Development of Eco-Friendly Cutting Fluid for Machining of AISI 1010 Steel in Automotive Industry

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Abstract: In spite of better performance, the disposal of used petroleum-based cutting fluids threatens our environment. Thus, it is essential to develop eco-friendly cutting fluids for performing machining operations in industries. The main contribution of this paper is to develop an eco-friendly cutting fluid for the plain turning of AISI 1010 steel which is used in the automotive industry. In the present work, boric acid (H₃BO₃) was mixed with the neem seed. Neem seed oil is easily available in many countries including India. The effectiveness of the proposed cutting fluid was evaluated by conducting different tests as per the standards. The mean biodegradability value of the developed cutting fluid is 97% which is better than other cutting fluids. The average cutting force required by the proposed cutting fluid is only 127.2 N which is much less than the cutting force requirements of dry machining and conventional cutting fluids. The average surface roughness of the machined component using the proposed cutting fluid is 122.9 µm. The mean flank wear of the tool is only 289 µm. The flash point of the proposed cutting fluids is more than 250 °C which is better than the conventional cutting fluids. The results of the stability test and the microhardness test revealed the effectiveness of the proposed cutting fluids. The results obtained in this work are superior to several other cutting fluids reported in the existing literature. Hence, it is suggested to replace the existing petroleum-based metal cutting fluid with this eco-friendly cutting fluid in the automotive industry in Hosur, India.

Keywords: cutting fluid; machining; neem seed oil; boric acid; AISI 1010; eco-friendly

1. Introduction

In the automotive industry, several machining operations are carried out. Many types of cutting fluids are used during machining operations. Cutting fluids progress the lifetime of a cutting tool by reducing the tool wear. Cutting fluids also increase the value of the machined components and reduce the power consumption [1]. The cost of cutting fluids contributes approximately 15% of the manufacturing cost. To reduce the cost of cutting fluids, researchers proposed dry machining processes. Dry machining processes would affect the characteristics of the components and reduce the tool lifespan. Hence, the usage of cutting fluids is inevitable in machining industries. Synthetic oil-based metal fluids...
are generally used in industries. As synthetic cutting fluids create adverse effects on our environment such as global warming, it is necessary to find alternatives for oil-based cutting fluids. In addition, synthetic cutting fluids affect the health of workers in the automotive industries [2–4] and the disposal of used oil is a challenging task. Hence, in this work, it is proposed to investigate a sustainable cutting fluid for the plain turning operation of AISI 1040 steel which is used in several automotive applications such as rivets, washers, nails, and bushings. Researchers suggested numerous vegetable oil-based cutting fluids as they have several advantages such as high flash point [4], low cost, ease of use and disposal, providing a cleaner environment, etc. [5]. In this work, the plain turning operation being performed in the automotive industry is addressed. Hence, previous works related to the application of vegetable oils for plain turning operations are considered.

Abdalla and Patel [1] developed several vegetable oil-based cutting fluids for machining components made of stainless steel and aerospace-grade titanium alloys and proved that vegetable oil-based cutting fluids were effective as they had low friction values. Elmunafi et al. [6] used minimum quantity lubrication (MQL) of castor oil for the turning of hardened stainless steel. They proved that applied metal fluid provided better tool life and surface roughness than the dry turning process. Researchers investigated the performance of several metal fluids developed using vegetable oils mixed with diverse proportions of additives to reduce the surface roughness and cutting and feed forces. They considered the turning process of AISI 304L austenitic stainless steel in their work. They also proposed Taguchi’s mixed-level parameter design for the experimental design and regression analyses to calculate the surface roughness and cutting and feed forces [7,8]. Srikant and Ramana [9] evaluated the performance of vegetable emulsifier-based cutting fluids in the turning of AISI 1040 steel. They used sesame oil and coconut oil-based emulsifiers for the machining and concluded that the proposed cutting fluid could be used for high-speed machining processes.

