International Journal of Heat and Mass Transfer 114 (2017) 380–394

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Review

# An overview of current status of cutting fluids and cooling techniques of turning hard steel

Pay Jun Liew[a,*], Ainusyafiqah Shaaroni[a], Nor Azwadi Che Sidik[b,c,*], Jiwang Yan[d]

[a] Faculty of Manufacturing Engineering, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
[b] Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, UTM Skudai, 81310 Johor, Malaysia
[c] Malaysia – Japan International Institute of Technology (MJIIT), Universiti Teknologi Malaysia Kuala Lumpur, Jalan Sultan Yahya Petra (Jalan Semarak), 54100 Kuala Lumpur, Malaysia
[d] Department of Mechanical Engineering, Faculty of Science and Technology, Keio University, Hiyoshi 3-14-1, Kohoku-ku, Yokohama 223-8522, Japan

ARTICLE INFO

*Article history:*
Received 27 March 2017
Received in revised form 16 June 2017
Accepted 16 June 2017

*Keywords:*
Nanofluids
Hard turning
Cutting fluid
Cooling techniques

ABSTRACT

In the recent years, there has been increasing interest in hard turning over grinding for machining of hardened steels. There are some issues in the process which should be understood and dealt with such as friction and heat generation at the cutting area that can affect the tool life and surface finish apart from other machining results to achieve successful performance. Researchers have worked upon several aspects related to hard turning and came up with their own recommendations to overcome these problems. They have tried to investigate the effects of tool materials, cutting parameters, different cooling type and cooling technique on different machinability responses like tool life, surface roughness, cutting forces, chip morphology, etc. This paper presents a comprehensive literature review on cutting fluids and cooling technique on turning of hardened steels. Type of tools and cutting parameters used by the researchers have been summarized and presented in this paper as well to give proper attention to the various researcher works.



**Contents**



* Corresponding authors at: Malaysia – Japan International Institute of Technology (MJIIT), Universiti Teknologi Malaysia Kuala Lumpur, Jalan Sultan Yahya Petra (Jalan Semarak), 54100 Kuala Lumpur, Malaysia (N.A.C. Sidik).
*E-mail addresses:* payjun@utem.edu.my (P.J. Liew), azwadi@mail.fkm.utm.my (N.A.C. Sidik).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.06.077
0017-9310/

## 1. Introduction

Conventional machining or traditional machining is cutting processes which remove the material from the various surface of a work piece by producing chips. The machine tools, such as lathes, milling machines, drill presses, or others, are used with a sharp cutting tool to remove material to achieve a desired geometry [1]. Conventional machining includes turning, boring, drilling, milling, broaching, sawing and so much many more.

Today, as the manufacturing technology changing rapidly, the demands on the better quality on the hardened part are increasing. Historically, grinding is more preferred as a method to machine hardened materials with high hardness for the final machining operation [2–6]. However, by the emergence of tool materials that have ultimate hardness, such as ceramic and cubic boron nitride (CBN) tools, has made it possible to circumvent the traditional machining practice for hardened steel. At significantly higher material removal rates, hard turning also can produce as good or better surface finish compared to grinding although grinding is known to produce good surface finish at relatively high feed rates [5,7,8]. Hard turning is defined as a process in which hardened steels (above 45 HRc) are finish turned. In other words, a lathe or turning center provides the last operation bringing the workpiece to final shape and surface condition. Hard turned parts do not need to be finish ground.

During the turning process, as Sharma and his co-worker [9] observed that between the tool and workpiece, the heat released and the friction often caused problems in terms of tool life and surface finish. This phenomenon is explained by Kalpakjian & Schmid in 2013 [1]. According to them, in conventional machining, there is contact between the tool and the material workpiece. The contact causes the friction force to occur. The increasing of friction can cause the tool to wear or broken as the structure the lathe tool has the sharp tip for cutting purpose. This is because cracks propagate due to sharpness of crack tip. The cutting condition has a considerable effect on the tool wear and surface roughness. On the other hand, the plastic deformation and crack propagation inside the work material, and process stability are influenced by these occurrences. Meanwhile, Bhuiyan et al. [10] reminded us, the tool wear is a normal phenomenon occurring in any metal cutting process. It dulls the tool cutting edge, increases the friction between the tool and the workpiece and also increases the power consumption.

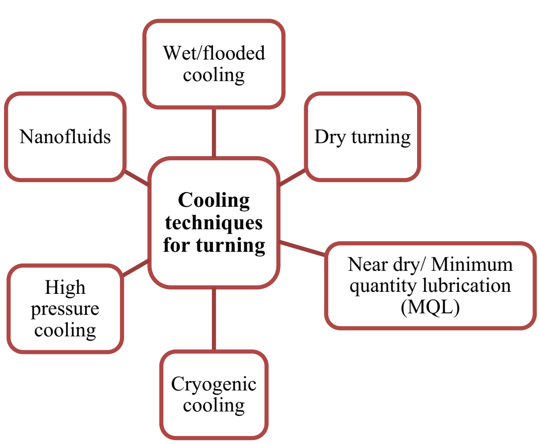



**Fig. 1.** Cooling techniques in turning hard steel.

Conventionally, cutting fluids have been used as lubricants and coolants to address these problems. Cutting fluids put in practice during machining operations to improve the tribological process, which occurs when the tool and the workpiece make a contact. Cutting fluids is really helpful in machining as it can increase tool life, surface condition of the workpiece and the process as a whole. Besides that, it also helps in reducing heat and carrying away debris produced during machining [11–13]. However, the use of cutting fluids has several adverse effects such as environmental pollution, dermatitis to operators, water pollution and soil contamination during disposal [14–16].

Many researchers have been researching on various aspects of hard turning and come up with their own proposals regarding the process. The process parameter is basically various forms of inserts, tool materials and coatings on process performance by different cooling technique. There are various cooling techniques in turning process however only the techniques shown in Fig. 1 will be described in this paper. A good amount of experimental studies and researches also have been done in order to understand the impact of process parameters on the cutting responses such as surface integrity, cutting forces and the tool wear or tool life through experiments as well as modeling. However, none of this previous research provides a picture of the comprehensive review on the use of cutting fluids. Therefore, this paper focuses in reviewing various cooling techniques, especially the use of cutting fluids, in turning hard steel materials.

## 2. Hard turning

In recent year, demand for extremely tough and hard steels is increasing in industry so that it creates challenges for machining operation to produce high performance or quality product.

In the manufacturing industry, the aim is to produce high quality products with lower cost and time constraints. Hard turning has been introduced as an effective and emerging metal cutting of steel with a hardness exceeding 45 HRc. Hard turning can be defined as the process of effective finish turning material using single point cutting tools which have high hardness (45–70 HRc) and high wear resistance [4,17,18]. Meanwhile, according to Bartarya and Choudhry [7], hard turning is a phenomenon of high-speed machining where the speed will typically 250 m/min, sometimes even more than this. High-speed machining for a given material also can be defined as that speed above which shear-localization develops completely in the primary shear zone [19]. Therefore, the ability of the machine tool should be including high rigidity, high surface speed, constant surface speed and high precision surface finish is required.

As a process involving machining of material that more than 45 HRc, therefore, tougher and harder tool materials with low wear capabilities is needed as the generated power and forces are expected to be high. Mostly, the researchers have used cubic boron nitride (CBN), Polycrystalline cubic boron nitride (PCBN) and coated CBN tool inserts for the purpose [5,11,20,21–24]. Some researchers have used coated carbide insert [25–32] as well as tungsten carbide coated with TiN [27,33–35]. Besides that, there are also a few researchers used ceramic (alumina) for turning hardened material [17,21,36–40].

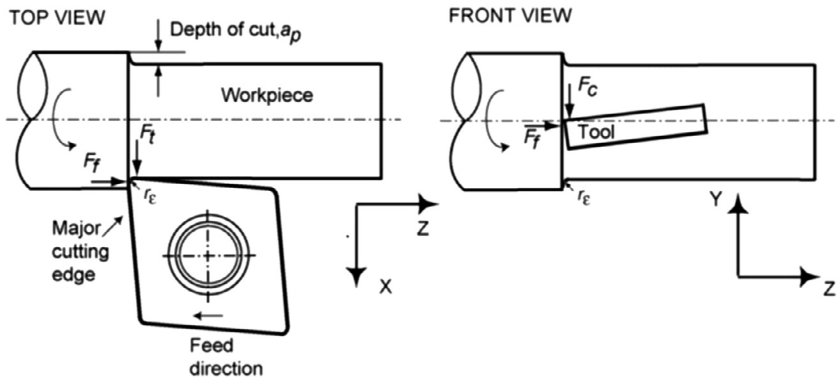



**Fig. 2.** Schematic diagram of longitudinal turning [49].

In hard turning, friction between the two surfaces such as workpiece and cutting tool or cutting tool and chip interfaces cause rise in temperature. Like in most cases of machining, the most of the heat generated at the cutting interface mainly dissipated through the chips and thus, significantly reducing the temperature of the workpiece and tool [24,41,42,43]. This is supported by Yallese et al. [44] where they said that the ratio chip to workpiece temperatures is 16 at speed of 360 m/min.

