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Efficacy of Nanocutting Fluids in Machining- an Experimental Investigation

Vamsi Krishna Pasam[1,*], Padmini Rapeti[2], Surendra Babu Battula[2]

[1]Department of Mechanical Engineering, National Institute of Technology, Warangal, Telangana State, India.

[2]Department of Industrial Engineering, GITAM Institute of Technology, GITAM University, Visakhapatnam, Andhra Pradesh, India.

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Abstract

This paper presents the experimental investigations on the performance of eco-friendly vegetable oil based nanofluids in turning operation. Cutting temperatures, cutting forces, tool wear and surface roughness under constant cutting conditions are measured during machining. The influence of nanofluids prepared from nanoboric acid (NBA) and carbon nanotubes (CNT) mixed separately with coconut oil (CC), on machining performance is examined. Comparative analysis of the results obtained is done under dry, soluble oil (SL) and lubricant environments at 0.25% nano particle inclusions (NPI). To understand the influence of NPI, the experiments are conducted using CCNBA and CCCNT at varying NPI also. Application of CCCNT resulted in improved machining performance compared to CCNBA. Reduction in cutting temperatures, main cutting force, tool wear and surface roughness is approximately 13%, 37.5%, 44% and 40% respectively by the application of CCCNT compared to dry machining. Thus application of CCNBA and CCCNT at 0.5% NPI is more effective in improving machining performance.

Keywords: nanocutting fluids, vegetable oil, MQL, surface roughness

1. Introduction

Cutting fluids have been most frequently used from the perspective of cooling and lubricating actions during machining in manufacturing industry. The number of investigations revealed that application of conventional cutting fluids hinders the ecological balance and negatively affects the safety of operators [1-2]. These investigations led to the search for environmentally benign cutting fluids. This resulted different alternatives to conventional cutting fluids in terms of cryogenic cooling, vegetable oils, solid lubricant, nanofluids, and minimum quantity lubrication (MQL) technique.

Being biodegradable, operator friendly, abundantly available and affordable, vegetable oils have been thoroughly experimented to examine their applicability in machining operations. Rapeseed oil, coconut oil, sunflower oil etc., are some of the vegetable oils which caught the sight of researchers giving rise to interesting results. Investigations on the effect of new formulations of vegetable oils on surface integrity and part accuracy in reaming and tapping operations with AISI 316L stainless steel were done. Vegetable oil based cutting fluids exhibited better performance than mineral oils by way of tool life, tool wear, cutting forces and chip formation [3].The applicability of coconut oil as a base fluid in industrial applications was examined and machining performance was improved and compared to conventional cutting fluid [4]. Solid lubricant assisted machining has evolved as one of the novel techniques. Graphite, boric acid, and MoS_2 are some of the solid lubricants which have improved

* Corresponding author. E-mail address: vamsikrishna@nitw.ac.in

tribological properties that have grabbed the attention of tribologists. Owing to these properties, solid lubricants aid in wear reduction. These materials are characterized by weak atomic interactions between their layered structures, allowing low shear strength. Improvement in process using graphite, CaF_2, BaF_2 and MoS_2 in grinding operation was reported [5-6]. An attempt was made to use graphite as a solid lubricant to reduce the heat generation at the milling zone [7], resulting in remarkable reduction of cutting force, specific energy and surface roughness. Comparative analysis of machining with a cutting fluid in terms of cutting forces, surface quality and specific energy using graphite and MoS_2 during end milling process revealed encouraging results with solid lubricants [8]. Experiments were conducted to assess the performance of solid lubricants during hard turning while machining bearing steel with mixed ceramic inserts at different cutting conditions and tool geometry [9]. It was reported that surface finish improved from 8 to 15% with the use of solid lubricants compared to dry hard turning. Investigations on the performance of boric acid in machining revealed that, process performance improved with reduced particle size while using dry solid lubricants. Cutting forces, cutting temperatures and tool flank wear were reduced and surface finish improved [10].