Ojolo et al. [10] addressed the influence of many vegetable oils on the cutting force and coefficient of friction during the machining of ductile materials including aluminum, copper, and mild steel. They proved that the groundnut oil exhibited better performance. Zhang et al. [11] performed experiments to appraise the efficacy of a cutting fluid derived from soybean for the turning operation in a computer numerical control (CNC) machine. They used chromium alloy steel with high carbon (E52100) material in their work. They reported that the soybean-based metal fluids had better performance than the conventional metal fluids. Agrawal and Patil [12] proposed Aloe vera oil as a cutting fluid for the machining of molybdenum high-speed steel. They proved that the surface bumpiness and tool wear properties were improved by using aloe vera oil. Lawal et al. [13] investigated the effect of coconut oil on the turning process of austenitic stainless steel. They used a carbide tool for machining and concluded that the surface roughness was upgraded by an average of 14% and the tool wear was considerably reduced by the coconut oil. Xavior and Adithan [14] addressed the effect of metal fluids on tool wear and surface roughness while machining austenitic stainless steel. They proved that coconut oil was better than petroleum-based cutting fluids.

Nizamuddin et al. [15] stated that karanja-based metal fluid increased tool life by reducing chip thickness by 11% while performing orthogonal machining operations of medium carbon steel (AISI 1045). Jeevan and Jayaram [16] studied machining characteristics including cutting force and surface roughness during the turning of AA 6061 using Jatropha and Pongamia oils as cutting fluids. They applied the metal fluids using the MQL method. They conducted experiments and concluded that the cutting force was minimized by the vegetable oil-based cutting fluids and the surface finish was improved. The various types of vegetable oils proposed for diverse cutting processes can be found in [17–19]. Though a wide variety of vegetable oils were addressed by several researchers, there are many limitations including thermal and oxidation stability [4,5] which may be prevented by the addition of additives. Different types of additives are added to vegetable oils [20].
Researchers proved that the inclusion of nanofluids might improve the superiority of machined surfaces and reduce cost [21,22]. Su et al. [23] investigated the machining of medium carbon steel (AISI 1045) using vegetable oils and man-made metal fluids with two different concentrations of graphite nanoparticles. They reported that the cutting force was reduced to 26% by the vegetable oils and the cutting temperature was reduced by 21%. Padmini et al. [24] developed several vegetable oil-based nanofluids using canola, coconut, and sesame oils. They added various percentages of nano molybdenum disulphide to the vegetable oils and investigated the machining characteristics of turned AISI 1040 steel. Padmini et al. [25] investigated the effect of the addition of boric acid (HNO_3) and MoS_2 (molybdenum disulphide) to coconut and sesame oils during the machining of AISI 1040 steel with standard machining parameters. They proved that the nanofluids provided better results than the micro fluids. Rao and Krishna [26] proved that the inclusion of HNO_3 would reduce the cutting force, temperature, and wear and also amend the surface finish.

Krishna et al. [27] studied the performance of HNO_3 mixed with mineral oil and coconut oils at different percentages. They concluded that the coconut oil with 0.5% HNO_3 performed better. Pavani et al. [28] addressed the effect of boric acid on the tool temperature, cutting forces, and surface roughness of a turned component using coconut oil and soybean oil. They proved that the addition of boric acid enhanced the surface roughness of the machined part. Marichelvam et al. [29] also reported that the addition of boric acid enhanced the quality of machined surfaces. They proved this by adding boric acid to coconut oil for the plain machining process.

Anand et al. [30] proved that neem oil could be used as a potential lubricant. Singh and Gupta [31] proved that neem oil-based cutting fluids have better biodegradability. Neem seed oil is used in this work due to its availability, better biodegradability, and low cost. Neem oil possesses better viscosity and in-built antimicrobial properties. [32]. The neem oil consists of various fatty acids such as 41.9% oleic acid, 19.5% linoleic acid, 18.68% stearic acid, and 15.56% palmitic acid [33]. Paul and Pal [34] proposed karanja oil and neem oil as cutting fluids for the machining of low carbon steel using a high-speed steel tool. They investigated and concluded that the surface roughness produced by the cutting fluids was superior to the dry machining and conventional metal fluids. However, they did not address either the tool life or the cutting force. Jabba and Usman [35] proposed the application of neem oil while carrying out the machining of mild steel in a laboratory working environment in an academic institution. They reported that the neem oil could be used for machining as the quality of turned parts was improved and the tool wear was diminished.

Gupta et al. [36] developed a wide variety of cutting fluids using sunflower oil mixed with aluminum oxide, molybdenum disulfide, and graphite for the machining of Inconel-800 Alloy. The surface roughness, cutting forces, and tool wear characteristics were studied by them. They concluded that the performance of graphite-based cutting fluids was better. Recently, Tuan et al. [37] developed cutting fluids by mixing soybean oil and emulsion oil with nanoparticles of aluminum oxide and molybdenum disulfide. They conducted many turning experimental trials by following the experimental design on hard materials. They proved that the developed cutting fluids show better properties. A detailed literature review on the research developments of cutting fluids for machining operations can be found in [38].

