Performance evaluation of aluminium oxide nano particles in cutting fluid with minimum quantity lubrication technique in turning of hardened AISI 4340 alloy steel

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Abstract

The current research comprises various machinability aspects of 4340 hardened alloy steel which are scrutinized with in context of improvements in main cutting force, tool flank wear, crater wear, surface roughness, microhardness, machined surface morphology, chip morphology, chip reduction coefficient and apparent coefficient of friction under three different cutting fluid applications i.e. compressed air, water soluble coolant based MQL, and nanofluid (using eco-friendly radiator coolant as the base fluid and Al\textsubscript{2}O\textsubscript{3} as the nanoparticle) based MQL technique using cermet cutting inserts and a comparative assessment was performed to select which fluid performed better in terms of various machining attributes among three cutting fluids. The minimum quantity lubrication technique was used in which a smaller volume of coolant sprinkled at high pressure. This method is found as the most effective alternative to minimize health risks and machining costs, which is quite high in other setups. The test specimen was machined at three different cutting speeds i.e. 100, 120 and 140m/min along with two machining parameters i.e. feed and depth of cut were kept constant respectively at 0.2mm/rev and 0.4mm. Outcomes made a conclusion that Al\textsubscript{2}O\textsubscript{3} enriched ecofriendly nano-coolant outperformed both compressed air and water soluble coolant in terms of every machinability aspects.

Keywords: AISI 4340; Cermet inserts; MQL, Nanofluid; Machinability.

Nomenclature

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Introduction

The production industry is becoming equipped with newer advancements with modern technologies day by day. To sustain and grow in the competitive era, new implicative researches are becoming extremely necessary to produce furnished products without disturbing the ecological harmony and keeping the production costs in check. Hence, effective alternatives are required at the moment. One such focused area in the manufacturing domain is hard turning which is derived from the fundamental “turning” operation. It is a single point cutting process usually effective for the materials having hardness magnitude more than 45 HRC. The workpiece can be reduced to its final shape in the hardened state during hard turning. Hard turning was found as a better alternative to cylindrical grinding after adequate exploration as the set up time reduced, process flexibility enhanced, production cost lowered and finishing was almost equivalent to that of grinding. But non-favorable situations always popup such as high degree of heat dissipation which demands expensive high performance cutting tools and extremely rigid machine tools. There are various machinability aspects through which quality of the finished products can be controlled such as surface roughness, machining forces and tool life [1]. Heat generation is an undesired natural phenomenon for any machining operation. It generates at various zones during metal cutting, basically in tool-work and tool-chip interfaces. Heat reduction is tremendously essential as it affects different machinability aspects. So for the reduction of heat and machinability aspects enhancement, newer metal working fluids are used numerously by various industries. Generally, cutting fluids in machining process are used to (1) reduce frictional force at contact areas, (2) cool both cutting tool and workpiece, and (3) help to remove chips from material removal region. Various metalworking fluids delivery techniques are implemented. The commonly used one is the flood cooling. In this technique, the coolant comes out through the nozzle with a greater flow rate but a messy environment increases the health risk factor and time consuming clean up reduces its application. Adding to that cost becomes another constraint. Thus, proposing new environmental cooling and lubricant systems is highly required especially to improve the cutting quality characteristics and achieve a sustainable machining system. The modern approach to machining places an emphasis on the elimination or minimization of the use of lubricant fluid during the machining process due to environmental aspects. This approach is based on optimized cutting fluid application methods (e.g. high pressure coolant, minimum quantity lubrication, and nanofluid based MQL) [2]. Based on the research results, using advanced techniques in cutting fluids application (such as MQL) in the machining process leads to a reduction in cutting forces and heat rejection in cutting regions and improves the durability of cutting tool and surface finish of the workpiece; however, the excessive heat generation problem has not been completely solved. Proposing new nano-cutting fluids can contribute in facing the heat dissipation challenge during cutting processes as it offers a higher observed thermal
conductivity value in comparison with the base lubricants. Additionally, it is shown that nano-cutting fluids have superior cooling properties due to their good heat extraction capabilities [3].