In view of enhanced thermo physical properties of nanofluids, various studies to evaluate these properties of nanofluids like specific heat and thermal conductivity were conducted and sufficient improvement in thermal and physical properties of nanofluids was observed [11-13]. In this context, CNTs (carbon nanotubes) with enhanced mechanical, optical and chemical characteristics enable their application in machining operations. CNTs have a high surface to volume ratio, good electrical conductivity and more over their linear geometry makes their surface highly accessible to the electrolyte. The strength to weight ratio of CNT is 500 times greater than aluminum. Analysis of surface characteristics of the tool steel material using multiwall carbon nanotubes to improve the surface finish of material to nano level was done [14]. Carbon nanotubes are special interests to researchers because of the novel properties like extraordinary strength, unique electrical properties and efficient con duction of heat. Depending on the available literature, it has been found that nanofluids have a much higher and strongly temperature-dependent thermal conductivity at very low particle concentrations than conventional fluids. MQL is a promising technique of applying lubricants during machining, which minimizes the usage of cutting fluid and reducing the cost of manufacturing. Research works conducted to examine the nature of the MQL technique during turning operation revealed that MQL reduces induced thermal shock and helps to increase the workpiece surface integrity in situations of high tool pressure [15]. Extensive research was carried out to analyze the performance of different types of nanofluids prepared from Al_2O_3, ZnO, nano diamond particles in MQL grinding [16]. It was concluded by using nanofluids as lubricants basic properties and machining parameters showed considerable improvement. Experimental investigation on the performance of nano boric acid suspensions in SAE-40 and coconut oil showed that nano solid lubricant suspensions in vegetable oil improved the performance parameters during turning of AISI 1040 steel [17].

The affirmative aspects of nano solid lubricants, vegetable oils through MQL technique are being explored by researchers worldwide in order to bring out environmentally safe and user friendly cutting fluids to overcome the disadvantages of conventional ones. In this context, the present work is an attempt to investigate the affect of vegetable oil based nanofluids on machining parameters. Nano boric acid and CNT are used as suspensions (0.25% by weight) in coconut oil and machining is carried out at constant cutting conditions. Cutting forces, cutting temperatures and surface roughness are measured and compared in dry machining environment; using soluble oil, and two nanofluids prepared.

2. Materials and Methods

The present work deals with the application of two nanofluids namely CCNBA (coconut oil + nanoboric acid) and CCCNT (coconut oil + CNT) which are used as lubricants during machining. Other lubricant environments considered include dry machining, CC (coconut oil) and conventional soluble oil (SL) to perform comparative analysis of the performance of nanofluids. Nano boric acid suspensions are added to coconut oil on weight percentage basis (0.25% to 1%) and mixed manually. To enable proper dispersion of nanoparticles in coconut oil, sonication is done for a period of one hour. Thus, two nanofluids namely CCNBA and CCCNT are prepared and applied as cutting fluids during turning.

All the machining experiments are conducted on PSG-124 lathe with a carbide tool (NC6110); heat treated AISI 1040 steel of 30±2 HRC is used as work piece(30mm diameter and 100mm length). Cutting temperatures during turning are sensed by embedded thermocouple (K-type shielded) placed at the bottom of the tool insert in the tool holder. Details of machining are consolidated in Table 1. Cutting force (F_z) is tracked and recorded online using KISTLER 5070 dynamometer. Tool flank wear is measured with Tool makers microscope, cutting temperatures are measured with embedded thermocouple, Surftest – SJ301 with stylus radius 0.0025 mm and cut-off length 0.8 µm was employed for measuring average surface roughness (R_a). The values are recorded thrice and average is considered to avoid discrepancies in measurement.

Machining is initially conducted under dry condition, followed by application of SL, CC, CCNBA, CCCNT as cutting fluids one after the other. Cutting fluids are supplied using the MQL technique with a flow rate of 10 ml / minute. Experiments are conducted at constant cutting conditions (speed: 560 rpm; feed: 0.14mm; depth of cut: 0.5 mm) and 0.25% NPI followed by varying NPI. Machining conditions are chosen referring to previous literature [17, 21]. Cutting temperatures, cutting forces, tool flank wear and surface roughness are measured during all the cases and comparative analysis reflecting the performance of nanofluids with other cases is done. Schematic representation of experimentation is given in Fig. 1.