Many researchers [37,45–47] agreed that most important aspects in hard turning are surface roughness and tool wear. This is because the surface roughness affects corrosion resistance, fatigue strength, pace and tribological properties of machined parts meanwhile tool wear affects the dimensional accuracy of the finished products, surface finish, residual stress, the integrity of the surface (white layer) and the tool life. However, according to Khan et al. [48], the limitation for good surface finishing in continuous turning are; regular feed marks left by the tool-tip on the finished surface, irregular deformation of the auxiliary cutting edge at the tool-tip due to chipping, fracturing and wear, vibration in the machining system, and built-up edge formation.

Fig. 2 shows the schematic diagram of longitudinal turning [49]. Although there are many advantages of hard turning technology compared to grinding as finishing process, there are still limiting factors regarding the performance of materials. According to Grzesik et al. [50], the limitations of the process are as below:

- Low magnitudes of compressive residual stresses and the stress profile with the position of maximum stress at a certain distance beneath the surface. In general, the residual tensile stresses exist at the surface.
- The process-induced white layer which can lead to substantial variations in component service performance.
- Dimension, geometric form and surface roughness errors resulting from tool wear. The other error-drive factors are cutting forces and thermal expansions on workpiece and cutting tool.

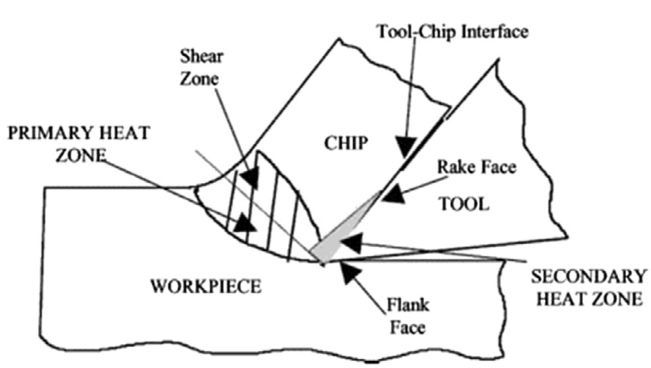



**Fig. 3.** Regions of heat generation in turning [54].

## 3. Cutting fluid

Traditionally, in order to improve engine cooling and lubrication during operation, the cutting fluid was used. Cutting fluid originally used to lubricate the interface chip and tool as well as tool and workpiece, remove heat from the workpiece and the cutting zone, carrying away chips from the cutting area and prevent erosion. Even though the definitions of cutting fluids can be described from those four functions, it is widely believed that the main function of a cutting fluid is for lubrication and cooling [15,51].

### *3.1. Function of cutting fluid*

As mention before, the main function of using cutting fluids in machining processes is to reduce the cutting temperature and friction wear either through lubrication or through cooling by conduction of heat [35].

However conventional cutting fluids growing public health concern worldwide and following this issues, in 2008, Aggarwal and his co-worker [52] have written the following limitations towards conventional cutting fluids:

- Environmental pollution due to chemical divorce/break-up of cutting fluid at high shear.
- Biological (dermatological) problems to the operators such as skin problems and respiratory problems when come in physical contact with the cutting fluid.
- Contamination of water and soil pollution during disposal.
- The need for additional floor space and additional system for pumping, storage, refining, recycling, cooling, etc.
- The cost of disposal of cutting fluids becomes higher as environmental regulations become more difficult.

Efficient cooling strategies in the metal cutting industry are an important part of a sustainable and profitable production. The requirements for the cooling lubricants as stated by Anton et al., [14] are:

- the resulting heat absorption process
- cooling of machines, materials, equipment and tools
- breaks in favor of chips and transport chips
- reduction of friction
- reduction of the built-up edge formation
- corrosion protection for machine and workpiece

As mention before, heat is generated at cutting zone during machining. Most of the resulting heat remains in the chip, but some of it is conducted into the tool and the workpiece [53]. According to O'Sullivan and Cotterell [54], tool life is greatly affected by cutting temperature as a small reduction in temperature can prolong tool life. Fig. 3 shows the regions of heat generation in turning. Meanwhile, according to Sharma et al. [9], thermal conductivity of tools, tool design and cooling methods are the factors that affect the amount of heat lost from the cutting zone. However, during dry machining, the cutting fluid to take away the heat generated from the cutting zone is absent, resulting an increase in tool and workpiece temperature [55]. When cutting fluid is applied during machining operation, it removes heat by carrying it away from the cutting tool/workpiece interface and reducing the main cutting force due to improved and intimate chip-tool interaction [31]. Therefore, this cooling effect avoids the tool from surpassing its critical temperature range beyond which the tool softens and wears rapidly [28].

### 3.2. Types of cutting fluid

There are four main categories of conventional cutting fluids that differ in their thermophysical properties, the application process, and methods of treatment [15,36,41].

#### 3.2.1. Straight oils

Straight oil is made up from entirely mineral oil (neat cutting oil) or vegetable oils (biodegradable), and is used primarily for operations where lubrication is required. Although being excellent lubricating oil, their heat transfer capabilities exhibit very low. Mineral oil, which is highly flammable, has low efficiency at high cutting speed and relatively high cost [15].

Khan et al. [48] reported that vegetable oils are nontoxic and environmental friendly in terms of resource renewability, biodegradability, and performance efficiency in many applications. This is proved by Elmunafi et al. [26] where, in their research, they found that the use of vegetable oil in MQL has shown some positive results.

#### 3.2.2. Soluble oils

Soluble oil is a mixture of oil and water and has increased cooling capacity than straight oil and provided rust protection. This type water-based cutting fluids is suitable for turning, milling and grinding process due to the used of new cutting tool materials such as hard metals and high cutting speeds. It is also found that water based cutting fluids will reduce the effect of generated heat on cutting tool wear [15].

Priarone et al. [32] investigated the machinability of a Ti-48Al-2Cr-2Nb (at.%) alloy. They applied low cutting fluid (water and emulsion) volumes to the cutting area in the form of a precision-metered droplets mist. They found that the tool life with the emulsion mist is better than those of MQL with vegetable oil.

#### 3.2.3. Semi-synthetics

In terms of performance, semi-synthetic is not much different or the same as the soluble oil. However, it is different in composition as 30% or less of the total concentration, it contains inorganic material or other water-soluble compounds. Adding emulsified oil in synthetic cutting fluid results in semi-synthetic fluids that have properties combined. It is also characterized by better maintenance than soluble oil, but tarnishes easily when exposed to other machine fluids and can cause dermatitis risk to workers [15,36].

#### 3.2.4. Synthetics

Synthetic is a chemical liquid containing inorganic or other chemical that are soluble in large quantity of water and offer superior cooling performance.

**Table 1**
Summary of cutting fluids used in turning of hard steel.

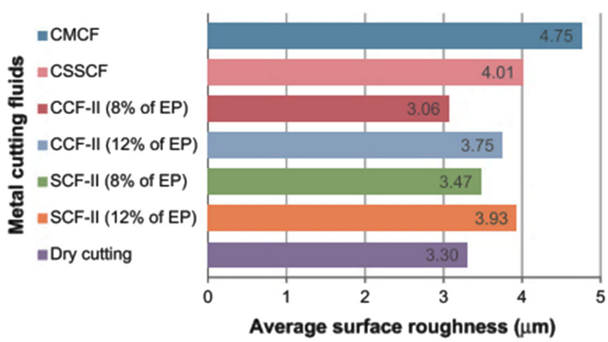
| No | Type | Sub-type | Cooling technique | References |
|---|---|---|---|---|
| 1 | Straight oil | Mineral oil | MQL machining | [3,43,51,52] |
| 2 | | Food-grade vegetable oil | MQL machining | [44] |
| 3 | | Castor oil | MQL machining | [53] |
| 4 | | • Sunflower based cutting fluids with 8% of extreme pressure additive<br>• Sunflower based cutting fluids with 12% of extreme pressure additive<br>• Canola based cutting fluids with 8% of extreme pressure additive<br>• Canola based cutting fluids with 12% of extreme pressure additive | Flooded cooling | [52] |
| 6 | Soluble oil | Water based cutting fluid containing 5% oil | Flooded cooling | [5] |
| 7 | | Mixture of oil and water | MQL machining | [54] |
| 8 | | Soluble oil was used with a proportion oil-water of 1:20 | MQL machining | [16] |
| 9 | Semi-synthetics fluid | HYSOL XF oil based emulsion | Flooded cooling | [34] |
| 10 | | 7% emulsion based on oil Primol OLMA 3000 | Flooded cooling | [20] |
| 11 | | Emulsion combining mineral oil | Flooded cooling | [32] |
| 12 | | Semi-synthetic, 4% dilution | Flooded cooling | [55] |
| 13 | | 5% emulsion of Vasco 5000 ester-based oil | Flooded cooling | [28] |
| 14 | | Chemical-based water soluble oil | High pressure cooling | [31] |
| 15 | Synthetics fluids | Commercial oil BP Microtrend 231L | MQL machining | [10] |
| 16 | | Coolube 2210EP metalworking lubricant | MQL machining | [56] |
| 17 | | High lubricity emulsion | Flooded cooling | [38] |
| 18 | | High lubricity emulsion | High pressure cooling | [38] |
| 19 | | Emulsion oil | Flooded cooling | [32] |
| 20 | | Emulsion oil | MQL machining | [26] |
| 21 | | Emulsion Yushiroken MIC 2500 | Flooded cooling | [24] |
| 22 | | Alkanolamine salts of the fatty acid dicyclohexylamine | High pressure cooling | [25] |
| 23 | | Liquid nitrogen | Cryogenic cooling | [20,34,47,56,57] |
| 24 | Straight oil + particle | $nMoS_2$ + coconut oil<br>$nMoS_2$ + sesame oil<br>$nMoS_2$ + canola oil | MQL nanofluid | [58] |
| 25 | | $MoS_2$ (1000 nm) + grease<br>graphite fiber (150 nm) + grease<br>Cu (200 nm) + grease<br>CuO (48 nm) + grease | Nanofluid | [59] |

Regarding towards to green manufacturing, biodegradable lubricant plays important role. Biodegradable lubricant has gradually and steadily replacing synthetic lubricants. Biodegradable cutting fluids that achieve the lowest amount of environmental pollution can provide high reliability and satisfactory economic conditions. In addition, the productions of bio-based cutting fluids are much cleaner and contribute less pollution in the air, thereby reducing the risk of occupational health. While the bio-based cutting fluids are not perfect in all aspects, they have a minimal negative impact on the environment compared with other cutting fluids [28].

