REVIEW OF RECENT DEVELOPMENTS IN THE USE OF NANOFLUIDS AS COOLANTS IN METAL CUTTING OPERATIONS

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Abstract: Metal cutting operation is one of the manufacturing industries operations that can benefit tremendously from the application of nanofluids as coolants. Nanofluid is one of the recent inventions in the field of Nanotechnology. Nanofluids can be simply thought of as fluids prepared by the suspension of nanoparticles (1 – 100 nm) in a base fluid. This is done in order to improve the thermophysical properties of the base fluid as regards it intended application. However, from available literature research as shown that nanofluid does have improved thermophysical properties compared to other fluids under same application as well as positive effect on the machining parameters. In addition, there is still the need for standardization in it mode of preparation, percentage by volume of its inclusion in the base fluid, nanoparticle size and it application. Therefore, this paper presents some recent experimental investigation on the use of nanofluids as coolants in metal cutting operations.

Keywords: Nanofluids, nano-cutting fluids, machining, metal cutting operations

Introduction

One of most widely used manufacturing processes is Machining. This is due to its ability to adaptably produce components to a high tolerance and is employed in various metal industries for the production of automotive, aerospace, medical, and other products. Metalworking fluids have an essential role in machining processes in providing lubrication and thermal conductivity (Niyaghi *et al.*, 2014). The process of regular removal of material from the surface of a material with the use of appropriate cutting tool is known as metal cutting operation. Machining operation entails firstly the plastic deformation of the workpiece material and secondly friction between tool to chip and tool to workpiece interface. Metal cutting operation demands a significant level of energy which is usually expressed as heat. Machining of some materials particularly those of the ferrous group and other high strength alloys are associated with very significant heat generation. In machining operation brilliant surface finish is desirable (aerospace industry for example) which is usually achieved through high speed machining.

Consequently, high speed machining results in a significant heat being generated between the tool to chip and tool to workpiece interface due to friction. The generated heat needs to be reduced considerably (Shailesh, 2015). One of the challenges confronting machining operation in industries is the effective removal of the significant heat generated as a result of friction between tool to chip and tool to workpiece interface. The heat removal is usually achieved by applying appropriate cutting fluid (Dutta *et al.*, 2002; El-Tamimi & El-Hossainy, 2008; Gaitonde *et al.*, 2009; El-Hossainy *et al.*, 2010; Denni & Yusof, 2010). The effective removal of the heat avert undesirable consequences such as reduced tool life, poor surface finish of the machined material and reduction in overall performance of the machining operation which are some of the major reasons for the introduction of cutting fluids (Coolant, Lubricant or Nanofluids) in metal cutting operations (Sahijpaul, 2015). Fluids used in machining operations are called cutting fluids or machine coolants; they are primarily for the purpose of heat dissipation, lubrication and corrosion prevention. The uprising development in cutting fluids emanated from the discovery of the cooling properties of mineral oils. The different types of cutting fluids are straight oils, soluble oils or semi synthetic oils and synthetic oils (Yusuf *et al.*, 2016).

In metal cutting operations, cutting fluids prevent metal to metal contact and decrease internal friction. The addition of a fluid between the two sliding surfaces (tool and workpiece) separates the two surfaces by forming a film, thereby reducing the frictional resistance and wearing (Bartz, 2001). The Cooling ability of a fluid helps to control undesirable temperature of tool, workpiece and chip. During machining process, cutting fluids wash and remove generated chip (Weinert *et al.*, 2004). They can also be used to prevent re-welding, corrosion protection, reduction in machine energy consumption, and increasing tool life (Byers, 2012; Yusuf *et al.*, 2017).

Nanotechnology is emerging rapidly in recent years and it is becoming a strong new trend in global technology. This trends show that nanotechnology is likely to impact our daily life in a big way in the coming decades (Islam & Miyazaki, 2009). Nanotechnology involves producing, controlling and using collections of materials of extremely reduced size, in the nanometer range and the integration of the resulting nanostructures into larger systems. Nano-materials exhibit new properties which can be used in various applications. Nanotechnology has been described as a major key for the economic expansion in the twenty-first century (Saidur *et al.*, 2011).

The sudden breakthrough in this new field of technology is as result of a natural evolution of different disciplines over several decades in the areas of surface science, colloids, interfaces and aggregates, advances in physics and chemistry of nano objects, breakthroughs in instrumentation with the possibility of manipulating atoms, miniaturization trends in microelectronics, fabrication and characterization of micro and nano systems (Pepina *et al.*, 2011; Park & Bang, 2014). With the advancement of nanotechnology, nano-materials are found in wide applications that bring the character manifested under the nano scale by atoms and molecules under control in the development of new materials, components, processes and systems and that the manufactured nanotechnology products are developed with the goal of being slim and light.

Heat removal and management have been the major concerns for any technology that deals with high power and small size. Application of nanofluids to address these issues has been the main subject of interest for many researchers around the world (Lee *et al.*, 2013; Hajjar *et al.*, 2014; Sharifpur *et al.*, 2015; Sharma *et al.*, 2016). In several cases, nanofluids can be customized to fit a particular requirement and can act as a flexible cooling method, adjusting to the needs of a specific system. Basically, nanofluids have the potential to become the world's first smart/adaptable coolant (Sadeghinezhad *et al.*, 2016). Nanotechnology provides new area of research to process and produce materials with average crystallite sizes below 100 nm called nanomaterials.

The term "nanomaterials" encompasses a wide range of materials including nanocrystalline materials, nanocomposites, carbonnanotubes (CNTs) and quantum dots (Gupta *et al*., 2012). Nnanoscience and nanotechnology and their applications have definitely become the new research areas that every industry is required for their technological development (Chien-Yun *et al.*, 2012). Nanotechnology is being used in many applications targeted to provide cleaner, more efficient energy supplies and uses. These applications have the potential to reduce the need for the electricity, petroleum distillate fuel, or natural gas that would otherwise be moved through energy transmission system. Application of nanotechnology can result in more efficient energy generation thereby reducing the amount of construction, maintenance, repair, and decommissioning activities (Prasher *et al.*, 2006; Naphon *et al.*, 2008; Sharma *et al.*, 2009).

Heating or cooling of fluids is very important to many industrial sectors like manufacturing, transportation, electronics and energy supply. The thermal conductivity of these fluids plays an important role in the development of energy-efficient heat transfer equipment (Hwang, et al., 2006). Nano-cutting fluid is prepared by suspending nanoparticles in conventional cutting fluid; this is necessitated by the demanding cooling and lubricating challenges in machining (Khandekar *et al*., 2012).