Table 1 Machining Environment

Cutting conditions	Speed : 60m/min ; Feed : 0.14mm/rev ; Depth of Cut :0.5 mm
NPI	0.25%, 0.5%, 0.75%, 1%
MQL flow rate	10ml/min
Lubricant Environment	a. Dry, SL, CC, CCNBA, CCCNT at 0.25% NPI b. CCNBA & CCCNT at varying NPI
Tool	PSLNR 2020 K12
Cutting tool	CNMG120408 NC6110 (Coated Carbide)
Cutting tool geometry	-6^0, -6^0, 0^0, 6^0, 6^0, 6^0, 0.8mm

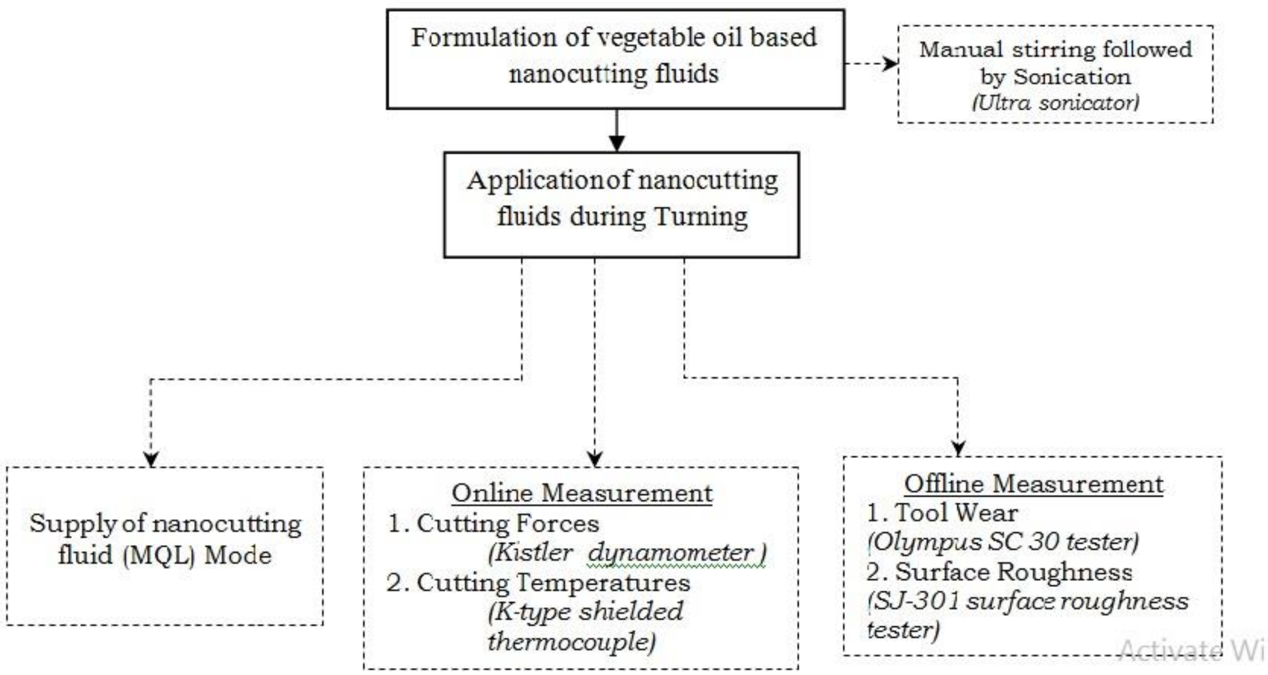

Fig. 1 Schematic representation of experimental work

3. Results and Discussion

Machining is carried out in dry environment and using SL, CC,CCNBA,CCCNT as cutting fluids. The results reflecting the variation of cutting temperature, cutting forces (Fz) and surface roughness (Ra) with respect to time during dry and other environments are presented and discussed in the following sections.

3.1. Cutting Temperatures

Variation of cutting temperatures with machining time is presented in Fig. 2. It is observed that cutting temperatures increased with increase in time for all the lubricant environments. CC, CCCNT and CCNBA are effective in reducing temperatures when compared to dry machining and SL assisted machining. The affirmative behavior of CC can be attributed to the presence of saturated fatty acids to an extent of 90% and length of carbon chains of CC which belongs to medium chain category (6-12 carbons). The chemical composition and fatty acid profile of CC are the primary reasons behind its performance as cutting fluid. Molecular structures of vegetable oils like CC are termed as triacylglicerides. They contain medium chain of fatty acids (MCFA - 6 to 12 carbons length) which are joined at the hydroxyl groups (OH) through ester linkages. CC with high % of SFA and MCFA, at higher temperatures enables formation of a stable film which separates the surfaces in contact [18, 19] exhibits good wettability. Thus, its interfacial properties are enhanced, which plays vital role in lubricant application. [20].The phenomenon of formation of CC film on the metallic surface is more significant in case of vegetable oils like CC. This behavior of CC is accelerated by the additions of nanoparticles (CCNBA and CCCNT) [21]. The reasons behind cooling property of nanofluids is the increase in thermal conductivity and heat transfer coefficient which improve the heat dissipation capacity of nanofluids, thus reducing cutting temperatures at machining zone. Owing to these reasons, nanoparticles in CC tend to reduce cutting temperatures. The performance of CCCNT is found to be slightly better by way of reduction in cutting temperatures due to its thermal properties [22]. The percentage improvement in the reduction of cutting temperatures by using vegetable oil based nanocutting fluids is found to be 13% compared to dry machining. Thus it can be inferred that vegetable oil based nanofluids are more efficient in reducing cutting temperatures.