Kuzu et al. [4] experimentally investigated chip morphology and machinability of compacted graphite iron in plain turning under dry and MQL conditions. They have concluded that MQL resulted in lower friction coefficient and provided reduction in cutting force along with, surface roughness by 2-5% and 25%, respectively in comparison to dry finish turning condition. Amini et al. [5] investigated on how the near dry machining can be improved and also studied the effect on tool wear in turning of AISI 4142 alloy steel. From the experiments, they found that tool life in near dry machining was longer than that in dry machining. Further, it showed a positive impact on the surface roughness, which meant that higher cutting speeds, could be used by MQL method compared to dry machining method. Ramanuj Kumar et al. [6] reported that high latent heat absorbed by the water droplets during evaporation through spray impingement cooling technique (similar to MQL technique), cutting temperature is reduced and thus reduces the evolution of tool wear and induced environment friendly cleaner machining. Mia et al. [7] experimentally investigated the effect of different cooling-lubrication conditions (dry cutting condition DC, conventional flood condition FC, minimum quantity lubrication condition MQL, and solid lubrication mixed with compressed air cooling condition SL+CA) on prominent machining indices (cutting temperature, surface roughness, chip characteristics, and tool wear) in hard turning AISI 1060 steel. Consequently, pugh matrix environmental approach has been used to establish the sustainability assessment model (in terms of environmental effect, operator health, coolant cost, recycling cost and disposal, part cleaning, and selected machining responses) among the aforementioned cooling-lubrication conditions. Their research finding show that MQL system can ameliorate the heat transfer problem and divulge quite promising results to improve the desirable machinability characteristics, along with it provides environmental friendliness as well as cleaner production. In another study with the similar workpiece materials, Mia et al. [8] used Grey-Taguchi method for multi-objective optimization of tool-chip interaction parameters (chip compression ratio, effective shear angle, friction coefficient at tool rake surface and chip-tool interface temperature) under two sustainable cutting conditions, i.e., dry and MQL. Later, Mia et al. [9] applied least-square support vector machine (LS-SVM) followed by interior point method (IPM) for prediction and optimization of surface roughness.

Nemati et al. [10] reported that addition of nanoparticles to fluid, the Nusselt number increases, thereby resulting the conduction as significant for heat transfer mechanism rather than convection. Amrita et al. [11] made a performance evaluation of nano graphite inclusions in MQL technique in turning of AISI 1040 steel. Due to the inclusion of nano graphite, reductions in surface roughness, tool flank wear, temperature and cutting forces were observed. Sharma et al. [12] reviewed the research work of many researchers in the field of nano-cutting fluid and found that addition of nanoparticles into base fluid enhances its thermal conductivity, which in turn, improves surface quality, tool life and reduces the cutting force and cutting temperature. It has been found that inclusion of graphite nanoparticles into conventional lubricants enhances its tribological property due to reduced coefficient of friction. Because of their low friction behaviour graphite and MoS2 solid
lubricants reduced surface roughness and cutting force during machining. During hard turning of high-carbon-high-chromium AISI D2 steel (66 HRC) with nanofluid based minimum quantity lubrication (NFMQL) technique, Sharma et al. [13] investigated the effect of multi wall carbon nano tubes (MWCNT) on cutting temperature as well as surface roughness, and concluded that tremendous improvement in surface finish as well as quality of the machined part along with, the reduction of the cutting zone temperature due to the inclusion of MWCNT nanoparticles in the cutting fluid leads to lesser tool wear. Su et al. [14] evaluated the performance of graphite based nanofluid using vegetable based oil or ester oil in cylindrical turning of AISI 1045 steel and the thermos-physical properties like viscosity, surface tension, wettability, thermal conductivity were measured. It was observed that cutting force and temperature were reduced significantly when nanofluid was used. Potole and Kulkarni [15] applied nanofluids in longitudinal plain turning, of AISI 4340 grade HSLA steel by the MQL technique for experimental investigation and multi response optimization. Furthermore, comparative analysis was made to evaluate the cutting performance of multi walled carbon nanotube (MWCNT) nanoparticles mixed with two different base fluids such as, ethylene and water. Results showed that MWCNT nanoparticles mixed with base fluids as ethylene gives better surface roughness as compared to other lubrication systems due to better heat carrying capacity. Similarly, Khajehzadeh et al. [16] studied the effect of TiO2 nanoparticles’ size and concentration on contact length during hard turning of AISI 4140 steel using experimental as well as numerical methods. Based on their results, TiO2 nanoparticles into nanofluid are able to decrease tool-chip contact length, cutting forces and friction coefficient as compared to dry machining. Amrita et al. [17] investigated the application of emulsifier oil based nano cutting fluids in metal cutting process and found that performance of the cutting fluid was measured by various factors like cutting forces, cutting temperature near the chip tool interface, tool wear and surface roughness for each turn. In hard turning of AISI 304 stainless steel, Sharma et al. [18] investigated the machining performance of alumina–MoS2 mixed hybrid nanofluid and alumina-graphite hybrid nano-cutting fluid [19] by MQL technique. In comparison to Al2O3 mixed nano-cutting fluid, the alumina–MoS2 hybrid nano-cutting fluids have shown a significant reduction of 7.35%, 18.08%, 5.73% and 2.38%, respectively in cutting force, feed force, thrust force and surface roughness while, the application of alumina-graphite hybrid nanofluid with MQL technique reduced the abovementioned response by 9.94%, 7.25%, 17.38% and 20.28%, respectively.