Some researchers (Wen & Ding, 2004; Yang *et al.*, 2005; Ding *et al.*, 2006; Das *et al.*, 2009; Srivatsan, 2010) have showed that the convective heat transfer coefficient increases substantially for nanofluids. Increased relative surface area and quantum effects are the two most principal factors that affect the properties of materials at nanoscales. Quantum effects intensely enhance properties such as optical, electrical and magnetic behavior of materials. The smaller the size of a particle the greater the proportions of atoms in the surface compared to those inside (Karthikeyan *et al.*, 2008; Shalkevich *et al.*, 2010; Sarkhosh & Mansour, 2015).

The outstanding chemical, physical and mechanical properties of nanomaterials are utilized in a wide range of applications such as sunscreens, displays, batteries, cosmetics, paints, sensors, catalysis, medicine, coolant, energy, stain resistant textiles, agriculture and plastic packaging. The quest for efficient cooling materials led to the emergence of a new field of research called nanofluid (Warzoha *et al.*, 2015). Usually, this field falls in the realm of colloidal science and hence abundant knowledge on preparation; characterization and stabilization of nanofluids exist. The vigorous Brownian motion of suspended nanoparticles in base fluids makes nanofluids more stable compared to microfluids, which is one of the attractions of nanofluids for heat transfer applications (Angayarkanni & Philip, 2015).

Nanofluids are produced by distribution of solid nanoparticles in a base fluid in order to; increase the thermal conductivity factor for the improvement of the heat transfer ability. Some typical nanofluids are ethylene glycol based copper nanofluids and water based copper oxide nanofluids, Nanofluids are dilute suspensions of functionalized nanoparticles composite materials developed about a decade ago with the specific aim of increasing the thermal conductivity of heat transfer fluids, which have now evolved into a promising nano-technological area. Such thermal nanofluids for heat transfer applications represent a class of its own difference from conventional colloids for other applications (Serrano *et al.*, 2009; Mintsa *et al.*, 2009; Godson *et al.*, 2010).

The order of the magnitude of thermal conductivities of solids is larger than those of conventional heat transfer fluids. For example, copper thermal conductivity in ambient temperature is about 700 times more than water and 3000 times more than engine oil (Wong & Castillo, 2010; Shekarian *et al.*, 2014). It is acknowledged that due to their nanostructural features, nanomaterials exhibit enhanced properties (such as mechanical, thermal, physical and chemical), phenomenon and processes than conventional materials (Xuan & Li, 2000). In addition, the mathematical expression of Newton's law of cooling describes better the features of nanofluids.

Newton's law of cooling: $Q = hA\Delta T$

Where Q = rate of heat transfer, h = coefficient of heat transfer, A = heat transfer area, and T = temperature difference that results in heat transfer. Therefore, from this equation, increase in heat transfer in nanofluids 'Q'can be achieved by: (i) increasing h, (ii) increasing A, and (iii) increasing ΔT. The strategies of increasing heat "A" and "ΔT"cannot be employed in some applications such as machining and metal cutting operations. Heat transfer improvement in these applications is achieved by increasing the heat transfer coefficient "h" which is achievable by improving the transport properties of the heat transfer material. Heat transfer coefficient can be increased by enhancing the properties of the coolant for a given method of heat transfer which is an important area of nanotechnology application.

Beside the convectional additives that are often added to liquid coolants to improve specific properties, heat transfer coefficient can be improved through the addition of solid particles (nano- particles) (Moghaddam*et al.*, 2013; Ghozatloo *et al.*, 2014; Sarkar *et al.*, 2015). Materials commonly used as nanoparticles include chemically stable metals (e.g. gold, copper), metal oxides (e.g., alumina, silica, zirconia, titania), oxide ceramics (e.g. Al_2O_3, CuO), metal carbides (e.g. SiC), metal nitrides (e.g. AIN, SiN) and carbon in various forms (e.g., diamond, graphite, fullerene). Furthermore, Carbonnanotubes (CNTs) are also employed due to their significant high thermal conductivity in the longitudinal (axial) direction.

Therefore, in this paper, recent developments in the use of nanofluids as coolants, methods of production of nanofluids, application of nanofluids in various machining and metal cutting operations are analyzed.

Nano-coolants

Liquid coolants have long been used in the manufacturing, metallurgical, automotive and other industries. The fluids used in machining operations are called cutting fluids or machine coolants. The effective selection of cutting fluid is based on the awareness of their thermo-physical properties. Cutting fluid provide the advantage of good surface finish of the machined material as well as reduced cutting force during matching (Shailesh, 2015). The typical methods of improving the cooling rate in metal cutting operation has been exhausted and new technological developments are increasing thermal loads that require faster cooling (Brnic *et al*., 2009; Deng *et al.*, 2010; Rama *et al.*, 2010; Nirmal *et al.*, 2010). Therefore, the inherently low thermal conductivity of conventional heat transfer fluids such as water, mineral oil and glycols has led to the search for improved heat transfer liquids. Manufacturers are always looking for more efficient cooling technologies in order to increase the overall system performance with reduction in financial and environmental impact. In the past few decades, rapid advances in nanotechnology have led to emerging of new generation of fluids called "nanofluids". Nanofluids are a relatively new class of fluids, they are now