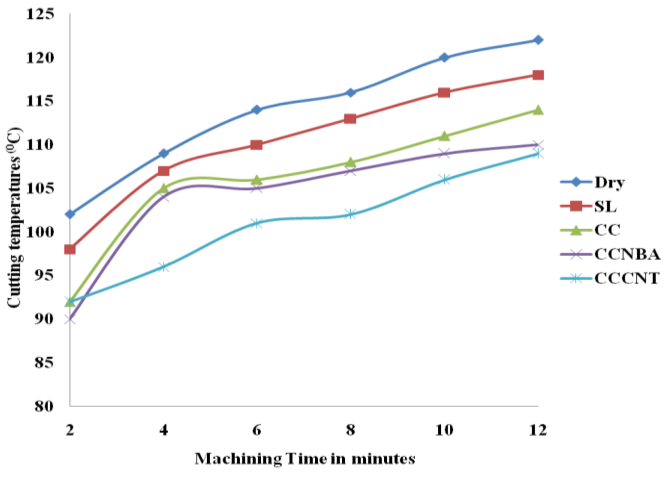

Fig.2 Variation of Cutting temperatures with machining time (Speed: 560 RPM; Feed: 0.14mm/rev; Depth of Cut : 0.5mm; NPI : 0.25%)

3.2. Cutting forces

Cutting force (F_z) is measured at constant cutting conditions and the variation with machining time is shown in Fig. 3. It is noticed that, performance of CC, CCNBA and CCCNT is effective in reducing F_z compared to dry and SL assisted machining. Cutting forces are reduced because of the reduction in coefficient of friction between rubbing surfaces by the application of CC and CC based nanofluids. CC has strong intermolecular interactions get stuck to metallic surfaces resulting in a consistent lubricant layer which persists longer even at high temperatures. The film formation ability is found to be more pronouncing with

CC which comprise of MCFA and which have high amounts of SFA [23]. Another reason which influences reduction in cutting force is viscosity of nanofluids. When viscosity is low heat dissipation capacity of nanofluid increases and when viscosity is high the ability of a nanofluid to form a consistent film separating both the surfaces in contact during machining gets enhan ced [24-25]. Thus, the coefficient of friction between the surfaces in contact reduces which in turn leads to reduction in cutting forces. In the present case, it is found that this phenomenon is more pronouncing by the application of CCCNT compared to all the other lubricant environments. The percentage improvement in reduction of cutting force with CCCNT is approximately 37.5% compared to dry machining.

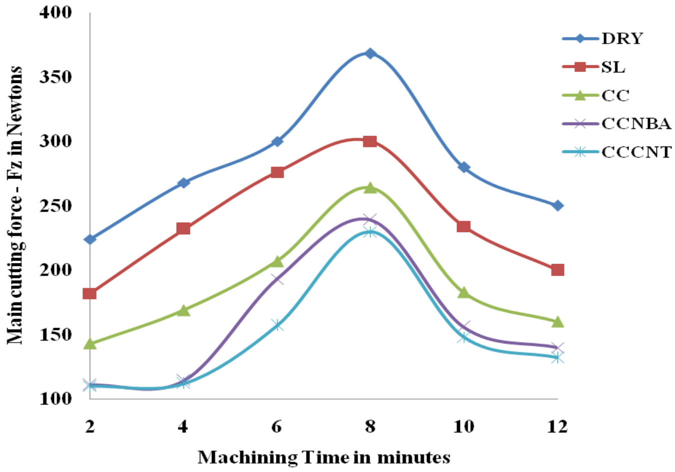

Fig. 3 Variation of Cutting Force with machining time (Speed : 560 rpm; Feed : 0.14mm/rev; Depth of cut : 0.5mm; NPI : 0.25%)