Based on the literature review as well as to the best of author’s knowledge, till date, the research application of eco-friendly radiator coolant based nano-cutting fluid in hand turning process have not yet been reported. Furthermore, the literature does not reveal the presence of any article systematically describing the machinability assessment during hard turning of AISI 4340 steel under dry, MQL, and NFMQL conditions, respectively. Comparatively new, yet, this combination of cooling-lubrication techniques has not been studied in hard turning. From the above mentioned published works, the performance of cermet inserts under cutting condition (aluminum oxide nanoparticle into radiator coolant) using MQL technique in the context of sustainable and clean manufacturing is still inadequate to offer a holistic understanding of the process performance. In perspective of the aforementioned research gap, the aim of the present experimental work is to evaluate the performance of different cutting
fluids including Al$_2$O$_3$ nanoparticles based coolant in hard turning of AISI 4340 alloy steel in terms of main cutting force, tool flank wear, crater wear, surface roughness, microhardness, machined surface morphology, chip morphology, chip reduction coefficient and apparent coefficient of friction using cermet inserts. The present study deals with a vast area of knowledge about the application of different cooling-lubrication methods in finish hard turning process where the problem of chip control and the cutting tool wear plays a very important role for enhancement of machining performance as well as improvement of machinability.

2 Experimental details

In the present experimental work, three different cutting fluids were used i.e. compressed air, water soluble coolant and Al$_2$O$_3$ based nanofluid and machinability aspects were evaluated for hardened alloy steel (AISI 4340) using the minimum quantity lubrication technique. Three different levels of industrially implemented cutting speed were considered whereas feed rate and depth of cut were kept unaltered. The tool used was uncoated cermet insert. Machinability aspects especially cutting force, tool flank wear, crater wear, surface roughness, microhardness, machined surface morphology, morphology of chip surface, coefficient of chip contraction and apparent coefficient of friction were evaluated for each case and a comparative assessment was performed among them. The experimental runs were carried out at three speed levels i.e. 100, 120 and 140m/min for the machining time of 30, 60, 90, 120, 180, and 240 s. Feed and depth of cut were fixed at 0.2mm/rev and 0.4mm, respectively.

Three cutting forces in three mutually perpendicular directions, axial, tangential and radial were measured using three dimensional dynamometer (Manufactured by Kistler, Switzerland). Each component was measured thrice for the error minimization and then the principal cutting force (Fc) was evaluated for thorough analysis. To measure the surface roughness of the machined part, Taylor Hobson roughness tester (Model: Surtronic 3+) was used. Four locations were chosen and roughness was measured around the machined specimen circumference. The procedure was repeated thrice and the average value was finally considered as mean value. Both the flank wear and crater wear of the inserts were measured using an advanced optical microscope (Manufactured by Carl Zeiss, Model: Axio Cam ERc 5s). Scanning electron microscope (SEM) was used at flank and rake faces for better morphological analysis. On the worn out faces i.e. both rake and flank faces of inserts, wear was quantified at three divergent positions for better accuracy and their mean values were treated as the final one for further analyses. Machined surface morphology for three cutting conditions was analyzed using SEM. The chip morphology was examined using both SEM and photographic images. Chip thickness was measured using vernier caliper at five different locations and the mean value was considered as final. Samples were cut from machined surface for microhardness analysis and mounted thereafter. Each sample was polished after mounting with different grades of polishing papers. Vickers micro hardness tester (Manufactured by Leco, Model: LM248AT) was used to obtain the microhardness at the machined samples in all the three cutting environments. The microhardness measurements were performed into the sub-surface region of the test specimen along a
straight line perpendicular to the machined surface (radially). A gap of 10 µm was kept between two consecutive indentations. 10 s and 0.025 N were set as the dwell time and test load respectively.