From the above literature, it is evident that the application of neem seed oil mixed with boric acid for plain turning operation is limited. The existing literature does not consider the machining operations performed in a real industry. Therefore, there is a gap between academic research and industrial needs. Moreover, few researchers only considered the biodegradability of the cutting fluids along with other characteristics such as cutting force, tool tip–workpiece interface temperature, surface roughness, fire and slash point temperatures, etc. Hence, in this work, an effort is made to develop a neem oil-based cutting fluid for the machining of AISI 1010 steel in the automotive industry. Then, several tests were conducted to validate the proposed cutting fluids.
2. Materials and Methods

The neem seed oil and the AISI steel were purchased from Vijay Metals, Virudhunagar, India. The physical properties of neem oil are depicted in Table 1. Table 2 shows the chemical composition of AISI 1010 steel. The properties of AISI 1010 steel are presented in Table 3. The boric acid was purchased from TechLab, India. The particle size of the boric acid was 100 μm. The other properties of boric acid are presented in Table 4.

Table 1. Properties of neem oil.

| Sl. No. | Properties     | Values      |
|--------|----------------|-------------|
| 1      | Adhesiveness   | 689 g/m²    |
| 2      | Density        | 892 kg/m³   |
| 3      | Dynamic viscosity | 0.035 cP   |
| 4      | Fire point     | 286 °C      |
| 5      | Flash point    | 249 °C      |
| 6      | Specific heat  | 1.682 kJ/kg K |

Table 2. Chemical composition of AISI 1010 steel.

| Sl. No. | Elements | Content       |
|--------|----------|---------------|
| 1      | Carbon   | 0.080–0.13%   |
| 2      | Silicon  | ≤0.010%       |
| 3      | Manganese| 0.30–0.60%    |
| 4      | Sulphur  | ≤0.050%       |
| 5      | Phosphorous | ≤0.040%      |
| 6      | Iron     | 99.08–99.52%  |

Table 3. Properties of AISI 1010 steel.

| Sl. No. | Properties                  | Values       |
|--------|-----------------------------|--------------|
| 1      | Density                     | 7870 kg/m³   |
| 2      | Elastic modulus             | 190–210 GPa  |
| 3      | Poisson's ratio             | 0.27–0.30    |
| 4      | Coefficient of thermal expansion | 0.0122 mm/m/°C |
| 5      | Thermal conductivity        | 49.8 W/mK    |
| 6      | Specific heat capacity      | 450 J/kg K   |

Table 4. Properties of boric acid.

| Sl. No. | Properties     | Values  |
|--------|----------------|---------|
| 1      | Density        | 1440 kg/m³ |
| 2      | Molecular weight | 61.83 g/mol |
| 3      | Melting point  | 160 °C   |
| 4      | Boiling point  | 300 °C   |
| 5      | Purity         | 99.999   |

2.1. Preparation of Cutting Fluids

The cutting fluids were developed using a two-step procedure. The boric acid was ground using a high-energy ball mill as described by Marichelvam et al. [29] to obtain the HNO₃ with a particle size of 50 nm. Then, the boric acid was mixed with neem seed oil using a Vibra-Cell ultrasonic processor (model: VCX-750) for one hour to confirm the homogeneousness of the solution. By adding 0.25%, 0.5%, 0.75%, and 1.0% of boric acid to coconut oil, four different samples of cutting fluids were prepared. The details are shown in Table 5.
Table 5. Details of sample cutting fluids.

| Particulars          | Sample I | Sample II | Sample III | Sample IV |
|----------------------|----------|-----------|------------|-----------|
| Quantity of neem oil (mL) | 400      | 400       | 400        | 400       |
| Percentage of boric acid | 0.25     | 0.50      | 0.75       | 1.00      |
| Mass of boric acid (g)    | 0.892    | 1.784     | 2.676      | 3.568     |