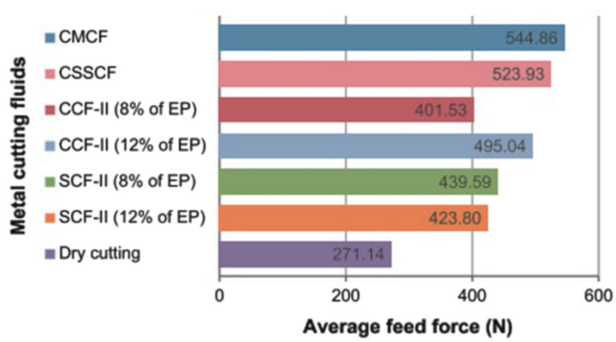
A summary of literature review of coolants used under different cooling conditions for turning hard steel is listed in Table 1.

## 4. Cooling techniques

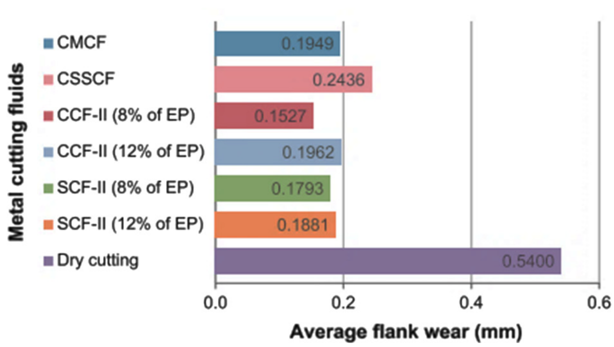
In order to reduce heat during machining process, there are various cooling techniques employed from time to time. In this present paper however only six techniques are described and are related to turning of high hardness steel.




(a) Effects of metal cutting fluids on average surface roughness




(b) Effects of metal cutting fluids on average feed forces




(c) Effects of metal cutting fluids on average flank wears

**Fig. 4.** The effect of cutting fluid on different responses (a) surface roughness, (b) feed forces and (c) flank wears [56,52].

### 4.1. Wet/flooded cooling

Wet or flood cooling is a technique in which cooling jet aimed at the active zone for cooling, lubricating and get rid of chips produced during machining. This technique is most suitable for grinding and turning where high temperatures or sparks may occur can be avoided due to the water content of the coolant, which is present in the emulsion used [14].

During their analysis of the cutting fluid, Adler et al. [15] found one of the advantages of cutting fluids in machining operation is the ability to transfer heat. Heat transfer can be of great benefit in the reduction of error surface, where the size of the machined surface irregularities of a surface produced under ideal conditions. In addition, the mechanical energy is used to form the chip to generate heat and high temperatures in the cutting region. Rise to increase the temperature, the faster it wears. The main purpose of using cutting fluids in machining processes is to reduce the cutting temperature [52].

Together, Ávila and Abrão [36] compared the performance of different types of cutting fluid to dry cutting using alumina insert in machined high strength low alloy AISI 4340 steel (49 HRc). They used three different types of cutting fluids, which are fluid A: Emulsion without mineral oil, fluid B: Synthetic and fluid C: Emulsion containing mineral oil. The results showed that cutting fluid A provided the longest tool life, followed by dry cutting and fluid B. Worst result given by fluid C. From the investigation, the superior performance of fluid A may attribute to the presence of grease. The application of a cutting fluid based on an emulsion without mineral oil can increase the tool life compared to dry cutting. This proves that the use of cutting fluid is responsible for reducing the scatter in the surface roughness values when finish at high cutting speed. In 2010, Isik [31] highlighted that cutting fluid managed to reduce a good amount of heat and friction of turning process. The tool wear is reduced more for wet cutting compared to dry cutting. This is because the application of liquid flooding reduces the coefficient of friction at the interface between the tool and the chip on the rake face.

To study the performances of both new evolved vegetable oil cutting fluids (refined sunflower and canola oils) including different percentage of extreme pressure (EP) additive and two commercial cutting fluids (semi-synthetic and mineral cutting fluids) in turning processes, in their novel study, Ozcelik et al. [56] took AISI 304 steel as their working material. By constant the cutting speed, feed rate and depth of cut, they found that canola based cutting fluids with 8% of EP additive gave the best performance in terms of

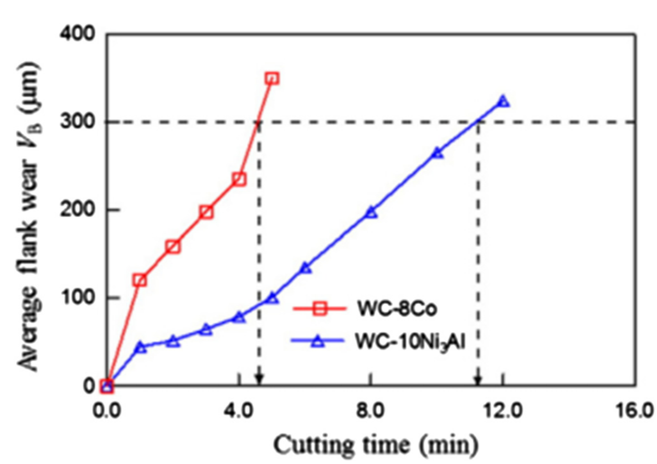



**Fig. 5.** Average flank wear (Vb) of WC–10Ni$_3$Al and WC–8Co carbide tools at a cutting speed $v_c$ = 100 m/min [60].

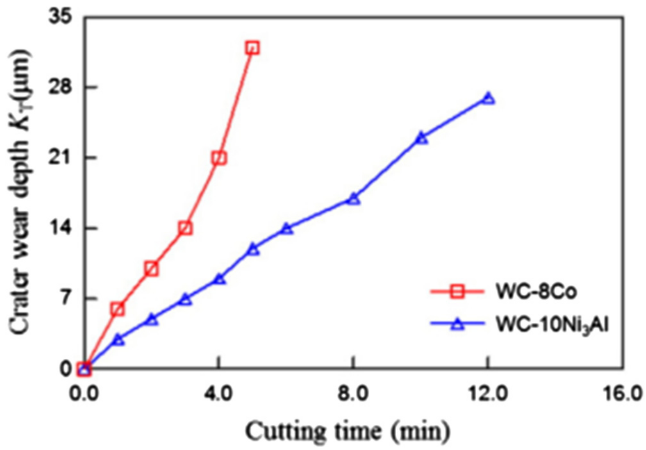



**Fig. 6.** Crater wear depth (KT) of WC–10$Ni_3$Al and WC–8Co carbide tools at cutting speed of $v_c$ = 100 m/min [60].

the surface roughness, feed forces and tool wears (Fig. 4). Meanwhile, Xavior and Adithan [57,60] revealed that coconut oil was found to be a better cutting fluid than the conventional mineral oils in reducing the tool wear and surface roughness in machining AISI 304 steel using cemented carbide tool. Therefore, it could be said that vegetable oil has given better properties compared to others cutting oil in turning AISI 304.

Leppert's [58,61] experimental analysis concluded that the surface properties of finishing product is significantly affected by cooling and lubrication. However, they found that it depends on the effectiveness of the cooling and lubricating. In 2014, Chinchanikar et al. [59,62] investigated the effects of different cooling mediums and cutting parameters on surface roughness through mathematical modeling. Experiments were performed by them using physical vapor deposition (PVD) coated nanolaminated TiSiN–TiAlN carbide tool on hardened AISI 52100 steel (60–62 HRc) under three different conditions (dry, with water-based and coconut oil-based cutting fluids). From their study, they indicated that hard turning under dry condition produced lower values of surface roughness. However, at higher cutting speeds it showed lower values of surface roughness when using coconut oil. Meanwhile, Debnath et al. [28] studied the effect of various cutting fluid levels and cutting parameters on surface roughness and tool wear using chemical vapor deposition (CVD) coated carbide. In their seminal study, it shows that feed rate is the most significant factor where it contributes 34.3%, while cutting speed contributed the most (43.1%) to tool wear. Cutting fluid also showed a significant contribution to surface roughness (33.1%) as well as to tool wear (13.7%).

Previously, Biček et al. [24] also conducted a study on turning of hardened AISI 52100 steel using 7% emulsion based on oil Primol OLMA 3000 as cutting fluid. In their experiment, they compared the output responses which are cutting force, flank wear, surface roughness, MRR under different cutting condition (conventional flood, dry and cryogenic) using ceramic insert. The result showed that cryogenic machining considerably improved tool life of cutting inserts and increased productivity.