3.3. Tool wear

Tool wear measured corresponds to Tool flank wear which is measured after every pass. The readings are recorded by using Olympus analysis software. The tool is set on the adjustable table of the SC30 optical microscope such that the cutting edge of the tool is just above the focus of 5x and 10x zoom lenses. Tool wear is marked at different zones to get the precise value of wear. The measured tool flank wear is tracked after every turn and average tool wear is taken and graphs are plotted. It is seen from Fig. 4 that tool wear has decreased from dry machining to CCCNT assisted machining. Machining is influenced by high amounts of heat generated at the two deformation zones, which are termed as primary and secondary. This heat induces high temperatures in tool and workpiece. Endowed with better thermal conductivity, enhanced heat transfer rate, CC based nanofluids lead to tool wear reduction [25]. This is accelerated by SFA and MCFA of CC due to which stable film of nano-lubricant persists as discussed in section 3.2. This in turn reduces the shear resistance along the interface and the nano-lubricant film separates the tool-work interfaces, which reduces plastic contacts tending to lower the tool wear [26-27]. Compared to dry machining CCCNT is observed to reduce tool wear to an extent of 44%.

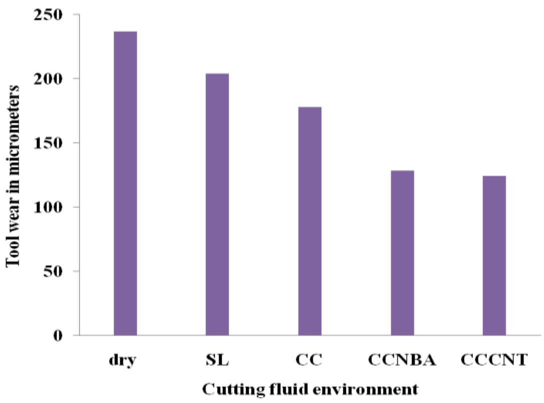

Fig. 4 Variation of Tool wear with cutting fluid environment (Speed : 560 rpm; Feed : 0.14mm/rev; Depth of cut : 0.5mm; NPI : 0.25%)

3.4. Surface roughness

Results of surface roughness (R_a) measurement are shown in Fig. 5. It is observed that the surface roughness is very high during dry machining, followed by SL assisted machining. CC performed midway between CCNBA and CCCNT in improving surface quality. The application of CCNBA and CCCNT resulted in reduced surface roughness compared to other environments. Significant reduction in R_a is obtained by the application of CCCNT. Lubricity of CC, high chemical affinity of nanoparticles towards ferrous surfaces results in covering the valleys between asperities and pores on the surface of workpiece during machining [27]. Improved cooling and lubrication of nanofluids, impart better surface quality to the workpiece by reducing cutting temperature, cutting forces and tool wear. Thus, the application of coconut oil based nanofluids imparts good surface quality to machined surface. An improvement of 40% in the reduction of surface roughness is observed by the application of CCCNT compared to dry machining.

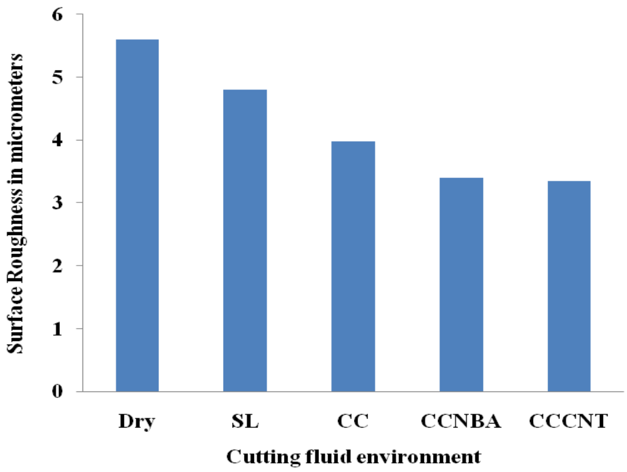

Fig. 5 Comparasion of Surface Roughness in different lubricant environments(Speed : 560 rpm; Feed : 0.14mm/rev; Depth of cut : 0.5mm; NPI : 0.25%)