2.2. Machining Conditions

A cylindrical bar made of AISI 1010 steel with a diameter of 25 mm and 100 mm long was used for machining. A coated carbide tool (SNMG 120408, Balaji Diamond Tools, Coimbatore, India) was used for turning. The experiment was conducted on a High-Speed Precision Lathe NH 22/26/32 lathe (model: HMT, Bangalore, India). In the present work, machining operations were carried out at a fixed spindle speed of 450 rpm. Dry machining was first performed on a workpiece by varying the depth of cut and feed. The turning operation was first performed using the conventional metal fluid (SAE 20W40, Castrol, Madurai, India) and then using a variety of neem oil-based cutting fluids. The experiments were conducted at different depths of cut and feed. The process parameters of the turning process are shown in Table 6. Each workpiece was turned for 10 min. During the experiment, a spray nozzle was used to spray the cutting fluid at a rate of 10 mL/min at 2.5 MPa. Each experiment was carried out 10 times and the average values are reported.

Table 6. Process parameters during turning.

| Parameters          | Values               |
|---------------------|----------------------|
| Spindle speed (rpm) | 450                  |
| Feed rate (mm/rev)  | 0.125, 0.250, and 0.375 |
| Depth of cut (mm)   | 0.50, 0.75, and 1.00 |

3. Experimental Procedure

The experimental procedures of different tests conducted are presented in this section.

3.1. Biodegradability Test

As the present work focuses on developing a biodegradable cutting fluid for automotive productions, biodegradability measurement is essential. The biodegradability test of the sample cutting fluids was performed as per ASTM D 5864 standard [39].

3.2. Cutting Force Measurement

Cutting force is the key characteristic affecting the accuracy of the dimensions, surface roughness, and wear. Machining parameters and the type of cutting fluid will affect the cutting force [16]. The cutting force would be reduced by the effective utilization of a cutting fluid. The reduction of cutting force indicates minimal power consumption and hence leads to a sustainable environment. Cutting force consists of three components, namely feed force ($F_X$), radial force ($F_Y$), and main force ($F_Z$) that are measured by a dynometer (Kistler 9257B), Faridabad, India. By measuring these three components, the magnitude of the cutting force was calculated using Equation (1) [29,40].

\[ F = \sqrt{F_X^2 + F_Y^2 + F_Z^2} \]  

(1)

where,

$F_X = \text{feed force}$,

$F_Y = \text{radial force}$,

$F_Z = \text{main force}$. 


3.3. Determination of Flash Point and Fire Point

The safe handling of cutting fluids can be ensured by measuring the flash point. The Pensky–Martens apparatus was used to measure the flash point and fire point of the cutting fluids. The cutting fluid was poured into the test cup up to the indicated level. Then, the cutting fluid was heated at a moderate and consistent rate of stirring. The stirring ensures appropriate and even heating. A thermometer was used to measure the temperature. The flame was directed into the cup over the opening provided at the top cover at 1 °C. The flash was witnessed in the form of sound at a particular temperature. This temperature was the flash point of the cutting fluid and it was noted. The fire point is an extension of the flash point. The temperature at which the vapor burns continuously for at least 5 s is the fire point.

3.4. Measurement of Surface Roughness

The surface roughness is used to describe the quality of machined goods. Lower surface roughness values show superior quality of the component. The surface roughness was measured using Mitutoyo surface roughness tester (model: SJ 210, Micro Sharp Tools, Chikhli, India) [29].

3.5. Flank Wear Measurement

Flank wear is an important factor that determines the dimensional accuracy and the surface finish of the machined components. Flank wear is the result of friction caused by the improper usage of cutting fluid. The flank wear was measured using a Toolmaker’s microscope (Mitutoyo TM-1005B, Mitutoyo South Asia Pvt. Ltd., New Delhi, India).

3.6. Measurement of Tool Tip–Workpiece Interface Temperature

The tool tip temperature measurement is used to analyze the cooling effects of the cutting fluids. Lower tool tip temperature would improve the tool life and hence reduce the tooling cost. An infrared thermometer (model: Raytek, Cole-Parmer India Pvt. Ltd., Mumbai, India) was used to measure the temperature generated between the tool tip and work piece thermometer. For each experiment, we measured the temperature five times at different time intervals and the average value was recorded.

3.7. Stability Test

The stability of cutting fluid is very important for reliable functioning. The stability of cutting fluids was studied by conducting a temperature test and mechanical test [41]. In the temperature test, the sample cutting fluids were kept at room temperature and their appearance, color, consistency, and homogeneity were investigated. The experiment was repeated at a reduced temperature of 10 °C and at an elevated temperature of 65 °C. In the mechanical load test, the samples are exposed to centrifugal force.