2.1 Test specimen

AISI 4340 alloy steel was chosen to be the test specimen for this present experimental investigation having diameter 50mm and length 700mm. It was a medium carbon low alloy steel consisting of chromium, nickel and molybdenum. Molybdenum prevents the steel from temper embrittlement. This specimen is characterized by low specific heat, excessive hardness and high strain hardening. It has better impact resistance as well as wear and abrasion resistance in the hardened condition. It has high ductility in annealed condition. This alloy is extensively used in the manufacturing of power transmission gears and shafts, aircraft landing gears, automotive, oil and gas drilling etc. The chemical composition of the AISI 4340 was tested using Spectrometal analyzer, result is shown in the Table 1.

The experiment was performed on a heavy duty conventional lathe machine. The maker of this machine was Hindustan Machine Tools (HMT) Ltd., Bangalore, India and the model was NH26.

2.2 Heat treatment

Heat treatment becomes essential when microstructural alterations and sometimes chemical properties of a specimen is required to be changed. It is a complex process initiates from treating of the sample to an austenizing temperature of 920°C. The workpiece was kept at that temperature for 30 minutes thereafter to allow the reformation of crystalline structures. Then oil quenching was accomplished as this alloy’s hardenability was suited for this quenching process only. The sample was again heated after that to a temperature, which was below the critical temperature i.e. 400°C for tempering, and it was kept in similar condition for 2 hours. The salient feature of this process was to reduce the hardness in the material and enhance toughness. This was followed by gradual cooling of the workpiece in atmospheric condition to avoid any residual stresses and hence a homogenous structure was formed. With the courtesy of this process, there was an enhancement of hardness from 18 HRC to 48 HRC. After the heat treatment process, the martensite and ferrite structure was formed as shown in Fig. 1.

2.3 Selection of cutting insert and tool holder

Here, an uncoated cermet insert was chosen for the experiment. A cermet consists of a ceramic material dispersed in metal matrix. The ceramic quotient helps to provide wear resistance and the metal quotient enhances toughness. The advantage of using this inserts is that it provides superior resistance to thermal and mechanical fracture, reducing machining costs. The designation of this cermet was SNMG 120408. The grade of the tool was NS730, manufactured by Tungaloy Corporation. The designation of the tool holder was PSBNR 2020K12. Some of the properties of the insert were given in the Table 2 shown below. The detailed cutting geometries of the tool holder are illustrated in Fig. 2. The nomenclature of
the inserts is very important to understand its geometry. Table 3 given below describes the tool geometry in detail.

2.4 Selection and preparation of cutting fluids

As discussed earlier, three types of cutting fluids were selected i.e. compressed air, water soluble coolant and Al₂O₃ nanoparticles based cutting fluid. First compressed air was used as cutting fluid and it was supplied at 7 bar pressure and a flow rate of 150ml/h to the machining zone. For the second phase of experimental run, water soluble coolant was used. Servo cut metal working fluid was selected for the experiment. The coolant was prepared by intermixing water (base fluid) in the ratio of 10:1. Nanofluid was used in the last phase of experiment, which was a homogenous mixture of aluminium oxide nanoparticles and eco-friendly radiator coolant. Radiator coolant was chosen to be the base fluid as it possesses environmental friendliness and abundant heat dissipation capability. The nanoparticle was procured from Sigma Aldrich. The size of the nanoparticle was less than 50 nm. The coolant was manufactured by a German company Wurth. For the preparation of nanofluid, the radiator coolant and distilled water were intermixed in the ratio of 1:4 initially. The requisite amount of Al₂O₃ nanoparticles i.e. (for 500 ml solution, 2.5 gm. nanoparticle.) was further mixed with the base fluid. In order to improve the homogeneity of the mixture, magnetic stirrer was used. The solution was kept on the magnetic stirrer for 5 hours then it was kept in ultrasonicator for 2 hours, where the uniform colloidal solution was obtained. Figure 3 shows the set up for present experimental investigation.

3 Results and discussion

3.1 Study of chip morphology

Chips are generally of two types: (1) acceptable chips (2) unacceptable chips. Acceptable chips do not interfere with the workpiece or machine tool and can be easily disposed. Unacceptable chips do not acquire such properties.

For the initial phase of experimental investigation, compressed air was used as the working fluid and ribbon type chips were found. The chip color was found yellowish as shown in Fig. 4(a). This may be attributed to inadequate heat liberation. Hence, a negative impact on the workpiece and on the tool was observed especially in terms of surface finish and tool life. Water soluble coolant was used as the cutting fluid for the next phase of experiment and found that long wavy chips of blue color were formed as shown in Fig. 4(b). This might be because of the effective dissipation of heat than that of compressed air. The chips produced by nano cutting fluid shown in Fig. 4(c) was long, continuous and helical in nature. The helix angle of the chip was reduced by the use of aluminium oxide nanoparticles because due to the impingement of the nanoparticles on the chips, more curled chips were formed. The blue color of the chips was a clear indication that the heat generated was properly liberated.