of great interest for improving heat transfer performance that are related to energy savings (Cheng, 2009).
Nanofluids have been shown to exhibit higher thermal conductivities than conventional cooling liquids such as water, kerosene, ethylene glycol and microfluids. They have some unique features which are quite different from dispersions of mm or μm sized particles. They do not block flow channels and induce only a very small pressure drop during flow, which is beneficial for heat transfer applications (Angayarkanni & Philip, 2015).
In metal cutting operations, nanotechnology is being applied in the area of development of nanofluid as cutting fluids (nanocoolants) due to its renowned superior thermophysical properties to typical cutting fluids Hasan (Hasan, 2015). Nanocoolants are engineered colloids made of a base fluid and nanoparticles (1-100 nm). Common base fluids include water, organic liquids (e.g. ethylene, tri-ethylene-glycols, refrigerants, etc.), oils and lubricants, bio-fluids, polymeric solutions and other common liquids. In the past decade and half, there have been abundant experimental as well as numerical studies done to explore the advantages of nanofluids under wide variety of conditions (Vajjha & Das, 2012; Shahrul *et al.*, 2014). Studies showed that relatively small amounts of nanoparticles can enhance thermal conductivity of base fluids to a large extent. Hwang *et al.* (2006) investigated the characteristics of thermal conductivity enhancement of four kinds of nanofluids include multiwall carbon nanotube (MWCNT) in water, CuO in water, SiO_2 in water, and CuO in ethylene glycol. Thermal conductivities of these nanofluids were measured by a transient hot-wire method. The results obtained show that the thermal conductivity enhancement of nanofluids depends on the thermal conductivities of both nanoparticles and the base fluid.
Liu *et al.* (2006) investigated the enhancement of the thermal conductivity of ethylene glycol in the presence of copper oxide (CuO). The CuO nanofluids were prepared using a two-step method. The thermal conductivities of the CuO suspensions were measured by a modified transient hot wire method. CuO nanoparticles are examined using scanning electron microscopy (SEM) to determine their microstructure. The crystalline phases of the CuO powders are measured with x-ray diffraction patterns (XRD). The results showed that ethylene-glycol-CuO nanofluids have significantly higher thermal conductivities than the same ethylene glycol base liquids without solid nanoparticles. The thermal conductivity ratio enhancement for CuO nanofluids is approximately linear with the volume fraction of nanoparticles. For CuO nanoparticles at a small volume fraction of 0.05, the thermal conductivity was improved by 22.4 %. This shows that CuO nanofluids have good potential for effective heat transfer applications.
The convective heat transfer of Al_2O_3 water nanofluid inside a circular tube with constant wall temperature was investigated by (Zeinali *et al*., 2007). The results showed that the increase in heat transfer coefficient due to presence of nanoparticles is much higher than the prediction of single phase heat transfer correlation used with nanofluid properties and the heat transfer coefficient of the nanofluid increases by the increase in the concentration of nanoparticles. They also showed that the heat transfer enhancement was due to the nanoparticles presence in the fluid. Yoo *et al*., (2007) also studied and compared the thermal conductivities of TiO_2, Al_2O_3, Fe, and WO_3 nanofluids with each other. The nanofluids were prepared in a two-step procedure by dispersing nanoparticles in a base fluid. The transient hot wire method was used for the measurement of the thermal conductivity. The results showed a large enhancement of thermal conductivity compared with their base fluids which exceeds the theoretical expectation of two-component mixture system.
Vajjha & Das, (2009) investigated the thermal conductivities of three nanofluids comprising aluminum oxide, copper oxide and zinc oxide nanoparticles dispersed in a base fluid of ethylene glycol and water mixture in the ratio of 60:40 (by mass). The results showed an increase in the thermal conductivity of nanofluids compared to the base fluids with an increasing volumetric concentration of nanoparticles. The thermal conductivity also increases substantially with an increase in temperature. Yu *et al.* (2009) studied thermal conductivity and viscosity of ethylene glycol based ZnO nanofluid. The transient short hot-wire technique was used to measure the thermal conductivities of the nanofluids and the results obtained showed that the thermal conductivity of ZnO-EG nanofluids is independent of setting time from 20 to 360 min. Also, the thermal conductivity rises with the increase in the temperature and it is strongly dependent on the size of suspended nanoparticles while the enhanced ratios are almost constant.
The electrical conductivity of aqueous suspensions of aluminium oxide nanofluids was studied by Ganguly *et al.* (2009). Experiments were performed both as a function of volume fraction and temperature to examine the effects of their variations on the electrical conductivity of alumina nanofluids. The results indicated considerable enhancement of electrical conductivity with both increase in volume fraction and temperature. The dispersion stability and thermal conductivity of propylene glycol-based nanofluids containing Al_2O_3 and TiO_2 nanoparticles in the temperature range of 20 - 80^oC were studied by Palabiyik *et al.* (2011). The two-step method and no dispersant were used to formulate nanofluids with different concentrations of nanoparticles. The results obtained showed that the average particle size of nanofluids decreases with increase in temperature, and nanofluids showed an excellent stability over the temperature range of interest.
Dudda & Shin, (2013) investigated nanoparticle dispersions in a molten binary nitrate salt eutectic. The molten salt mixtures were used as heat transfer fluids and thermal energy storage in a concentrated solar power plant. The results obtained showed that the specific heat capacity of the nanomaterials was enhanced with increase of nanoparticle size. The observed enhancement was found to be 8, 12, 19 and 27 % for 5, 10, 30 and 60 nm, respectively. This shows that the nanostructures formed in the nanomaterials were responsible for the improvement in the specific heat capacity.
Heat transfer and pressure drop characteristics of CeO_2/water nanofluid in plate heat exchanger were studied by Tiwari *et al.* (2013). The results revealed that the nanofluid in plate heat exchanger has maximum of 39% higher heat transfer coefficient compared to water at optimum concentration of 0.75% by volume. Nanofluid yields substantial heat transfer enhancement with insignificant rise in pressure drop at peak concentration. The heat transfer coefficient of the nanofluid increases with an increase in the volume flow rate of the hot water and nanofluid it also increases with a decrease in the nanofluid temperature.
Thermal conductivity and viscosity of Ethylene Glycol (EG) based nanofluids containing ZnO nanoparticles with different mass fractions between 1.75 and 10.5% were investigated by Li *et al.* (2015) using a two-step method. Structural properties of the dry ZnO nanoparticles were measured with Transmission Electron Microscopy (TEM) and X-ray diffraction (XRD). The results showed that thermal conductivity enhancement depends strongly on particle concentration and increases nonlinearly with the concentration within the range studied. It also increases with increase in the temperature from 15 to 55^oC.

Angayarkanni & Philip (2015) carried out the thermal conductivity measurements of n-hexadecane alkane containing nano-inclusions of copper nanowire, multi-walled carbon nanotube, and graphene nano-platelets of different volume fractions in phase change under freezing. The results showed that the nano-inclusions at grain boundaries of alkane crystals led to the increase in the thermal conductivity. Though the thermal conductivity enhancement at higher particle loading was independent of the bulk thermal conductivity of dispersed nano-materials, large thermal contrast was observed at a very low concentration in copper nanowire suspension.

The above literatures and many other studies (Zhang *et al.*, 2007; Lee, *et al.*, 2008; Zhu *et al.*, 2009) have shown the immensely significant technological implications (heat transfer and thermal conductivity enhancements) of the use of nanoscale particulate suspensions in fluids nanoparticles. These studies also revealed high thermal conductivity has the major feature that is very important for heat transfer systems. For their analyses, the researchers explored the underlying physical mechanism that govern the heat transfer phenomena in a nanofluid, such as molecular-level layering of the liquid at the liquid-particle interface Brownian motion of the nanoparticles, nanoparticle clustering and the nature of heat transport in the nanoparticles.

Different types of nanofluids have been designed for a broad range of engineering applications; nanofluids have huge potential application prospects in energy industry, chemical engineering industry, machine tools, automobiles, refrigeration and air-conditioning, optical filters, solar devices automobile, construction, microelectronics, defect sensors and other fields such as materials, physics, and chemistry.