3.8. Microhardness Test of Chip Samples

The chips were collected under different machining conditions. The Vickers microhardness was measured by applying a load of 50 gf (Carl Zeiss micro durometer, Carl Zeiss India (P) Ltd., Chennai, India) [42]. The hardness was measured on two thicker and two thinner sections of the chip. The average of these four values is the hardness of the chips.

4. Results and Discussion

The results of various tests are addressed in this section.

4.1. Biodegradability of Cutting Fluids

The biodegradability values of different samples are compared with other cutting fluids [43]. The biodegradability comparison of different samples is shown in Table 7.
Table 7. Biodegradability values of different cutting fluids.

| Sl. No. | Properties          | Values         |
|---------|---------------------|----------------|
| 1       | Sample I            | 98.2 ± 0.50    |
| 2       | Sample II           | 97.6 ± 0.80    |
| 3       | Sample III          | 96.8 ± 0.30    |
| 4       | Sample IV           | 95.4 ± 0.10    |
| 5       | Mineral oil         | 15–35          |
| 6       | White oil           | 25–45          |
| 7       | Vegetable lubricants| 70–100         |
| 8       | Polyalphaoleins (PAO)| 5–30        |
| 9       | Polyisobutylene (PIB)| 0–25        |
| 10      | Phthalate and Trimellitate Esters| 5–80        |

From the table, it is observed that the neem seed oil-based cutting fluids have superior biodegradability values to other conventional metal fluids. The mean biodegradability of the proposed cutting fluids is 97%. The biodegradability value of the conventional cutting fluid is only 15–35%. Hence, the proposed cutting fluids could be used for industrial applications. Conventional metal fluids are used in the automotive industry located at Hosur in India. As the biodegradability of the neem seed oil-based cutting fluid is much better than other fluids, a suggestion was given to the industry to use the neem oil-based cutting fluids in the future.

4.2. Cutting Force

The cutting force was measured for dry machining (DM), conventional cutting fluid (CCF), neem oil (NO), and the sample cutting fluids (S I, S II, S III, S IV). The cutting force comparison of different machining conditions is presented in Table 8. From the table, it is concluded that the sample cutting fluid IV would reduce the cutting force significantly. The cutting force required by the sample cutting fluids is 60% less than the cutting force required by dry machining and 22% less than the conventional cutting fluids. The reduced cutting force would minimize power consumption. This not reduces cost but also the environmental impact. Hence, it is proved that the proposed cutting fluids are eco-friendly.

Table 8. Cutting force comparison.

| Experiment Number | Cutting Speed (m/min) | Feed (mm/rev) | Depth of Cut (mm) | Cutting Force (N) |
|-------------------|-----------------------|---------------|------------------|------------------|
|                   | DM                    | CCF           | NO               | S I              | S II             | S III            | S IV             |
| 1                 | 450                   | 0.125         | 0.50             | 291 ± 1          | 153 ± 1          | 126 ± 2          | 121 ± 1          | 120 ± 1          | 117 ± 1          | 114 ± 1          |
| 2                 | 450                   | 0.125         | 0.75             | 295 ± 1          | 156 ± 2          | 130 ± 1          | 124 ± 1          | 123 ± 1          | 120 ± 1          | 116 ± 2          |
| 3                 | 450                   | 0.125         | 1.00             | 298 ± 1          | 159 ± 1          | 132 ± 2          | 126 ± 1          | 125 ± 2          | 122 ± 1          | 118 ± 1          |
| 4                 | 450                   | 0.250         | 0.50             | 301 ± 1          | 160 ± 1          | 134 ± 1          | 128 ± 1          | 127 ± 1          | 124 ± 1          | 121 ± 2          |
| 5                 | 450                   | 0.250         | 0.75             | 303 ± 2          | 162 ± 2          | 137 ± 1          | 131 ± 2          | 128 ± 1          | 126 ± 1          | 123 ± 1          |
| 6                 | 450                   | 0.250         | 1.00             | 306 ± 1          | 164 ± 2          | 138 ± 1          | 134 ± 1          | 130 ± 1          | 128 ± 1          | 126 ± 1          |
| 7                 | 450                   | 0.375         | 0.50             | 308 ± 2          | 167 ± 1          | 142 ± 1          | 136 ± 1          | 132 ± 1          | 131 ± 2          | 128 ± 1          |
| 8                 | 450                   | 0.375         | 0.75             | 310 ± 1          | 170 ± 1          | 144 ± 2          | 138 ± 1          | 134 ± 1          | 133 ± 1          | 130 ± 1          |
| 9                 | 450                   | 0.375         | 1.00             | 314 ± 1          | 172 ± 2          | 146 ± 1          | 140 ± 2          | 137 ± 1          | 135 ± 1          | 132 ± 1          |