From Fig. 5(a) illustrated above, a distinctive white band and black band were observed known as ridges and feed marks respectively. Ridges are formed at areas at high temperature generation zones and feed marks are formed at low temperature zones. Since high heat was generated with the use of compressed air and this heat was distributed non-uniformly over the chip surface, ridges and feed marks were observed more prominently. Prominent saw tooth was observed on chip surface during compressed air machining. Shear localization and
plastic deformation were the two important factors for formation of saw tooth during machining. As more friction was observed in compressed air machining that resulted high temperature, which might be a reason for prominent saw tooth formation. There was a development of performance when water soluble coolant was used for the experiment. Side flow was observed in the chips and the serration was reduced appreciably in comparison to compressed air and no ridges and feed marks were found. In this experimental work, less deformation occurred and machining became difficult due to the application of water soluble coolant, which is shown in Fig. 5(b). This allowed the material to flow in a direction perpendicular to the feed leading to the material side flow. Negligible serrations and minor side flow was observed during machining operation with nanofluid as shown in Fig. 5(c) because huge amount of heat was liberated in nanofluid compared to compressed air and water soluble coolant.

3.2 Microhardness analysis

One primitive aspect of machining activity is surface microhardness. The variation obtained in microhardness at the top surface of the machined specimen for three cutting fluids after a machining time of 240 s with three different speed levels i.e. 100, 120 and 140 m/min was shown in Fig. 6. It was unveiled that the microhardness profile obtained with nano cutting fluid inclined in between compressed air and water soluble coolant for three ranges of cutting speeds. Its value was also reduced from the edge towards the center of the machined specimen. There was no substantial influence of water soluble coolant and nanofluid on microhardness alteration compared to compressed air. Further, a simplistic slope was noticed in the same diagram. This type of simplistic slope was observed due to the influence of cutting zone temperature accompanied with the coolant application. At high speed i.e. 140 m/min, surface temperature of the workpiece might be high due to insufficient heat transfer to surroundings because of less time. Hence, less microhardness was observed at the surface area compared to sub surface region with water soluble coolant and nanofluid application.

3.3 Chip reduction coefficient or coefficient of chip contraction

Chip length reduces which is termed as longitudinal chip contraction. Chip reduction coefficient or chip contraction coefficient is the ratio of chip thickness after cutting and chip thickness before cutting. It is also the inverse of chip thickness ratio. It is the quantification of plastic deformation occurred during the machining process. It mainly depends upon the formation of built up edge (BUE) and amount of friction present at tool-work and tool-chip interface [20]. It can be calculated by the following formula.

\[ \xi = \frac{t_c}{t_o} \]  
(1)

Where \( t_c \) is the chip thickness and \( t_o \) is the uncut chip thickness. The uncut chip thickness can be calculated by the following equation.
Where $\phi$ is the approach angle of the insert. In the present experimental investigation ($\phi = 75^0$ for SNMG or square shaped insert). And $f$ is the feed rate (mm/rev).

Figure 7 demonstrated the changes occurred in the chip reduction coefficient for three cutting fluids with different machining durations and cutting speeds. From the figure, it was concluded that high chip reduction coefficient was found for compressed air compared to water soluble coolant and nano-cutting fluid because of high friction. Minimum chip reduction coefficient was observed in case of nanofluid owing to less friction.

3.4 Apparent coefficient of friction

Apparent coefficient of friction is a significant parameter for machining operation. It generally occurs at interface of tool-work and tool-chip. It depends on tool wear and machining environment. In the present experimental investigation, the apparent coefficient of friction for three cutting fluids i.e. compressed air, water soluble coolant and nano cutting fluid was calculated using the following formula.

$$\mu = \frac{Fc \sin \gamma + F_t \cos \gamma}{Fc \cos \gamma - F_t \sin \gamma}$$

(3)

Where, $\gamma$ is the orthogonal rake angle of the insert.

$F_c$ is the cutting force and $F_t$ is the thrust force.

$F_t$ can be calculated by the following formula.

$$F_t = \sqrt{Fr^2 + Ff^2}$$

(4)

Where $F_t$ = Radial force

$F_f$ = Feed force

The alteration of apparent coefficient of friction with machining time for three cutting fluids at different speed levels was shown in Fig. 8. From figure, it was divulged that apparent coefficient of friction was high for compressed air compared to water soluble coolant and nanofluid. Minimum value of apparent coefficient of friction was obtained during application nanocoolant owing to its heat transfer capability. The temperature at tool-work-chip interface reduced resulted lesser magnitude of cutting force and friction.