Method of production of nanofluids

Nanofluids are prepared by dispersing nanometre-sized particles, generally less than 100 nm, in a base fluid such as water, ethylene glycol, propylene-glycol, oil and other conventional heat transfer fluids. Choi *et al.* (1995) from Argonne National Laboratory (US) first invented this fluid in 1995 and since then research is going on tremendously. Addition of high thermal conductivity metallic/non-metallic nano-particles into the base fluid increases the thermal conductivity of such mixtures, thus enhancing their overall heat transfer capability.

The compounds and elements often employed in nanofluid research are Aluminium oxide (Al_2O_3), Copper (II) oxide (CuO), Titanium (II) Oxide (TiO_2), Titanium carbide (TiC), Silicon carbide (SiC), Silver (Ag), Copper (Cu), Gold (Au) and Iron (Fe) nanoparticles (Ramakoteswaa *et al.*, 2014). Preparation of nanofluids is important for the measurement of their specific heats because particle agglomeration depends on the preparation methods. There are two techniques mainly used for synthesizing nanofluids: two step method and single step method.

Two-step technique

This method consists of two distinct steps, the first step is to produce the nanoparticles and the second step is to disperse the nanoparticles in a base fluid (Fig. 1). The merit of this technique is that it supports mass production of nanofluids while the demerit is that the nanoparticles form clusters during the preparation of the nanofluid which prevents the proper dispersion of nanoparticles inside the base fluid (Yu *et al.*, 2008). It is agreed that using the inert gas condensation technique nanoparticles can be produced in large quantities (Romano *et al*., 1997).

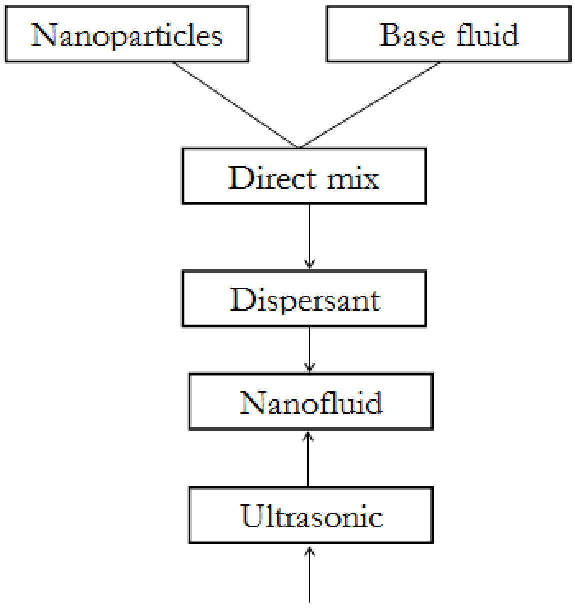

Fig. 1: Two-step preparation process of nanofluid (Gupta *et al*., 2012)

One-step technique

In this technique, the production of nanoparticles and dispersion of nanoparticles in the base fluid is combined in one step. There are some variations of this technique. These variations include the thermal decomposition of an organometallic precursor in the presence of a stabilizer, chemical reduction, polyol synthesis and direct evaporation. In direct evaporation one-step method, nanofluid is produced by the solidification of the nanoparticles initially in gaseous phase, inside the base fluid (Eastman *et al*., 2001). The one-step technique has an advantage over the two-step technique in that it produces better dispersion characteristics of the nanofluids. However, the pitfall of this technique is that only limited quantities can be produced (Yu *et al.*, 2008).

Machining processes

Machining is a major manufacturing process that adds to the bulk of products' cost. Economy of machining is affected by the frequent changing of cutting tool due to tool wears which usually prolong the production times and increase the cost of product. Quite a lot of parameters affect the condition of cutting tool but the most conspicuous among them are the cutting forces and temperatures (Amrita *et al*., 2014). Hence, it has always been the drive to develop appropriate methods for reducing friction and temperatures accompanying metal cutting operation.

The application of cutting fluids is prominent among such methodologies. It prevents thermal expansions of the workpiece and as a result, the fluids help in attaining longer tool life and better surface finish of the product (Srikant *et al.*, 2009). Recent developments in nanotechnology have shown that new generation coolants that contained nanoparticles suspension for the enhancement of the fluids' heat transfer and tribological properties are the prefer cutting fluids been use in the following machining operations.

Turning operations

This is the process of manufacturing cylindrical components on the Lathe machine. For example shafts, pins, and threads. In addition, some effects such as step turning, tapering, knurling can also be performed. Turning is said to be one of the most fundamental processes in manufacturing industries (Sodavadia & Makwana, 2014). In turning operation, a stationary tool travels along the axis of a rotary workpiece and regularly removes material from the surface of the workpiece in form of chip (Eastman *et al*., 2001). The constant contact between tool to chip and tool to workpiece interface results into friction thereby generating a significant amount of heat. The removal of this heat becomes a necessity hence the use of cutting fluid in turning operations (Lawal *et al*., 2012). According to available literature, quite a number of investigation and researches on metalworking fluids (synthetic oils for example) have been carried out in recent years particularly researches on nanofluids are predominant (Saravanakumar *et al.*, 2014; Su *et al.*, 2016)). Fig. 2 shows the turning operation with cutting fluid application.

Fig. 2: Turning operations

Fig. 3: Milling operation

Milling operations

This is a machining process capable of producing a variety of shapes involving flat surfaces, slots, and contours. Milling machine uses a multiple teeth cutter on a stationary workpiece. Each tooth of the multiple teeth cutter takes its own share of cut on the machined workpiece. Milling machines can be divided into three groups: horizontal, vertical and universal (Razfar, 2010). Cutting fluids are introduced in milling operation to reduce the temperature of cutting zone, increase surface quality and tool life of workpiece (Mayur & Borse, 2016). Fig. 3 shows the milling operation with cutting fluid application.

Drilling operations

This is the process of making a hole in the workpiece. The cutting tool is a spiral fluted tool with two or more symmetrical cutting edges known as the drill (Alinejad & Ghafari, 2011). Drills of various diameters are capable of producing round holes of various sizes and depths in the workpiece. Reaming, boring, tapping, counter-boring and honing operations are also carried out on the drilling machine. Significant heat and temperature is been generated as a result of the contact between the drill and the workpiece. Hence cutting fluid is applied for effective heat and temperature removal thereby preventing burning of the drill and decrease surface quality (Shokrani *et al.*, 2013). Fig. 4 shows the drilling operation with cutting fluid application.