### 4.2. Dry machining

Dry cutting is a process without the use of any cutting fluid during machining. Dry turning is usually use for machined hardened steel using polycrystalline cubic boron nitride and ceramic cutting tools. According to Ávila and Abrão [36], lower thermal conductivity and fracture toughness of ceramics may lead to early tool fracture due to thermal and mechanical shock. For this reasons, dry cutting is the best choice for ceramics cutting tools. However, in the recent study, Arulraj et al. [47] found that dry cutting very difficult to be implemented on the existing shop floor as it needs extremely rigid machine tool and ultra-hard cutting tool.

Liang et al. [60] studied the wear mechanisms of WC–10$Ni_3$Al carbide tool in dry turning of Ti6Al4V and found that WC–10$Ni_3$Al carbide tool showed a better flank wear resistance than WC–8Co carbide tool at higher cutting speed, as shown in Fig. 5. Fig. 6 shows the crater wear depth of both carbide tools at the cutting speed of 100 m/min. From the figure, it shows that crater wear depth (KT) of WC–8Co tools is much larger than that of WC–10$Ni_3$Al.

Bhemuni et al. [61] stated that significant parameter for tool flank wear is depth of cut. The speed and feed have little influence on the total variation as turned AISI D3 hardened steel. Dilbag and Rao [37] pointed out that dry turning can enhance the surface finish, but the tool life and wear problems are corresponding with it therefore an alternative way of increasing tool life is essential in hard turning. However, Debnath et al. [28] concluded that dry machining is applicable for conventional machining on steels, steel alloys and cast irons except for aluminum alloys. Even so, the high friction between the tool and the workpiece in dry cutting conditions significantly increase in temperature causes a higher level of abrasion, diffusion and oxidation.

Lima et al. [21] investigated the machinability of AISI 4340 steel (42 and 50 HRc) and high chromium AISI D2 cold work tool steel (58 HRc) by using different cutting tools. They found that the best surface roughness was obtained when machining the harder steel (58 HRc). Besides that, lower surface roughness value was obtained at higher cutting speeds due to the lower forces generated and when using higher nose radius of the PCBN tool and poorer surface roughness obtained when increase in feed rate. Years later, Das et al. [62] also found that the most significant parameter during dry turning of hardened AISI 4340 steel with CVD (TiN + TiCN + $Al_2O_3$ + ZrCN) multilayer coated carbide inserts was cutting speed. The two level interactions were also found to be significant between cutting speed-feed and depth of cut-feed on surface roughness. However, two years later in 2015, Das et al. [63] found that cutting speed has a negative effect for surface roughness performance. By the given range of parameter, surface roughness is principally affected by feed and the depth of cut has a negligible impact. The same result is supported by Suresh et al. [64] when machined AISI 4340 high strength low alloy steel with coated carbide inserts of ISO geometry 'CNMG 12040 multilayer CVD coating (TiN/MT-TiCN/$Al_2O_3$), surface roughness is highly sensitive to variations in depth cut at lower values of cutting speed as compared to higher cutting speed values. El-Wardany et al. [2] investigated the effects of cutting conditions and tool wear on chip morphology and surface integrity during high speed machining of D2 tool steel. They found that by increasing the feed resulting increasing of surface roughness. Asiltürk and Akkuş [17] also found that feed rate has the higher effect on surface roughness in their work by make a research to optimize the surface roughness of machined AISI 4140 steel.

Many researchers continue to explore technique because of the challenging in dry machining whereas concerns about rise in wear rates. By far, the most widely used tool material is cemented carbide [15]. The use of coatings on PCBN substrate can clearly bring benefits to tool life, extending it up to 38%, from 17.8 to 24.5 km, using TiAlN-nano coating, within the tested cutting condition under dry machining [65]. Davim and Figueira [39] investigated the turning of old work tool steel D2 (AISI) using ceramic cutting tools, composed approximately with (70%) of $Al_2O_3$ and (30%) of TiC. From the findings, they said that uncontrolled tool flank wear exists in the ceramic tools, which work with high cutting speed, has a deduction equal to the surface roughness. The roughness also influenced by feed rate (29.6%) and cutting time (32%). Other

**Table 2**
Summary of cutting tool used in dry turning for different materials.

| No | Cutting tool | Material | Workpiece dimension (mm) | Workpiece hardness (HRc) | References |
|---|---|---|---|---|---|
| 1 | Ceramic insert | AISI 4150 (50CrMo4) | D = 86 L = 140 | 52 | [34] |
| 2 | Mixed alumina insert | High chromium AISI D2 cold work tool steel | D = 50 L = 200 | 58 | [17] |
| 3 | Mixed alumina insert | High strength low alloy AISI 4340 steel | – | 49 | [32] |
| 4 | PCBN insert | Hardened bearing steel AISI 52100 | – | 64 | [20] |
| 5 | PCBN insert | AISI 4340 steel | D = 76.5 L = 300 | 50 | [17] |
| 6 | PCBN insert (with ~85% CBN) | AISI D2 steel | D = 97 L = 300 | 62 | [18] |
| 7 | PCBN insert (with 50–70% CBN) | Hardened AISI 4340 steel | D = 65 L = 381 | ~53 | [14] |
| 8 | CVD coated carbide (TiN/TiCN/$Al_2O_3$/ZrCN) | AISI 4340 steel | D = 45 L = 100 | 47 ± 1 | [29] |
| 9 | CVD Coated carbide | AISI 1050 steel | D = 80 L = 340 | 58 | [27] |
| 10 | $Al_2O_3$ and TiC-coated insert | AISI 4140 steel | D = 110 L = 600 | 56–57 | [13] |

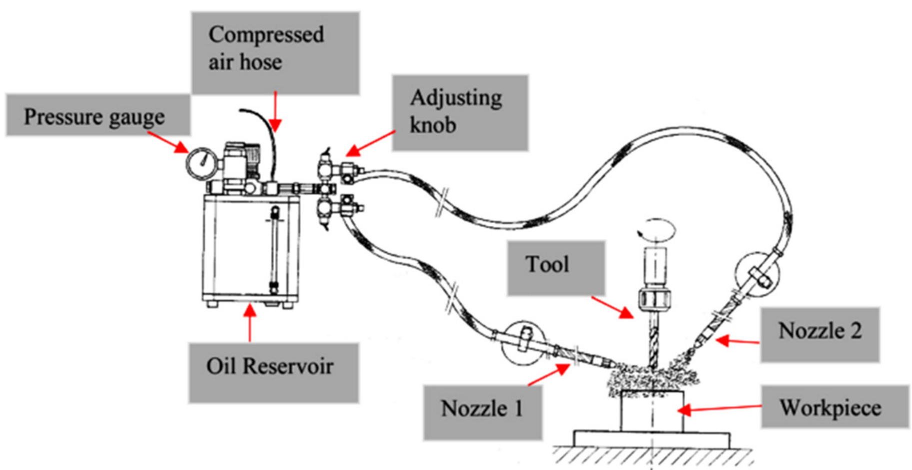



**Fig. 7.** Schematic view of MQL delivery system [67].

researcher, More et al. [18] compared the tool insert; CBN–TiN coated inserts on tungsten cobalt and PCBN tool in order to o optimize the machining conditions for hard turning applications using the CBN–TiN coated inserts. The result showed that the optimal machining conditions for the inserts is at the speed, feed rate and depth of cut at 125 m/min, 0.15 mm/rev, and 0.25 mm respectively. The cutting forces for the CBN–TiN coated carbide inserts were slightly higher than those of the PCBN tools due to larger nose radius. Based on a single cutting edge, it shows that the CBN–TiN coated carbide tool is able to reduce machining costs, and, therefore, will be an important complement to solid PCBN tool for hard turning applications. Table 2 present the selective research works for cutting tool used in dry turning.

Azwadi et al. [66] mentioned that by using dry machining, the manufacturing cost up to 7–17% can be reduced when compared to cutting fluid. However, in dry machining, high level of friction between the two surfaces (tool-workpiece and tool-chips), can be brought to a high temperature in the machining zone. The high temperature at the machining zone will eventually lead to tool life problems and inaccurate dimensions of the work piece. Therefore the disadvantages associated with it should be compensated in order to pursue dry machining [10].

### *4.3. Near dry/MQL/MQC machining*

Minimum quantity lubricant (MQL) was developed to merge the advantages of both dry and flood/wet cutting. Small quantities of cutting fluid (10–100 ml/h) is injected in the form of ultra-fine droplets at very high velocity (100 m/s) into the cutting zone which is also called as pseudo dry turning with the aid of compressed air [26,47]. This shows that MQL seeks to reduce the amount of cutting fluid used in an operation. Fig. 7 shows the schematic view of MQL delivery system [67].

MQL fluid is divided into two main groups of synthetic esters and fatty alcohol. Synthetic ester (usually vegetable oil) is more commonly used because the properties of their good lubrication, prevents corrosion, high flash and boiling points. However, the fatty alcohols achieve better heat removal and when vaporized, producing little in terms of waste compared to synthetic ester. Synthetic ester usually used in operations where lubrication is a key requirement for cutting fluids, while the fatty alcohols are used in applications that require cutting liquid for heat removal [15].

Arulraj et al. [47] and Beatrice et al. [68] investigated the use of mineral oil in MQL in machining H13 tool steel and concluded that MQL technique promoted green environment in the shop floor, minimized the industrial hazard and usage of large quantity of cutting fluid.