3.5 Analysis on main cutting force

Cutting force is a significant primitive machinability aspect to be studied as it influences various other machining parameters such as power consumption, tool life, temperature, surface quality and chip quality etc. Figure 9 illustrated the variations present in the main cutting force with respect to machining time under application of three cutting fluids. From
the figure, it was concluded that for a cutting speed of 100m/min, there was a steady increment of the main cutting force with the machining time for three cutting fluids. However, when speed went to 120m/min and 140m/min the main cutting force reduced slightly after of 180s machining time. Heat dissipation to the atmosphere is very difficult because of shortened timespan at high cutting velocities that sometimes causes thermal softening of workpiece. This might be a reason for the main cutting force reduction at high cutting speeds. Moreover, shear strength of the workpiece reduces resulting shear deformation, at high cutting speed, which affects the cutting force significantly. Greater magnitudes of main cutting forces were observed with compressed air cooling for three different cutting speeds while opposite outcome was observed using nanofluid [21, 22]. An interesting phenomenon was observed while applying nanofluid in machining operation. There was a sharp abatement in main cutting force approximately 55.05% and 25.55% with respect to compressed air and water soluble coolant. The credit goes to excellent cooling and lubricating property of the nanofluid and rolling and cushioning effect of spherical shaped Al₂O₃ nanoparticles, which absorbs any sudden load that lowers the cutting force. Similar observation is reported in the previous work [23]. There was no notable variation in the main cutting force was found between application of water soluble coolant and nanofluid.

3.6 Analysis on surface roughness

Surface roughness (Rₜ) was recorded after the accomplishment of machining with three cutting fluids, which were exhibited in Fig. 10. Higher degree of surface roughness was observed at 100m/min of cutting speed. However, when altered to high range speeds i.e. 120 and 140m/min, magnitudes of surface roughness decreased slightly. From figure, it was made clear that machining became smoother at relatively higher cutting velocities. In higher cutting speeds, thermal softening of specimen work occurs due to continuous machining resulted less cutting force that led to the achievement of finer surface quality. This might be a reason of getting less surface roughness at higher speeds. The chip characteristics highly influence the surface quality. At higher cutting speeds, chip forms and breaks at the tool tip area with a slight plastic deformation enhances the surface quality. This might also be a reason of having superior surface finish at higher cutting speeds. Less surface roughness was observed for nanofluid [17, 24] against water soluble coolant and compressed air for three different level of cutting speeds. This was due to the better cooling and lubrication aspects of nanoparticles based cutting fluid and friction observed at tool-work and tool-chip interfaces was less and so roughness was found lesser due to these characteristics. More friction was observed with compressed air owing to inadequate heat dissipation of air resulted improper cooling that led to higher roughness value.

3.7 Analysis of flank wear

In the present research, flank wear on inserts face was studied with the help of both SEM and advanced optical microscope. Figure 11 displayed the progress of average flank wear for different machining time at three different cutting speeds under three cutting fluids applications. A Steep increment in wear at the flank surface was observed after 120 s of cutting time at high range of cutting speeds i.e. 120 and 140m/min particularly when machining operation was performed with compressed air. However, no significant changes were observed in flank wear up to 60 s of machining time for three cutting speeds under three
cutting fluids applications. Minimum wear on flank face was observed in nanofluid machining due to its capability of effective cooling and lubrication [22].

The optical microscopic images demonstrated of advancement in flank wear for three different speeds with three dissimilar fluids with respect to the duration of 240 s of machining in Fig. 12. At higher cutting speeds, i.e. 140m/min wear was found more for three cutting fluids. Similar results were visible for other machining time spans. Figure 13(a)-(c) represented the SEM images of the flank faces of worn out inserts for three cutting fluids. As steel has sticky nature, Built up edge (BUE) was observed. BUE was observed prominent with compressed air application. Very small BUE was visible while using water soluble coolant. Nanofluid ceased any BUE to be formed. Similarly, rough abrasion marks and semi-rough abrasion marks were observed on flank face while using compressed air and water soluble coolant. However, smooth abrasion was observed with nanofluid because of its excellent cooling and lubricating properties that resulted in the sharp reduction of friction and temperature. It led to improve significantly in the cutting inserts performance especially in application of nanofluid under high speed machining.