4.3. Flash Point and Fire Point

When the percentage of boric acid added with the neem oil increased, it was observed that the flash and fire points have a tendency to increase. The fire point and flash point values of different cutting fluids are presented in Table 9. It is noted that the flash and fire points of the proposed cutting fluids were found to be higher. Hence, the developed cutting fluids could be used for industrial applications.
Table 9. Flash and fire points of different cutting fluids.

| Samples | Flash Point (°C) | Fire Point (°C) |
|---------|-----------------|----------------|
| NO      | 249 ± 1         | 286 ± 2        |
| CCF     | 210 ± 1         | 215 ± 1        |
| S I     | 256 ± 2         | 292 ± 1        |
| S II    | 268 ± 1         | 298 ± 2        |
| S III   | 282 ± 1         | 312 ± 1        |
| S IV    | 306 ± 1         | 332 ± 2        |

4.4. Surface Roughness

The surface roughness values of different machined parts are shown in Table 10. It is perceived that better surface roughness was provided by the cutting fluid with 1% boric acid (S IV). A better surface finish will reduce the assembly time and quality of the product which would increase profit.

Table 10. Surface roughness of machined surfaces.

| Experiment Number | DM  | CCF | NO  | S I  | S II | S III | S IV  |
|-------------------|-----|-----|-----|------|------|-------|-------|
| 1                 | 291 ± 6 | 153 ± 5 | 126 ± 7 | 121 ± 4 | 120 ± 8 | 117 ± 4 | 114 ± 4 |
| 2                 | 295 ± 7 | 156 ± 4 | 130 ± 6 | 125 ± 6 | 123 ± 5 | 121 ± 5 | 119 ± 5 |
| 3                 | 297 ± 4 | 159 ± 6 | 130 ± 8 | 125 ± 8 | 123 ± 6 | 121 ± 8 | 119 ± 7 |
| 4                 | 298 ± 5 | 159 ± 8 | 130 ± 5 | 125 ± 5 | 124 ± 7 | 121 ± 7 | 120 ± 8 |
| 5                 | 300 ± 8 | 160 ± 5 | 130 ± 4 | 125 ± 6 | 124 ± 4 | 121 ± 6 | 121 ± 5 |
| 6                 | 301 ± 9 | 160 ± 6 | 132 ± 6 | 126 ± 7 | 125 ± 7 | 123 ± 7 | 121 ± 8 |
| 7                 | 301 ± 5 | 160 ± 7 | 132 ± 8 | 127 ± 8 | 126 ± 6 | 123 ± 5 | 121 ± 6 |
| 8                 | 301 ± 6 | 160 ± 6 | 133 ± 8 | 128 ± 5 | 126 ± 8 | 124 ± 6 | 123 ± 6 |
| 9                 | 302 ± 7 | 161 ± 6 | 133 ± 6 | 128 ± 6 | 127 ± 6 | 124 ± 4 | 123 ± 6 |

4.5. Flank Wear

The flank wear of the cutting tool for different turning conditions is depicted in Figure 1. It is noted that the cutting fluid with 1% boric acid yields lower flank wear in cutting tool materials. As the lower tool wear would increase tool life, the requirement of a new tool is minimized. Hence, the power consumption for new tool manufacturing is reduced. This also improves environmental sustainability.

4.6. Tool Tip–Workpiece Interface Temperature

Table 11 shows the tool tip temperatures of different machining conditions and from the table, it is evident that the tool tip temperature drops with the increase in boric acid. The reduced temperature would improve surface roughness and hence the quality of components. The reduced tool tip temperature will minimize the secondary machining process such as grinding. This would reduce power consumption and hence environmental impact. The reduction in tool tip–workpiece interface temperature also improves tool life and hence the requirement for new tool materials.

4.7. Stability of Cutting Fluids

The appearance, color, consistency, and homogeneity of the sample cutting fluids did not change after the stability test. This revealed that the proposed cutting fluids are stable and hence could be used for industrial applications.