Zhang et al. [69] stated that although MQL is often used but the low cooling capacity limits its application. A recent study by Elmunafi et al. [70] involved the use of castor oil as cutting fluid in MQL. They found that MQL can be a good technique in turning hard stainless steel using coated carbide cutting tools when machine at speed of 170 m/min and feed rate = 0.24 mm/rev. However, there are limited by cutting temperature when machining under MQL because at high speed the effect of oil mist becomes evaporated. Liu et al. [71] investigated two turning conditions (dry and MQL) on the wear rate, wear pattern and wear mechanism of two kinds of nanocomposite coatings. The results of their

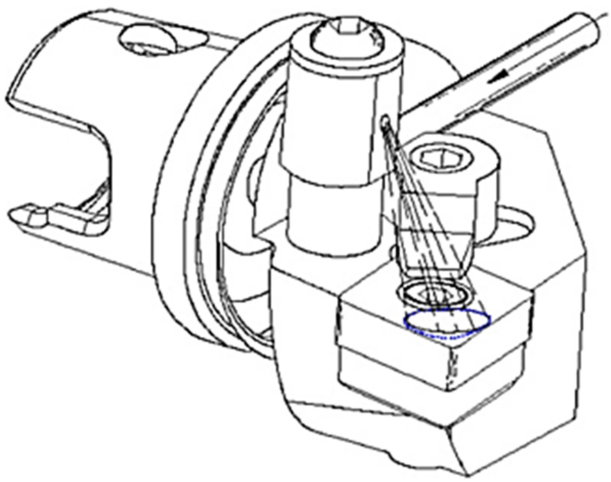


**Fig. 8.** A sample of cryogenic method [73].

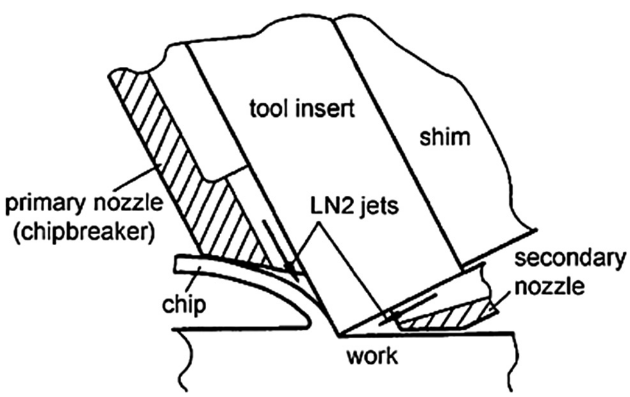



**Fig. 9.** Schematic diagram of liquid nitrogen system [73].

investigation showed that MQL condition was found to have more significant influence in prolong the tool life as compared to dry condition. In evaluate the surface roughness and specific cutting force, Gaitonde et al. [30] identified that feed rate is the most dominant parameter followed by flow rate of MQL and cutting speed in for optimization performance.

In order to improve performance in turning process, Chinchanikar and Choudhury [72] investigated the High Power Impulse Magnetron Sputtering (HiPIMS) coated carbide in MQL technique. Results of their experimental studies showed that higher tool life can be attributed to higher adhesion strength of the coating to the substrate and nanocrystalline coating structure of this tool. It also provides high hardness with high toughness. The tool has shown potential of improvement in tool life for hard turning almost by 20–25% at higher cutting speeds when using under MQL. Elmunafi et al. [26] reported that tool life decreases with increase in both cutting speed and feed and tool life is inversely proportional to both cutting speed and feed, with the effect of cutting speed is more significant than feed in turning under MQL with coated carbide.

To compensate for lower cooling capacity for traditional MQL technique, it cools the compressed air and removes heat from the cutting zone. So, MQL is an alternative to the supply and disposal of cutting fluids and energy-intensive production facilities related to high pressure. Furthermore, the tool life and surface quality can increase effectively compared to dry cutting [14]. The influence of MQL in the turning operation of AISI 52100 quenched steel is demonstrated by Diniz et al. [20] using CBN insert. They found that at most of the time, wet cutting did not present better values of surface roughness compared to MQL and dry cutting. However, the best cooling/lubrication system for this machining operation is dry cutting. Sreejith [12] investigated the effect of different lubricant environments when turning 6061 aluminum alloy using diamond-coated carbide tools. Together, it was seen that the use of coolant does not necessarily reduce the use of tools. This is because, under MQL condition, tool wear was found to be lower, but the amounts of coolant determine the adhesion material on the tool surface.

### 4.4. Cryogenic cooling

Cryogenics cooling is the use of materials or medium at very low temperatures which is below −150 °C. However, normal boiling points of permanent gases such as helium, hydrogen, neon, nitrogen and oxygen lies below −180 °C [73]. The two most commonly used in cryogenic cooling are liquid nitrogen (boiling point −195.82 °C) or frozen carbon dioxide (sublimation point −78.5 °C). With the nitrogen cooling, it allows an increase in cutting speed, higher productivity and extends the life of the tool. It also environmentally friendly coolant without the greenhouse effect and toxic properties [14]. Figs. 8 and 9 show the sample method and schematic diagram of cryogenic cooling, respectively.

Umbrello et al. [23] claimed that the Nitrogen is a safe, noncombustible, and noncorrosive gas because as a fact, 78% of the air we breathe in is nitrogen gas. The liquid nitrogen evaporates quickly under cryogenic machining leaving no wastes to contaminate its surroundings (workpiece, chips, machine tool, or operator) thus eliminating disposal costs. On top of that with increment machinability and minimize overall costs, cryogenic cooling can be used to machine materials at higher cutting speeds, and give better surface quality and integrity.

Aggarwal et al. [52] proposed an experimental in determining the optimum parameters for turned parts for optimize the tool life, cutting force, power consumption and surface roughness. They used liquid nitrogen as a coolant in machining and found that the highest expedience can be obtained at low level of cutting speed, feed, and depth of cut and at high nose radius of coated carbide insert. On the other hand, in their report, Biček et al. [24] concluded that optimum cutting parameters for cryogenic machining of normalized material are higher than optimum parameters for conventional turning. Besides that, it also shows improvement in surface roughness as its value is in cryogenic coolant compared to conventional dry and flood coolant during turning normalized bearing steel AISI 52100. Pusavec et al. [74] analyzed the influence of nitrogen phase on cryogenic machining performance and revealed that the liquid phase result in a higher cooling capability

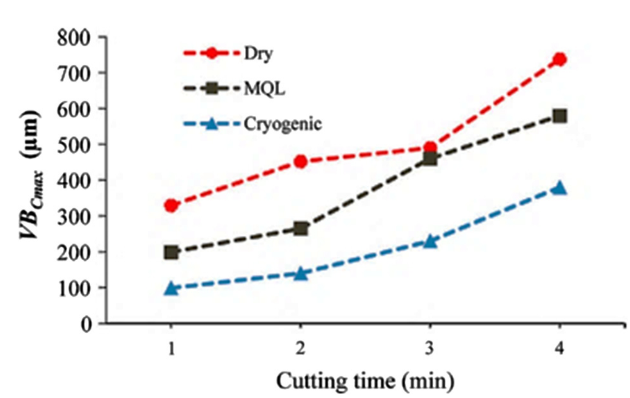



**Fig. 10.** The progression of maximum flank wear at the nose region with time under different cooling conditions [75].

and lower friction at tool-chip interface. From this investigation it shows that it is important to know what condition/phase of the fluid when using cryogenic machining.

Kaynak et al. [75] investigated on the progressive tool-wear of room-temperature-austenitic NiTi alloys under various machining condition (dry, MQL, and cryogenic). From the result (Fig. 10), they suggested that tool-wear rate was much lower in cryogenic machining. This is because the benefit of cryogenic machining was the elimination of notch wear on the nose region and substantially reduced progressive tool-wear over time in comparison with other conditions (dry and MQL). However, this is opposite with Stanford et al. [55] whereas they stated that cryogenic cutting environments showed flank wear rates that equal, or better, than those obtained under flood coolant conditions for the tool work combinations and cutting parameters investigated. Sun et al. [76] studied the performance of machining which is the cutting forces, surface roughness and tool-wear of Ti-5553 alloy by using cryogenic machining with liquid nitrogen and compared to flooded coolant and MQL. The results from their study shows that cutting and thrust forces generated from cryogenic machining were reduced up to 30% compared with that of flood-cooled and MQL machining. Nose wear of the insert also improved in cryogenic machining due to reduced material adhesion. However, better surface roughness was observed in MQL machining due to high temperature and lubricity effects with the associated softening of the work material. Meanwhile Umbrello et al. [23] compared the performance of cryogenic with dry cutting in machining hardened steel. The result reported that cryogenic cooling offers better surface properties and restrict the white layer thickness. Against it, dry machining while gave better result on residual stress profiles and, therefore would present to improve fatigue life. Navas et al. [38] asserted that by using liquid nitrogen in machining hard steel, it can reduce heating problems, leading to tool life improvement and better surface integrity (higher surface hardness, lower residual stresses and no white layer. Meanwhile, Jerold et al. [77] used $CO_2$ in cryogenic coolant for turning AISI 1045 steel and established that cutting temperature and cutting force is reduced around 5–22% and 17–38% respectively when compared to wet turning.