3.8 Crater wear analysis

Rake face wear or crater wear, the primitive type of tool wear analysis chiefly depends on the diffusion and adhesion wear. High temperature, pressure and chemical affinity of the test specimen are the three dominating parameters for such wear. Figure 14 demonstrated the optical microscopic images of the rake faces of inserts for compressed air, water soluble coolant and nano cutting fluid at three speed levels with respect to 240 s machining time. From Fig. 14, it was made clear that rake faces of the inserts were damaged because of catastrophic failure in compressed air machining environment than that of water soluble coolant and nanofluid machining. At the speed level of 140m/min, more wear was observed for all three cutting fluids. Similar results were observed for other machining times. Abrasion, adhesion, plastic deformation and BUE formation were the four major wear mechanisms found fit to the crater wear analysis in the current research. Adhesion was the most sound wear mechanism for three cutting fluids. Higher chemical affinity of the test specimen might be a reason for this adhesion as it has sticky nature. From the SEM images of the rake surfaces shown in Fig. 15 for three cutting fluids, it was observed that thin abrasion, adhering layer and BUE was present in water soluble coolant machining, thick abrasion marks, prominent adhering layers and plastic deformation was present with compressed air machining whereas very thin layer made due to adhesion was present. No plastic deformation, BUE or abrasion was observed while machining with nanofluid. This unveiled the superior functional capability of nanofluid and its advantage over compressed air and water soluble coolant.

3.9 Analysis of machined surface morphology

Machined surface morphology is a prominent aspect of a machining operation, normally characterized by macro morphology of machined part. Figure 16 illustrated the machined surface morphology using uncoated cermet inserts for three cutting fluids at 140m/min of cutting speed. Feed marks, void, plucking and deposited material were found on the machined surface with compressed air machining. Thin feed marks were observed when machining with water soluble coolant. For nanofluid machining, no surface defects were found while more damages were observed while using compressed air due to inappropriate
cooling and lubricating characteristics. High surface temperature of workpiece, more tool wear and severe plastic flow are the reasons for damage on machined surface. High surface temperature of workpiece resulted in plastic deformation that led to adhesion of chips to the machined surface.

4 Conclusions
Every experiment conducted has certain set of goals achieved. A set of conclusions drawn represents the front-end of the genuine research executed which are enlisted below.

- A large degree of deterioration in principal cutting force i.e., 55.05% and 25.55% was observed when machining with AISI 4340 hardened alloy steel with application of nanofluid than that of compressed air and water soluble coolant cutting conditions.
- A steep reduction of 78% and 49.04% in context of flank wear was observed by nanofluid application as compared to compressed air and water soluble coolant.
- Superior surface finish and better surface quality were observed with nanofluid machining compared to compressed air and water soluble coolant machining.
- Water soluble coolant based MQL and compressed air cutting environments affect microhardness of the machined part adversely at surface and sub-surface region, but the nanofluid based MQL treatment has not done so.
- Nanofluid can be successfully implemented as a metal working fluid during machining of hardened AISI 4340 grade alloy steel to get desired machining characteristics within a specified range of cutting parameters.
- Ecofriendly radiator coolant can be now utilized as a base fluid for the nano-coolant preparation as it is compatible with outer environment.

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Fig. 4. Chips produced using (a) compressed air, (b) water soluble coolant, and (c) nano cutting fluid  
Fig. 5. SEM image of chip with (a) compressed air, (b) water soluble coolant, and (c) nano cutting fluid  
Fig. 6. Variation of microhardness at cutting speed of: (a) 100m/min, (b) 120m/min, and (c) 140m/min.  
Fig. 7. Comparison of chip reduction coefficient at (a) 100m/min, (b) 120m/min and (c) 140 m/min  
Fig. 8. Variation of apparent coefficient of friction at (a) 100m/min, (b) 120m/min and (c) 140 m/min  
Fig. 9. Main cutting force variation at (a) 100m/min, (b) 120m/min and (c) 140 m/min  
Fig. 10. Surface roughness variation at (a) 100m/min, (b) 120m/min and (c) 140 m/min  
Fig. 11. Flank wear variation at (a) 100m/min, (b) 120m/min and (c) 140 m/min
**Fig. 12.** Flank wear at 100, 120 and 140 m/min of cutting speed with compressed air, water soluble coolant and nanofluid application at 240 sec of machining time

**Fig. 13.** SEM images of flank surface using (a) compressed air, (b) water soluble coolant and (c) nano fluid at 140 m/min speed

**Fig. 14.** Wear on rake face at 100, 120 and 140 m/min of cutting speed with compressed air, water soluble coolant and nanofluid application at 240 sec of machining time

**Fig. 15.** SEM images of rake surface using (a) nano cutting fluid, (b) water soluble coolant and (c) compressed air at 140 m/min speed.