Fig. 4: Drilling operation

Fig. 5: Grinding operation

Grinding operations

This is the process of machining workpiece that requires smooth surface finish and precise tolerance (Shen *et al.*, 2008). The cutter employed is a rotating wheel. Grinding operation is a high speed machining process which results in high workpiece to tool temperature. The challenge in grinding operation is to control this resulting high temperature to prevent the workpiece and cutting wheel from burning.

It is acknowledged that the surface quality in grinding operation is affected adversely by the generated heat (Sanchez *et al.*, 2010). The introduction of coolant and lubricant in grinding operation avert the burning of workpiece and the cutting wheel (Vasu & Kumar, 2011). Research has shown that the higher thermal conductivity and convection heat transfer factor of nanofluids makes them applicable coolants in high speed machining process (Setti *et al.*, 2012). Fig. 5 shows the grinding operation with cutting fluid application.

Application of nanofluids as coolants in metal cutting operations

Researchers have prepared Nanofluids using desired preparation technique and choice nanoparticles in different base fluids. The prepared Nanofluids were used as coolants on matching operations to evaluate it effects on machining parameters such as cutting force, surface roughness, machining temperature, chip morphology/chip thickness and tool wear. In light of the above, the reviews of some research are presented below.

Khandekar *et al.* (2012) prepared nanofluid using Al_2O_3 (1% by volume in base fluid). The prepared mixture consist of Servo Cut ''S'' plus additives plus Al_2O_3 nanoparticles and Water. The prepared nanofluid was used as cutting fluid for the turning operation and the result presented shows that the improved cooling and lubrication effect of the nanofluid helps to decrease the cutting force by 51.6 and 29.5% at machining time of 300 seconds as compared with dry and typical cutting fluid respectively. Similarly, surface roughness decreases by 64.3 and 28.6% as compared with dry and typical cutting fluid, respectively.

Setti *et al.* (2012) conducted a study on the performance of nanofluid as cutting fluid in grinding operation under Minimum Quantity Lubrication (MQL) technique. Nanocutting fluid was made by adding 4% by volume Al_2O_3 nanoparticles to conventional cutting fluid. It was discovered that the enhanced lubrication and cooling characteristics of nano cutting fluid helps to reduce the tangential grinding force and surface roughness by 55 % and 33.3 % respectively as compare with conventional coolant.

Prasad & Srikant, (2013), prepared the nanofluid by the inclusion of graphite powder (0.0 %, 0.1, 0.3 and 0.5% by weight) nanoparticles into water soluble oil. The experiment was conducted under Minimum Quantity Lubrication (MQL) and the machining operation used is the turning operation. The study revealed that increase in percentage addition of the nano graphite lead to better performance of the base fluids in terms of cutting force, temperature, surface roughness and tool wear.

Saravanakumar *et al.* (2014) experimented with synthesized silver nano particles dispersed in conventional cutting fluid. The experiment was conducted on the turning operation. The experimental result show that cutting force, tool tip temperature and surface roughness reduced considerably. Furthermore, Cutting force and Surface roughness were reduced by 8.8 and 7.5%, respectively.

Shailesh (2015) this paper presents an experimental study on the enhancement effect of Al_2O_3 nanoparticles dispersed in base fluid as cutting under Minimum Quantity Lubrication (MQL) technique in turning operation. The result clearly shows that addition of Al_2O_3 in the base fluid significantly reduces the dynamic fluctuation of cutting forces, cutting temperature, tool wear, and surface roughness. Furthermore, increase in percentage by volume of Al_2O_3 above 5% had adverse effect on the performance of the nanofluid. Ramesh *et al.* (2016), this paper presents the investigation of the performance of Al_2O_3 addition in base fluid. The prepared nanofluid was used as cutting fluid on turning operation and it effect on flank wear and crater wear were evaluated. It was observed that the nanofluid reduces flank wear and crater wear by 21 and 23%, respectively as compared with dry and Minimum Quantity Lubrication (MQL).

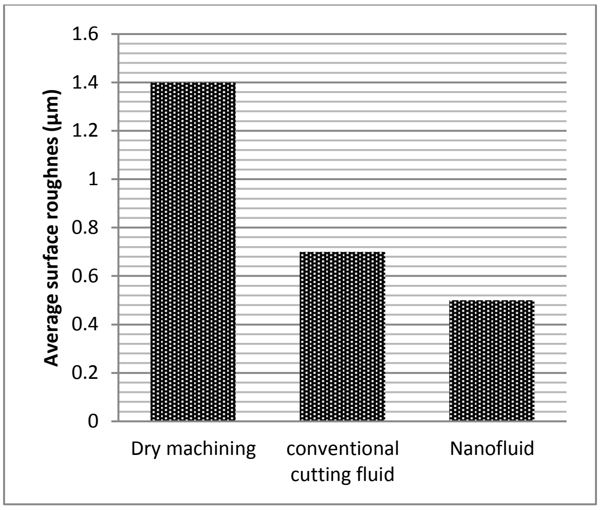

Fig. 6: Variation in average surface roughness (Mayur & Borse, 2016)

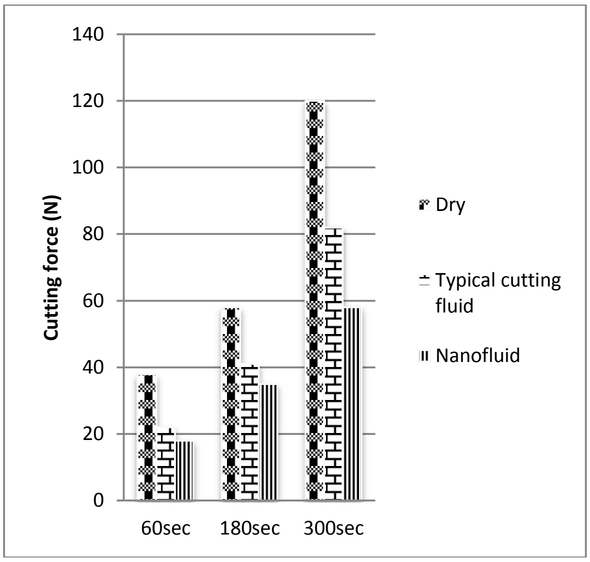

Fig. 7: Cutting force versus machining time (Khandekar *et al.*, 2012)