3.5 Influence of nanoparticle inclusions

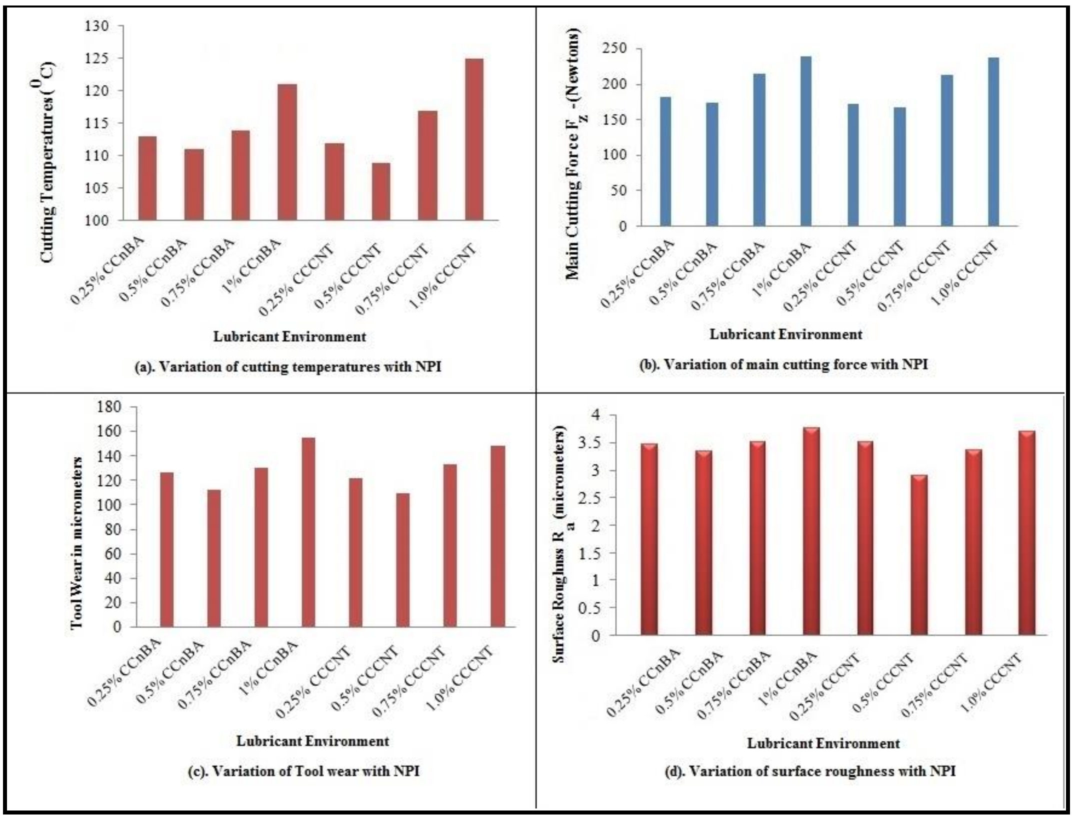

Fig. 6 Variation in machining performance with NPI (Speed : 560 rpm; Feed : 0.14mm/rev; Depth of cut : 0.5mm)

The variation of cutting temperatures, cutting forces, tool wear and surface roughness with varying NPI is presented in Fig. 6(a) to Fig. 6(d). It can be visualized that up to 0.5% NPI substantial improvement in machining is possible by reduction in temperatures, forces, tool wear and surface roughness by applying both types of nanofluids. CCCNT at 0.5% has exhibited better machining performance compared to that of CCNBA at 0.5% NPI. This can be attributed to the phenomenon of agglomeration which affects the uniform dispersions in base oil with increase in NPI [26-27]. Thus, formation of a consistent nano lubricant separating the surfaces in contact is hindered. Thus, beyond 0.5% NPI reduction in cutting temperatures, cutting forces, tool wear and surface roughness is not evident.

4. Conclusions

The effectiveness of vegetable oil based nanocutting fluids CCNBA, CCCNT is examined in this work. Comparative analysis of machining performance of these nanofluids using pure vegetable oil, soluble oil and dry states is done and the following conclusions are drawn:

(1) Vegetable oil based nanocutting fluids are found to be effective in reducing cutting temperatures, cutting forces, tool wear and surface roughness compared to dry machining and soluble oil assisted machining.

(2) Application of CCNBA and CCCNT as cutting fluids during machining resulted in better machining performance than that of CC based machining.

(3) On the total CCCNT with 0.5% NPI is found to exhibit better effectiveness compared to all the cutting fluid environments.

(4) Percentage improvement in machining performance by the application of CCCNT in reducing cutting temperatures, main cutting force, tool wear and surface roughness is observed to be 13%, 37.5%, 44% and 40% respectively compared to dry machining.

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