**Fig. 16.** SEM images of machined surface morphology using (a) nano cutting fluid, (b) water soluble coolant and (c) compressed air at 140 m/min speed.

### Table 1 Composition of AISI 4340 steel

<table>
<thead>
<tr>
<th>Element</th>
<th>Weight. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nickel, Ni</td>
<td>1.550</td>
</tr>
<tr>
<td>Chromium, Cr</td>
<td>0.900</td>
</tr>
<tr>
<td>Manganese, Mn</td>
<td>0.770</td>
</tr>
<tr>
<td>Carbon, C</td>
<td>0.397</td>
</tr>
<tr>
<td>Molybdenum, Mo</td>
<td>0.275</td>
</tr>
<tr>
<td>Silicon, Si</td>
<td>0.339</td>
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</table>

**Fig. 1.** Microstructure of hardened steel after heat treatment

### Table 2 Property of the insert

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Specific Gravity</td>
<td>6.8</td>
</tr>
<tr>
<td>Hardness in HRA</td>
<td>92</td>
</tr>
<tr>
<td>Transverse rupture strength in GPa</td>
<td>2.2</td>
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</tbody>
</table>
Fig. 2. Illustration of cutting geometry of tool holder

Table 3 Nomenclature of cutting inserts

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>Insert shape (90° point angle, square)</td>
</tr>
<tr>
<td>N</td>
<td>Clearance angle (0°)</td>
</tr>
<tr>
<td>M</td>
<td>Tolerance class [± 0.002 for inscribed circle (d), ± 0.003 for height of insert (m), ± 0.0005 for thickness (s)]</td>
</tr>
<tr>
<td>G</td>
<td>Insert features – Number of cutting edges with types of chip breaker geometry</td>
</tr>
<tr>
<td>12</td>
<td>Cutting edge length (12 mm)</td>
</tr>
<tr>
<td>04</td>
<td>Insert thickness (4.76 mm)</td>
</tr>
<tr>
<td>08</td>
<td>Nose radius (0.8 mm)</td>
</tr>
</tbody>
</table>
Fig. 3. Experimental setup

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<th>Cutting fluids</th>
<th>Cutting speeds (m/min)</th>
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<tr>
<td></td>
<td>100</td>
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<tr>
<td>Compressed air</td>
<td>![Image]</td>
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<tr>
<td>Water soluble coolant</td>
<td>![Image]</td>
</tr>
<tr>
<td>Nanofluid</td>
<td>![Image]</td>
</tr>
</tbody>
</table>

**Fig. 12.** Flank wear at 100, 120 and 140 m/min of cutting speed with compressed air, water soluble coolant and nanofluid application at 240 sec of machining time
Fig. 13. SEM images of flank surface using (a) compressed air, (b) water soluble coolant and (c) nano fluid at 140m/min speed
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<td>![Image]</td>
</tr>
<tr>
<td>Nanofluid</td>
<td>![Image]</td>
</tr>
</tbody>
</table>

**Fig. 14.** Wear on rake face at 100, 120 and 140 m/min of cutting speed with compressed air, water soluble coolant and nanofluid application at 240 sec of machining time
Fig. 15. SEM images of rake surface using (a) nano cutting fluid, (b) water soluble coolant and (c) compressed air at 140m/min speed.

Fig. 16. SEM images of machined surface morphology using (a) nano cutting fluid, (b) water soluble coolant and (c) compressed air at 140m/min speed.
Biographies

Anshuman Das is now working as a Research scholar in Industrial Design Department of National Institute of Technology, Rourkela. He graduated in Mechanical Engineering from Biju Patnaik University of Technology, Rourkela in the year 2007. He obtained M-Tech degree from National Institute of Technology, Jamshedpur with a specialization of “Design & Manufacturing”. His research interests include hard machining, machining process modelling, optimization, analysis and prediction, cryo treatment of cutting inserts and nanofluid applications in machining of hard materials.

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Sudhansu Ranjan Das is currently an Associate Professor in the Department of Production Engineering, Veer Surendra Sai University of Technology (VSSUT), Burla, India. He received his PhD in Manufacturing Engineering in 2016 from National Institute of Technology, Jamshedpur, India. His research interests include hard machining, machining process modelling, optimization, analysis and prediction. He has published more than 31 papers in refereed journals and conference proceedings.