4.8. Hardness Results of Chips

The hardness of chips developed during different cutting conditions is shown in Figure 2. From the figure, it is evident that the hardness of neem oil-based cutting fluids is
greater than other cutting fluids and dry machining. Better hardness values indicate that the chips, as well as the work piece, would offer more resistance to deformation.

Figure 1. Flank wear comparison of cutting fluids.

Table 11. Tool tip–workpiece interface: Temperature.

| Experiment Number | DM   | CCF  | NO   | S I  | S II | S III | S IV |
|-------------------|------|------|------|------|------|-------|------|
| 1                 | 60.4 ± 0.8 | 45.7 ± 0.6 | 46.4 ± 0.5 | 44.1 ± 0.4 | 41.9 ± 0.4 | 40.1 ± 0.4 | 38.1 ± 0.6 |
| 2                 | 61.0 ± 0.3 | 45.8 ± 0.9 | 47.4 ± 0.6 | 45.0 ± 0.6 | 42.8 ± 0.8 | 40.7 ± 0.6 | 38.9 ± 0.8 |
| 3                 | 61.5 ± 0.6 | 46.3 ± 0.3 | 47.5 ± 0.5 | 45.1 ± 0.6 | 42.8 ± 0.6 | 40.9 ± 0.8 | 38.9 ± 0.6 |
| 4                 | 62.9 ± 0.6 | 47.0 ± 0.2 | 48.2 ± 0.4 | 45.8 ± 0.8 | 43.5 ± 0.6 | 41.4 ± 0.6 | 39.5 ± 0.8 |
| 5                 | 63.6 ± 0.3 | 47.5 ± 0.1 | 48.6 ± 0.6 | 46.1 ± 0.6 | 43.8 ± 0.4 | 41.6 ± 0.4 | 39.8 ± 0.6 |
| 6                 | 63.9 ± 0.6 | 48.5 ± 0.1 | 48.6 ± 0.8 | 46.2 ± 0.8 | 43.8 ± 0.4 | 41.7 ± 0.6 | 39.8 ± 0.8 |
| 7                 | 64.0 ± 0.3 | 49.5 ± 0.6 | 48.7 ± 0.6 | 46.3 ± 0.6 | 43.9 ± 0.6 | 41.8 ± 0.8 | 39.9 ± 0.6 |
| 8                 | 64.9 ± 0.7 | 49.9 ± 0.7 | 49.2 ± 0.6 | 46.7 ± 0.6 | 44.3 ± 0.6 | 42.1 ± 0.6 | 40.3 ± 0.8 |
| 9                 | 65.2 ± 0.5 | 51.0 ± 0.7 | 49.3 ± 0.8 | 46.8 ± 0.8 | 44.5 ± 0.8 | 42.2 ± 0.4 | 40.4 ± 0.6 |

Figure 2. Microhardness comparison of cutting fluids.
5. Conclusions

In this paper, the performance of an eco-friendly cutting fluid was evaluated for the plain turning of AISI 1010 steel. The HNO$_3$ was added with the neem seed oil at different proportions to develop eco-friendly cutting fluids. By varying the machining parameters, several experiments were performed. The surface roughness, cutting force, and tool-tip temperature values were reduced by using the cutting fluid with 1.00% boric acid. The tool flank wear was also reduced. The boric acid-based cutting fluid showed better biodegradability. The biodegradability of the prepared cutting fluids is about 97% which is much better than other cutting fluids used in the industries. The cutting force is reduced by about 22%. The surface roughness is reduced by 60%. The flank wear is reduced by 30% while using the proposed cutting fluids. The flash point temperature of the sample cutting fluids is more than 250 °C which is higher than that of conventional cutting fluids. The fire point of the sample cutting fluids is also higher than that of conventional cutting fluids. The cutting fluids also show better stability. As the developed cutting fluids have superior properties, it was suggested to use these cutting fluids in the automotive industry in India. This will decrease the environmental impacts initiated by conventional metal fluids.

Though better results were reported in the present work, the morphological analysis was not done in the present work, which is a limitation of the current study. Economic analysis was not carried out in this paper. This is another limitation of our study. Hence, in our future work, the cost comparison of different cutting fluids along with the morphological analysis would be performed. Neem oil can be mixed with other types of vegetable oils to improve performance in our future work. The developed cutting fluids may be used for other machining operations.

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