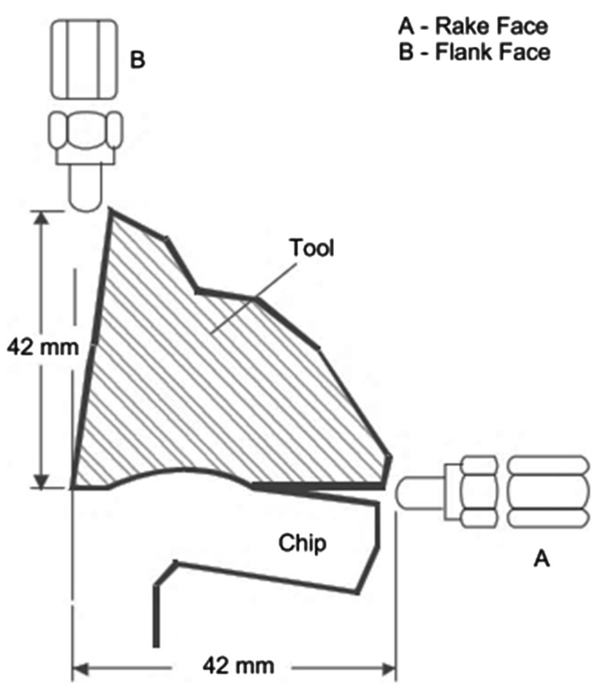



**Fig. 11.** Position of cutting fluid hoses [9].

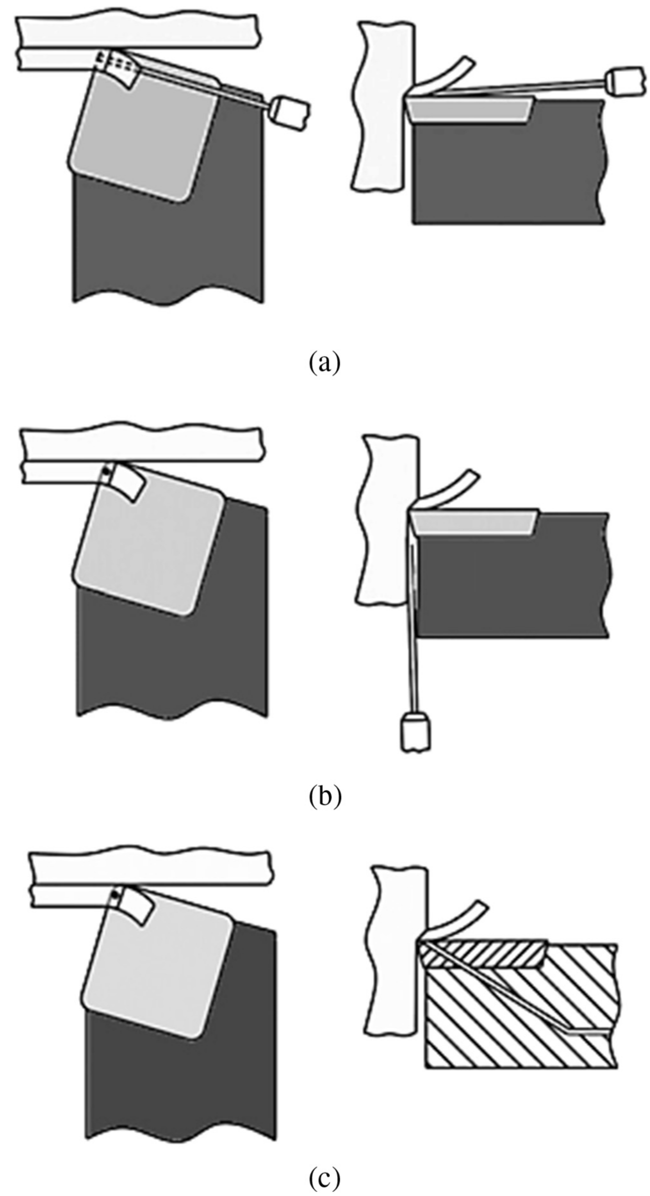



**Fig. 12.** Different HPC delivery: (a) between the rake face and the chip; (b) into the clearance; (c) towards the rake side through the tool [78].

According to Aggarwal et al. [52], advantages of cryogenic machining compared to conventional cutting fluid are:

- Cryogenic cooling is a clean technology and environmentally friendly than conventional coolant.
- It is non-toxic and non-explosive.
  It increases tool life and reduced tool wear mainly due to reduced tool-tip temperature.
- Cryogenic cooling technology also has benefits in terms of improving product quality and reducing power consumption and cutting force.

### 4.5. High pressure cooling (HPC)

Over the past century, high pressure systems have been developed. Coolant jets with very high pressures which around 100–1000 bar were designed as a part of the cutting system. The coolant jet is directed at very high pressure exactly in the gap between the clamping base and rake face of the cutting tool in this system [14]. Sharma et al. [9] stated that the high fluid pressure allows a better penetration of the fluid into the tool–workpiece and tool–chip contact regions as shown in Fig. 11. According to Kramar et al. [78], there are different HPC deliveries, such as the examples shown in Fig. 12.

Ezugwu and Bonney [29] investigated the effect of varying coolant pressure on tool performance when machining Inconel 718 alloy with coated carbide tools at high-speed conditions and found that tool life tend to improve with increasing coolant pressure. Meanwhile, Palanisamy et al. [35] investigated the effect of high pressure of cutting fluid onto tool life during machining of titanium alloys by using uncoated straight tungsten carbide. From this study, the application of coolant at high pressure (90 bar) increases tool life by almost three times whereas the insert lasted for more than 10 min compared when turning under lower pressure (6 bar). This is agreed by Silva et al. [42] where they investigated the behavior of Polycrystalline Diamond (PCD) tools when machining Ti–6Al–4V alloy at high speed conditions using high pressure coolant supplies. Their result also showed that increase in coolant pressure tends to improve tool life.

### 4.6. Nanofluid

In the last few decades, rapid advances in nanotechnology, the nanoparticles are produced with ease and are available commercially. Nanofluids are defined as colloidal suspensions of nanoparticles in a base fluid and these suspended metallic or nonmetallic nanoparticles change the transport properties and heat transfer characteristics of the base fluid [79–82].

Recent years, the use of nanofluids become a major area of interest within the regime of cooling, such as in the solar thermal systems [83–87]. From an investigation done by Mahian et al. [83], it proves that nanofluid provides an enhancement in evaporation rate compared to water as at $SiO_2$/water gives better result at high temperature while Cu/water yields the maximum enhancement at low temperature. Mahian et al. [84] also revealed that the most important challenges on the use of nanofluids in solar systems are high costs of production, instability and agglomeration problems which same as in machining industry. From their critical review also, they suggested that the nanofluids in different volume fractions should be tested to find the optimum volume fraction as using a nanofluid with higher volume fraction is not the best option. In the study of effects of nanoparticle shape and tube materials in analysis of minichannel-based solar collector where the working fluid is a suspension of boehmite alumina nanoparticles in a mixture of water and ethylene glycol, Mahian and his co-worker [85] revealed that when increasing volume fraction of nanoparticles, it will reduce the heat transfer coefficient and increase outlet temperature. However, a year later, in order to reduce preparation cost and instability problems, Meibodi et al. [86] suggested the use of lower volume fraction. Eventhough thermal efficiency is enhanced by the increase in volume fraction, yet they observed that the resulting thermal efficiencies value of 0.75% and 1% concentration of $SiO_2$ is slightly close.

In order to ensure the efficiency of nanofluid, the value of pH, zeta potential (stability), viscosity and thermal conductivity are the most important factors. During the steps in producing nanofluids, the adding of surfactant in nanofluid solution is important as it can stabilize the solution for long time. From novel study by Khairul et al. [88], by increasing the surfactant (SDBS) concentration, it also increases the stability of the concentration. From their observation also, they found that the viscosity of nanofluid is depends on the concentration of SDBS added. Meanwhile, Pryazhnikov et al. [89] stated that small concentration of surfactant does not affect the thermal conductivity of nanofluid. It is observed that besides the type of nanoparticle, base fluid is one of the factors that influenced the thermal conductivity. The lower the thermal conductivity of the base fluid, the higher the relative thermal conductivity of the nanofluids. Wei et al. [90] established that thermal conductivity of nanofluid increased by increasing the volume fraction. They also stated that thermal conductivity of hybrid particles ($SiC/TiO_2$) is higher that SiC or $TiO_2$ nanofluids.