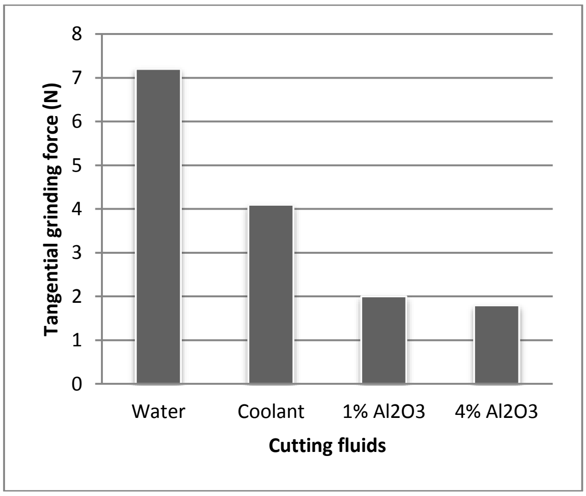

Fig. 8: Variation in tangential grinding force (Setti *et al.*, 2012)

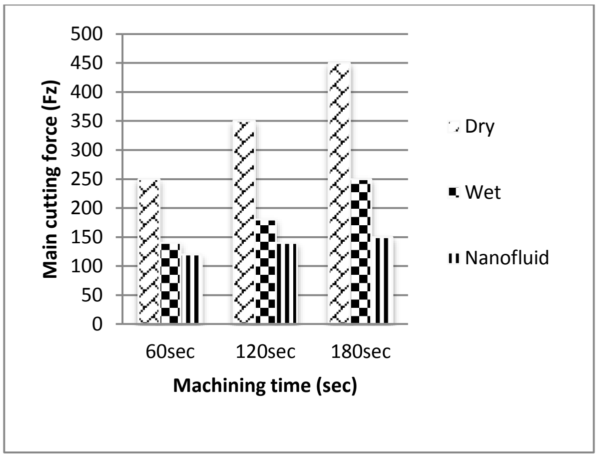

Fig. 9: Main cutting forces versus machining time (Mayur & Borse, 2016)

Conclusion

This paper presents a review of some recent literature and experimental investigation of the use of nanofluids as coolants in metal cutting operations under different machining operations. From the reviewed literature, the use of nanofluids as coolant presents interesting improvements on the considered machine parameters. These improvements if they are fully harnessed in metal cutting operation will lead to an unprecedented manufacturing improvement in such industry.

However, from available literature there exist diverging views of various researchers on the preparation and application of nano-cutting fluids. Therefore, standardization on the preparation of nano-cutting fluids still require more research in order to categorically specify which particular nanomaterial(s) in what volume % will perform best in which base fluid (s). This standard will largely enhance the application of this fluid as cutting fluids in metal cutting operations.

References

Alinejad G & Ghafari M 2011. *Principles of Universal Machining Machine Tool.* Babol, Iran: Babol University Technology press.

Amrita M, Shariq S, Manoj K & Gopal C 2014. Experimental investigation on application of emulsifier oil based nano cutting fluids in metal cutting process. *Procedia Engineering* , 115-124.

Angayarkanni, S., & Philip, J. (2015). Review on thermal properties of nanofluids: Recent developments. *Advances in Colloid and Interface Science* , 146-176.

Angayarkanni S & Philip J 2015. Thermal conductivity measurements in phase change materials under freezing in presence of nano-inclusions . *J. Applied Phy.*, 118.

Bartz W 2001. *Ecological and environmental aspects of cutting fluids* (57th ed.). Illinois: Lubrication Engineering.

Brnic J, Canadija M, Turkalj G, Lanc D, Pepelnjak T, Barisic B *et al*. 2009. *Tool Material Behavior at Elevated Temperatures.* Materials and Manufacturing Processes.

Byers J 2012. *Metalworking Fluids.* USA: CRC Press.

Cheng L 2009. Nanofluid heat transfer technologies. *Recent Patents on Engineering*, 1-7.

Chien-Yun D, Wan-Fei C, Yu-His Y & Chia-Hung Y 2012. A study on modification of knowledge, attitude and practice on vocational high school electronics courses integrated with nanotechnology concept. *Int. J. Thermal and Envtal. Engineering*, IV(1): 73-79.

Choi U, Singer D & Wang H 1995. Developments and applications of non-newtonian flows. New York: ASME – Fluids Engineering Division (FED).

Das S, Choi S, Yu W & Pradeep T 2009. *A Review of Nanofluids: Science and Technology.* Materials and Manufacturing Processes.

Deng W, Xia W, Li C & Tang Y 2010. *Ultrafine Grained Material Produced by Machining.* Materials and Manufacturing Processes.

Denni K & Yusof S 2010. *Hard machining of stainless steel using wiper coated carbide: Tool life and surface integrity* (25th ed.). (VI, Ed.) Materials and Manufacturing Processes.

Ding Y, Alias H, Wen D & Williams R 2006. Heat transfer of aqueous suspensions of carbon nano tubes (CNT nanofluids). *Int. J. Heat and Mass Transfer*, 240–250.

Dudda B & Shin D 2013. Effect of nanoparticle dispersion on specific heat capacity of a binary nitrate salt eutectic for concentrated solar power applications. *Int. J. Thermal Sci.*, 37-42.

Dutta A, Narasaiah N, Chattopadhyay A & Ray K 2002. *Influence of Microstructure on Wear Resistance Parameter of Ceramic Cutting Tools* (17th ed., Vol. V). Materials and Manufacturing Processes.

Eastman J, Choi S, Li S, Yu W & Thompson L 2001. Anomalously increased effective thermal conductivities of ethylene glycol-based nanofluids containing copper nanoparticles. *Applied Phycis Letter*, 718-720.

El-Hossainy T, El-Zoghby A, Badr M, Malawi K & Nasr M 2010. *Cutting parameter optimization when machining different materials* (25th ed., Vol. X). Materials and Manufacturing Processes.

El-Tamimi A & El-Hossainy T 2008. *Investigating the tool life, cutting force components, and surface roughness of AISI302 stainless steel material under oblique machining* (23rd ed., Vol. IV). Materials and Manufacturing Processes.

Gaitonde V, Karnik S, Figueira L & Paulo D 2009. *Analysis of machinability during hard turning of cold worktool steel* (23rd ed., Vol. IV). Materials and Manufacturing Processes.

Ganguly S, Sikdar S & Basu S 2009. *Experimental investigation of the effective electrical conductivity of aluminum oxide nanofluids.* Powder Technology.

Ghozatloo A, Rashidi A & Shariaty-Niassar M 2014. Convective heat transfer enhancement of graphene nanofluids in shell and tube heat exchanger. *Experimental Thermal Fluid Science*, 136-141.

Godson L, Raja B, Mohan-Lal D & Wongwises S 2010. Enhancement of heat Enhancement of heat transfer using nanofluids - An overview. *Renewable and Sustainable Energy Reviews*, 629–641.

Gupta H, Agrawal G & Mathur J 2012. An overview of nanofluids: A new media towards green environment. *Int. J. Envtal. Sci.*, III(1): 1-8.

