37. Shetty, R.; Gurupur, P.R.; Hindi, J.; Hegde, A.; Naik, N.; Ali, M.S.S.; Patil, I.S.; Nayak, M. Processing, Mechanical Characterization and Electric discharge machining of Stir cast and Spray forming based Al-Si alloy reinforced with ZrO_2 particulate composites. *J. Compos. Sci.* **2022**, *6*, 323. [CrossRef]
38. Shetty, R.; Hegde, A. Taguchi based fuzzy logic model for optimization and prediction of surface roughness during AWJM of DRCUFP composites. *Manuf. Rev.* **2022**, *9*, 2.