According to Halelfadl et al. [91], beside the increment of thermal conductivity, by increasing the volume fraction, the density which independent of temperature also increase. Besides that, the relative viscosity of nanofluids is affected by both the increase in nanoparticle volume fraction and shear rate. In experimental study done by Zhang et al. [92] surface roughness, Ra is increases gradually as mass fraction of nanoparticles increases. This phenomenon is due to the fact that viscosity of nanofluids is the main influencing factor of Ra, which is positively related with nanoparticle concentration. The contact angle between the nanofluid and workpiece also expands, thus narrowing the wetted area of nanofluids. Other researcher, stated that particle size, nanolayer, particle movements, interactions and surface chemistry of nanoparticles which are responsible for enhancing thermal conductivity of nanofluids. For smaller-sized nanoparticles and low volume fractions, dynamic mechanisms such as particle Brownian motion, particle interactions and surface chemistry are significant in enhancing the thermal conductivity of nanofluids [93]. This was supported by Yan et al. [94] as they said that smaller particles

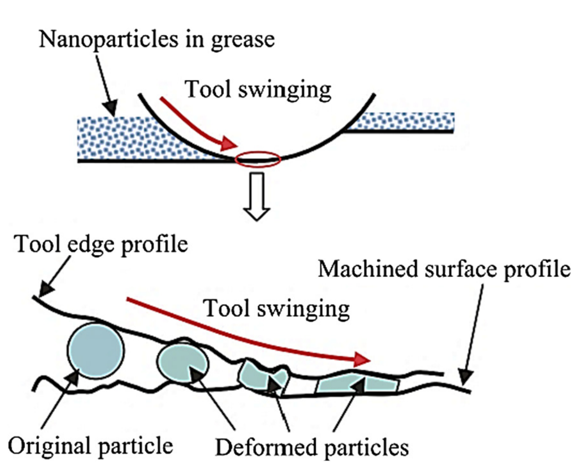



**Fig. 13.** Schematic models for nanoparticle-induced lubricating film formation in tool swinging cutting [94].

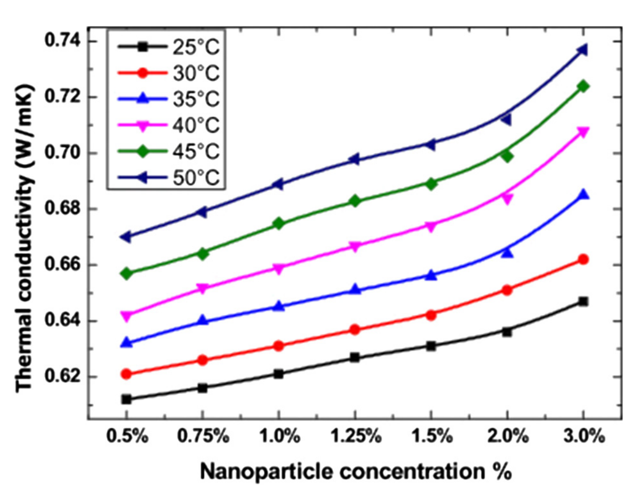



**Fig. 14.** Thermal conductivity w.r.t. nanoparticle concentration [101].

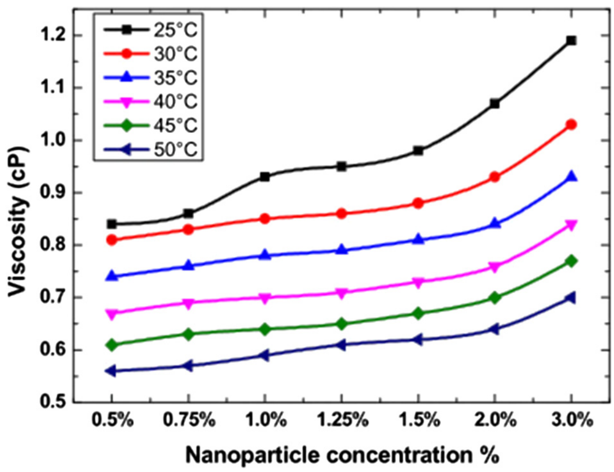



**Fig. 15.** Viscosity of nanofluid w.r.t. nanoparticle concentration [101].

are generally preferable to larger ones because smaller particles can enter the tool-workpiece interface more easily. Nanoparticle lubrication performance also may depend on microparticle fracture/deformation, which may generate an extremely thin solid lubricant film, significantly reducing direct asperity between the cutting tool and workpiece as shown in Fig. 13. The advantage of enhanced thermal conductivity, viscosity, and so on make the nanofluid suitable for application in metal cutting industry as coolants [43,82,95–98].

According to Ay and Yang [99], in cutting process, thermal aspect is important because it affects the machining precision such as thermal expansion and surface roughness as well as tool wear. Besides that, they also stated that groove wear and crater wear will produce as the number and size micropits formed at certain temperature increase during the turning operations. According to Teng et al. [100], by adding nanoparticles to fluid, it can effectively improve the thermal conductivity ratio of the fluid, and the weight fraction and temperature of added nanoparticles carry a proportional relationship with the thermal conductivity ratio. This is supported by Halelfadl et al. [91] where, from their investigation, the relative thermal conductivity, density and viscosity is independent of temperature and increases with particle volume fraction. Sharma et al. [101] investigated $Al_2O_3$ nanoparticle based cutting fluid in turning of AISI 1040 steel under minimum quantity lubrication (MQL) and found that thermal conductivity, viscosity and density of nanofluids are improved with increase of nanoparticle concentration while specific heat is decreased with increase of nanoparticle concentrations. Figs. 14 and 15 show the thermal conductivity and viscosity of nanofluid versus nanoparticle concentration at different temperatures. Hussein et al. [102] studied two different type of nanofluids; $SiO_2$ and $TiO_2$ nanofluid and disclosed that $SiO_2$ produced higher heat transfer enhancement than $TiO_2$ nanofluid. However, both nanofluids still have better heat transfer than pure water. Therefore, nanofluid produces better effects in cases of higher temperatures as it validates higher thermal conductivity ratio enhancement at higher temperatures. This property is very useful in terms of machining of hard steel as it produces high temperature. However, Jiang et al. [103] observed the opposite result. They found that thermal conductivity increased nonlinearly with the increasing nanoparticle volume fractions as they used carbon nanotube (CNT) in their investigations. The temperature also has a small role in improving thermal conductivity of CNT-based nanofluids. Aside that, Krishna et al. [104] also stated that nanofluids can provide preferable cooling and lubrication during machining and make it production-feasible due to its advanced heat transfer and tribological properties. Not only that it also showed astonishing decreasing in power consumption, specific energy, cutting force, surface roughness, nodal temperature, torque in drilling, tool wear (flank and crater), and friction coefficient in machining when mix the nanoparticles in base cutting fluids [105].

Srikant et al. [43] studied the characterizing changes in the heat transfer capacities of nanofluids with the inclusion of nanoparticles in the cutting fluid in turning of AISI 1040 and identified that thermal conductivity of the fluids increased with content of nanoparticles and enhanced heat transfer capacity up to 6% and decreases beyond thus better tool life may be obtained. This is also supported by Padmini et al. [106] as the thermal conductivity, specific heat and heat transfer coefficients are observed to increase with increase in nano particle inclusion for all nanofluids in the study of performance of vegetable oil based nanofluids on machining performance during turning of AISI 1040 steel through minimum quantity lubrication (MQL). Some researchers used nanofluid in MQL machining to reduce the uses of coolant. Bahera and his co-worker [96] used $Al_2O_3$ and silver nanofluid at different