Hajjar Z, Rashidi A & Ghozatloo A 2014. Enhanced thermal conductivities of grapheme oxide nanofluids. *Int. Commun. in Heat and Mass Transfer*, 128-131.

Hasan S 2015. A Review on nanoparticles: Their synthesis and types. *Res. J. Recent Sci.*, 1-3.

Hwang Y, Ahn Y, Shin H, Lee C, Kim G, Park H *et al.* 2006. Investigation on characteristics of thermal conductivity enhancement of nano fluids. *Current Applied Physics*, 1068-1071.

Islam N & Miyazaki K 2009. Nanotechnology innovation system: Understanding hidden dynamics of nanoscience fusion trajectories. *Techn. Forecasting & Soc. Change*, 128-140.

Karthikeyan N, Philip J & Raj B 2008. Effect of clustering on the thermal conductivity of nanofluids. *Materials Chem. and Phy.*, 50-55.

Khandekar S, Sankar M, Agnihotri V & Ramkumar J 2012. *Nano-cutting fluid for enhancement of l cutting performance.* Materials and Manufacturing Processes.

Lawal S, Choudhury I & Nukman Y 2012. Application of vegetable oil-based metalworking fluids in machining ferrous metals – A review. *Int. J. Mach. Tools Man*, 1-12.

Lee J, Hwang K, Jang S, Lee B, Kim J, Choi S *et al*. 2008. Effective viscosities and thermal conductivities of aqueous nanofluids containing low volume concentrations of Al2O3 nanoparticles. *Int. J. Heat and Mass Transfer*, 26.

Lee S, Kim K & Bang I 2013. Study on flow boiling critical heat flux enhancement of graphene oxide/water nanofluid. *Int. J. Heat and Mass Transfer*, 348-356.

Li H, Wang L, He Y, Hu Y, Zhu J & Jiang B 2015. Experimental investigation of thermal conductivity and viscosity of ethylene glycol based ZnO nanofluids. *Appl. Thermal Engr.*, 363-368.

Liu M, Lin M, Huang I & Wang C 2006. Enhancement of thermal conductivity with CuO for nanofluids. *Chem. Engr. Techn.*, 72-77.

Mayur L & Borse S 2016. Effect of Nano fluid in High Speed Machining of Metals: A review. *Int. J. Scientific Res. & Dev*.

Mintsa H, Roy G, Nguyen C & Doucet D 2009. New temperature dependent thermal conductivity data for water-based nanofluids. *Int. J. Thermal Sci.*, 363-371.

Moghaddam M, Goharshadi E, Entezari M & Nancarrow P 2013. Preparation, characterization, and rheological properties of graphene–glycerol nanofluids. *Chem. Engr. J.*, 365-372.

Naphon P, Assadamongkol P & Borirak T 2008. Experimental investigation of titanium nanofluids on the heat pipe thermal efficiency. *Int. Commun. in Heat and Mass Transfer*, 1316-1319.

Nirmal S, Sehgal K & Sharma V 2010. *Cryogenic treatment of tool materials: A review. Materials and Manufacturing Processes* (25th ed., Vol. X).

Niyaghi F, Haapala K, Harper S & Weismiller MC 2014. *Stability and biological responses of zinc oxide metalworking nanofluids using Dynamic Light Scattering and Zebrafish Assays.* Tribology Transactions.

Operation LM (n.d.). Retrieved May 29, 2017, from http://t0.gstatic.com/images?q=tbn:ANd9GcTAw3gcBixTY3_V_AcebnRfEX1zGG3ZfS8Nquk1aXxiPZmsCMWYWw;

Palabiyik I, Musina Z, Witharana S & Ding Y 2011. Dispersion stability and thermal conductivity of ropylene glycol-based nanofluids. *J. Nanoparticle Res.*, 5049-5055.

Park S & Bang I 2014. Experimental study of a universal CHF enhancement mechanism in nanofluids using hydrodynamic instability. *Int. J. Heat and Mass Transfer*, 844-850.

Pepina A, Bernier P & Lannoo M 2011. Recent developments in nanoscience and nanotechnology. *Advanced Materials Res.*, 324: 3-7.

Prasad M & Srikant R 2013. Performance evaluation of nano graphite inclusions in steel. *Int. J. Res. Engr. and Techn.*

Prasher R, Phelan P & Bhattacharya P 2006. *Effect of aggregation kinetics on the thermal conductivity of nanoscale of colloidal solutions (nanofluids).* Nano Letter.

Rama KK, Srinivas J, Babu K & Kolla S 2010. *Prediction of optimal cutting states during inward turning: An experimental approach* . Materials and Manufacturing Processes.

Ramakoteswaa R, Leena G & Ranganayakulu S 2014. Synthesis, applications and challenges of nanofluids – Review. *Int. Conf. on Advances in Engr. & Techn.* 21-28.

Ramesh K, Prathap J & Padmanabhan P 2016. Experimental investigation of tool wear in turning of inconel718 material. *Int. Conf. on Emerging Engr. Trends and Sci.*, 1-6.

Razfar M 2010. *Principles of Machining.* Tehran, Iran: Amirkabir University of Technology Press.

Romano J, Parker J & Ford Q 1997. Application opportunities for nanoparticles made from the condensation of physical vapors. *Adv. Pm. Part*, 12-13.

Sadeghinezhad E, Mehrali M, Saidur R, Mehrali M, Latibari S, Akhiani A *et al*. 2016. A comprehensive review on graphene nanofluids:Recent research, development and applications. *Energy Conversion and Management*, 466-487.

Sahijpaul Y 2015. A review on recent developments in nano particle based cuttin g fluids in machining processes. *Int. J. Res. Mechan. Engr.*, I(2), 1-3.

Saidur R, Leong K & Mohammad H 2011. A review on applications and challenges of nanofluids. *Renewable and Sustainable Energy Reviews*, 1646-1668.

Sanchez J, Pombo I, Alberdi R, Izquierdo B, Ortega N, Plaza S *et al*. 2010. Machining evaluation of a hybrid MQL-CO2 grinding technology. *Journal of Clean Production*, 1840-1849.

Saravanakumar N, Prabu L, Karthik M & Rajamanickam A 2014. Experimental analysis on cutting fluid dispersed with silver nano particles. *J. Mech. Sci. and Techn.*, 645-651.

Sarkar J, Ghosh P & Adil A 2015. A review on hybrid nanofluids: Recent research, development and applications. *Renewable and Sustainable Energy Reviews*, 164-177.

Sarkhosh L & Mansour N 2015. Study of the solution thermal conductivity effect on nonlinear refraction of colloidal gold nanoparticles. *Laser Physics*, 7.

Serrano E, Rus G & Martínez J 2009. Nanotechnology for sustainable energy. *Renewable and Sustainable Energy Reviews*, 2373-2384.

Setti D, Ghosh S & Rao P 2012. Application of nano cutting fluid under minimum quantity lubrication (MQL) technique to improve grinding of Ti–6Al–4V alloy. *Proceedings of World Acad. Sci., Engg. Tech.*, 512-516.

Shahrul I, Khaleduzzaman S, Saidur R & Sabri M 2014. A comparative review on the specific heat of nanofluids for energy perspective. *Renewable and Sustainable Energy Reviews* , 88-98.

Shailesh K 2015. *Application of Nano-fluid Lubrication during Machining of Aero engineering Grade Stainless Steel.* Odisha India: M.tech Thesis, submitted to the Department of Mechanical Engineering National Institute of Technology Rourkela 769008.

Shalkevich N, Escher W, Burgi T, Michel B, Si-Ahmed L & Poulikakos D 2010. On the thermal conductivity of gold nanoparticle colloids. *American Chemical Society: Langmuir*, 663-670.

Sharifpur M, Adio S & Meyer J 2015. Experimental investigation and model development for effective viscosity of Al2O3–glycerol nanofluids by using dimensional analysis and GMDH-NN methods. *Int. Commun. in Heat and Mass Transfer*, 208-219.

Sharma A, Tiwari A & Dixit A 2016. Rheological behaviour of nanofluids: A review. *Renewable and Sustainable Energy Reviews*, 779-791.

Sharma KV, Sundar L & Sarma PK 2009. Estimation of heat transfer coefficient and friction factor in the transition flow with low volume concentration of Al2O3 nanofluid flowing in a circular tube and with twisted tape insert. *Int. Commun. in Heat and Mass Transfer*, 503-507.

Shekarian E, Tarighaleslami A & Khodaverdi F 2014. Review of effective parameters on thenanofluid thermal conductivity. *J. Middle East Appl. Sci. and Techn.*, 776-780.

Shen B, Shih AJ & Tung S 2008. Application of nanofluids in minimum quantity lubrication grinding. *Trib. Trans.*, 730-737.

Shokrani A, Dhokia V, Muñoz-Escalona P & Newman S 2013. State-of-the-art cryogenic machining and processing. *Int. J. Com. Integrated Man*, 616-648.

Sodavadia K & Makwana A 2014. Experimental investigation on the performance of coconut oil based nano fluid as lubricants during turning of AISI 304 austenitic stainless steel. *Int. J. Advance Mechanical Engr.*, 55-60.

Srikant R, Rao D, Subrahmanyam M & Krishna V 2009. Applicability of cutting fluids withnanoparticle inclusion as coolants in machining. *Proc. Ins. Mech. Eng., Part J: J. Eng. Trib.*, 221-225.

Srivatsan T 2010. *A review of contact angle, wettability, and adhesion.* Materials and Manufacturing Processes.

Su Y, Gong L & Chen D 2016. Dispersion stability and thermophysical properties of environmentally friendly graphite oil-based nanofluids used in machining. *Advances in Mechanical Engr.*, 1-11.

Tiwari A, Ghosh P & Sarkar J 2013. Heat transfer and pressure drop characteristics of CeO2/water nanofluid in plate heat exchanger. *Applied Thermal Engineering*, 24-32.

Vajjha R & Das D 2012. A review and analysis on influence of temperature and concentration of nanofluids on thermophysical properties, heat transfer and pumping power. *Int. l J. Heat Mass Transfer*, 4063-4078.

Vajjha R & Das D 2009. Experimental determination of thermal conductivity of three nanofluids and development of new correlations. *Int. J. Heat and Mass Transfer*, 4675-4682.

Vasu V & Kumar K 2011. Analysis of nanofluids as cutting fluid in grinding EN-31 steel. *Nano-Micro Lett.*, 209-214.

Warzoha, R., Weigand, R., & Fleischer, A. (2015). Temperature-dependent thermal properties of a paraffin phase change material embedded with herringbone style graphite nanofibers. *Applied Energy*, 716-725.

Weinert K, Inasaki I, Sutherland J & Wakabayashi T 2004. Dry machining and minimum quantity lubrication. *CIRP Annals Manufacturing Techn.*, 53: 511-537.

Wen D & Ding Y 2004. Experimental investigation into convective heat transfer of nano-fluids at the entrance region under laminar flow conditions. *Int. J. Heat and Mass Transfer*, 5181–5188.

Wong K & Castillo M 2010. Heat transfer mechanisms and clustering in nanofluids. *Advance Mechanical Engr.*, 1-9.

Xuan Y & Li Q 2000. Heat transfer enhancement of nanofluids. *Int. J. Heat and Fluid Transfer*, 58–64.

Yang Y, Zhang Z, Grulke E, Anderson W & Wu G 2005. Heat transfer properties of nanoparticle-in-fluid dispersions (nano-fluids) in laminar flow. *Int. J. Heat and Mass Transfer*, 1107–1116.

Yoo D, Hong K & Yang H 2007. Study of thermal conductivity of nanofluids for the application of heat transfer fluids. *Thermochimica Acta*, 66-69.

Yu W, France D, Routbort J & Choi S 2008. Review and comparison of nanofluid thermal conductivity and heat transfer enhancements. *Heat Transfer Engineering*, 432-460.

Yu W, Xie H, Chen L & Li Y 2009. Investigation of thermal conductivity and viscosity of ethylene glycol based ZnO nanofluid. *Thermochimica Acta*, 92-96.

Yusuf T, Bolaji B & Ismaila S 2017. Analytical test of water-extract from fermented ground maize as an alternative base for engine coolants. *Walailak J. Sci. and Techn., XIV*.(2): 76-82.

Yusuf T, Bolaji B, Ismaila S & Adewumi J 2016. Determination of thermo physical properties of water-extract from fermented ground maize (WEFGM) as possible alternative to water use as cutting fluid. *Silpakorn Univ. Sci. and Techn. J., X*(2): 51-60.

Zeinali H, Nasr E & Etemad S 2007. Experimental investigation of convective heat transfer of Al2O3/water nanofluid in circular tube. *Int. J. Heat and Fluid Flow*, 203-210.

Zhang X, Gu H & Fujii M 2007. Effective thermal conductivity and thermal diffusivity of nanofluids containing spherical and cylindrical nanoparticles. *Experimental Thermal Fluid Science*, 593-599.

Zhu D, Li X, Wang N, Wang X, Gao J & Li H 2009. Dispersion behaviour and thermal conductivity characteristics of Al2O3-H2O nanofluids. *Current Applied Physics*, 131-139.