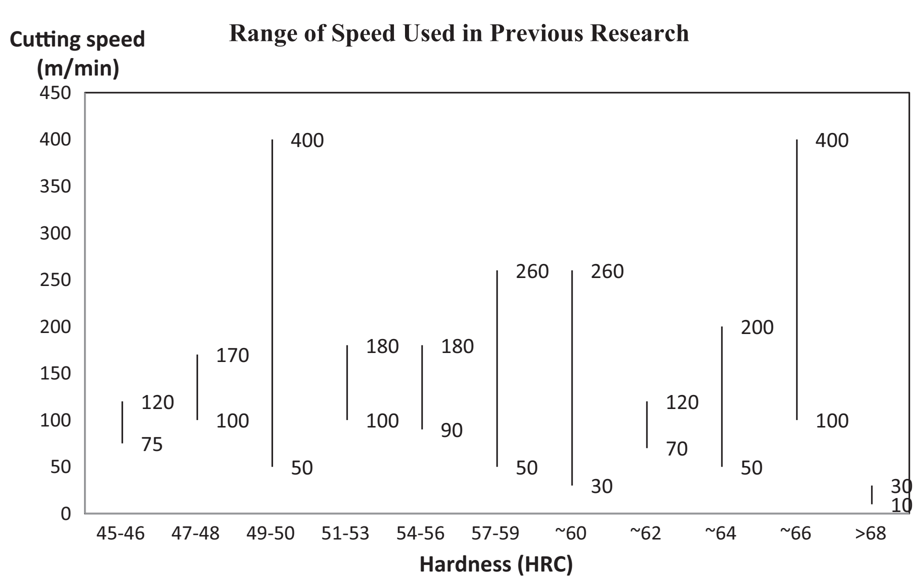



**Fig. 16.** Range of speed used for turning hard steel (45 → 68 HRc).

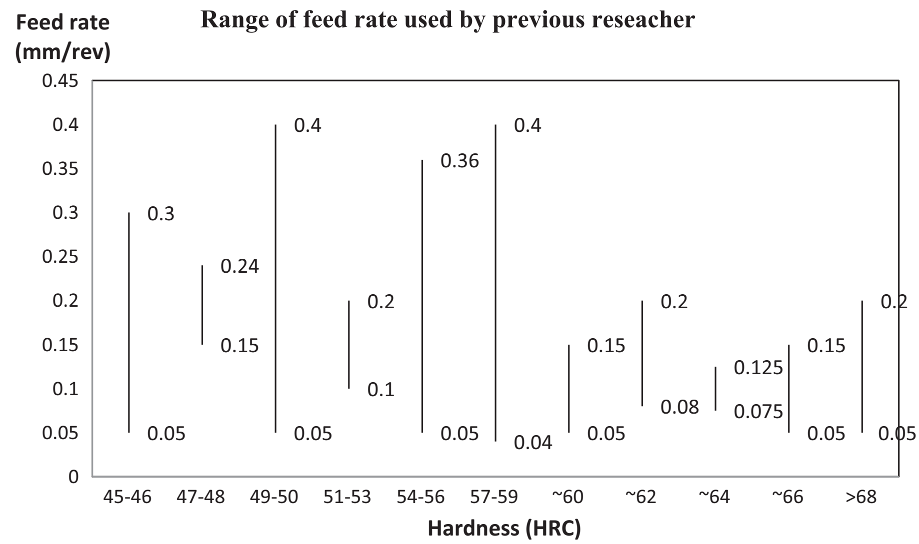



**Fig. 17.** Range of feed rate used in turning hard steel (45 → 68 HRc).

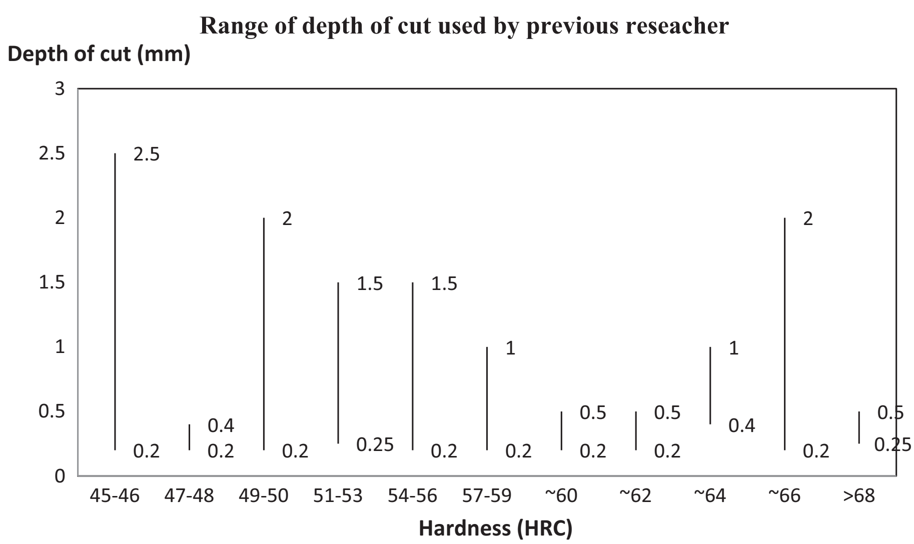



**Fig. 18.** Range of depth of cut used in turning hard steel (45 → 68 HRc).

concentrations in turning process and found that $Al_2O_3$ nanofluid gives lowest cutting force. They also stated that the tribology film formed by $Al_2O_3$ reduced the sliding friction forces which also lead to reduce flank wear and tool nose wear compared to silver nanofluid. From their investigation also shows that nanofluids can reduce the chip thickness and chip reduction coefficient compared to dry machining. Khalil et al. [107] also used $Al_2O_3$ in their study and acquired the same result as dry machining caused high too wear growth. They mentioned that $Al_2O_3$ nano particles suspended in base oil helps to alleviate and flush away the heat generated during turning AISI 1050 steel. The experimental results done by Su et al. [108] in turning of AISI 1045 showed that application of graphite in vegetable oil nanofluid MQL reduced the cutting force and temperature significantly and showed better performance than graphite in ester oil especially at high cutting speed. In researching the effects of nanofluids on turning AISI D2 steel using MQL, Sharma et al. [109] dispersed carbon nanotube (CNT) into mineral oil (SAE20W40 oil). The results showed that when including the CNT particle, cutting zone temperature decreases compare when only used mineral oil. This is also because the thermal conductivity of cutting fluid and its carrying heat capacity increase. Besides that, it also observed that nanofluids can enhance surface quality as it reduces tool wear. The same result also found in the investigation done by Zhang et al. [92] as it showed that MQL nanofluid by using of hybrid nanofluid (CNT + $MoS_2$) gives higher machining precision and surface quality.

Nanoparticles used in nanofluids have been made of various materials, such as oxide ceramics ($Al_2O_3$, CuO), nitride ceramics (AlN, SiN), carbide ceramics (SiC, TiC), metals (Cu, Ag, Au), semiconductors ($TiO_2$, SiC), carbon nanotubes, and composite materials such as alloyed nanoparticles Al70Cu30 or nanoparticle core–polymer shell composites. The liquid type for nanoparticle inclusion that mostly used are water, ethylene glycol, and oil [95,96,98,110].

From the literature, the advantages of nanofluids are as below [79,82,111–113]:

- High specific surface area and therefore more heat transfer surface between particles and fluids.
- High dispersion stability with predominant Brownian motion of particles.

- Reduced pumping power as compared to pure liquid to achieve equivalent heat transfer intensification.
- Reduced particle clogging as compared to conventional slurries, thus promoting system miniaturization.
- Adjustable properties, including thermal conductivity and surface wettability, by varying particle concentrations to suit different applications.

### 4.7. Summary of machining parameter for material that having hardness above 45 HRc

This section shows the machining parameters (cutting speed, feed rate and depth of cut) used for turning material that having hardness above 45 HRc. These parameters are the common used to investigate the output response for the turning process for the flooded/wet cooling, dry machining, MQL, high pressure, cryogenic and nanofluid machining.

Fig. 16 shows the range of speed used by previous researcher for turning hard steel. The speed is classified according to it range of hardness. From the figure, it can be seen that the highest speed used is 400 m/min. However, from the figure, it can be concluded that the most suitable speed is around 180 m/min.

Fig. 17 shows the common range of feed rate used in turning hard steel. The lowest feed rate used is 0.04 mm/rev and the highest is 0.4 mm/rev. However, 0.05–0.15 mm/rev is the most commonly used for each class of hardness. This is possible as it may provide good performance around these values.

The range of depth of cut for turning hard steel is shown in Fig. 18. From Fig. 18, 0.2 mm is the most widely used depth of cut value in turning hard steel. It can be seen that high value of depth of cut is seldom used as by increase the depth of cut, the tool life is decreases and surface roughness is increases.

## 5. Future work recommendations

In order to advance the cooling technology in turning, future work on cooling techniques shall continue profoundly. From the literature review, surprisingly, very few published studies have been published that specifically assess the use of nanofluid in turning. Therefore, it is suggested that more research is required on the application of nanofluids in turning process to better understand the influence of nano particles towards turning performance. Besides that, it is also recommended that further studies are needed to be carried out on hybrid cooling technique in turning process to improve machining performance.

## 6. Conclusions

This paper presents an overview of important published experimental investigation on turning hard steel under various cooling technique. It also covers a brief description of experiment and the findings in systematic manner. According to literature review, there are many cooling techniques proposed by the researcher in order to produce a better and high quality product especially when handling high hardness material. Most of the experimental studies also showed that the choice of cutting fluid is important for each machining process.

The following conclusion can be drawn from the literature:

- Surface roughness and tool life/tool wear is the most important aspect in hard turning to measure the performance.
- Depth of cut and cutting speed are the most significant factors for flank wear.
- The most significant factors that affect the surface roughness are cutting speed followed by feed rate.
- The used of cutting fluid when turning hard steel can reduce the heat generated and improve tool life.
- For turning on steels, steel alloys and cast irons dry turning is applicable except for aluminum alloys.
- Near dry/MQL can reduce the use of cutting fluids and therefore promote green environment compare to flood turning.
- Cryogenic turning is to be said provided better product quality compared to dry turning and MQL.
- The increasing of pressure in hard pressure turning can improve tool life.
- The inclusion of nanoparticle in cutting fluid (nanofluid) can enhance the thermal conductivity ratio of the cutting fluid.

## Conflict of interest

The authors declare that there are no conflicts of interest.

## References


[1] S. Kalpakjian, Manufacturing Engineering and Technology, Pearson Education India, 2001.

[2] T. El-Wardany, H. Kishawy, M. Elbestawi, Surface integrity of die material in high speed hard machining, Part 1: Micrographical analysis, Trans.-Am. Soc. Mech. Eng. J. Manuf. Sci. Eng. 122 (2000) 620–631.

[3] C.R.V. Kumar, B. Ramamoorthy, Performance of coated tools during hard turning under minimum fluid application, J. Mater. Process. Technol. 185 (2007) 210–216.

[4] N. Coppini, A. Diniz, M. Bonandi, E. De Souza, E. Baptista, Hard turning of sintered cemented carbide Parts: a shop floor experience, Proc. CIRP 8 (2013) 368–373.

[5] S. Hosseini, R. Dahlgren, K. Ryttberg, U. Klement, Dissolution of iron-chromium carbides during white layer formation induced by hard turning of AISI 52100 steel, Proc. CIRP 14 (2014) 107–112.

[6] Z.R. Mohammad, H. Bo, D. Songlin, M. John, B. Milan, Electrical discharge grinding of polycrystalline diamond- material erosion rate, J. Adv. Res. Mater. Sci. 31 (2017) 10–18.

[7] G. Bartarya, S. Choudhury, State of the art in hard turning, Int. J. Mach. Tools Manuf. 53 (2012) 1–14.

[8] Y. Yusoff, A. Zain, H. Haron, Experimental study of genetic algorithm optimization on WC/Co material machining, J. Adv. Res. Mater. Sci. 21 (2016) 14–26.

[9] V.S. Sharma, M. Dogra, N. Suri, Cooling techniques for improved productivity in turning, Int. J. Mach. Tools Manuf. 49 (2009) 435–453.

[10] M. Bhuiyan, I. Choudhury, M. Dahari, Monitoring the tool wear, surface roughness and chip formation occurrences using multiple sensors in turning, J. Manuf. Syst. 33 (2014) 476–487.

[11] C. Chan, W. Lee, H. Wang, Enhancement of surface finish using water-miscible nano-cutting fluid in ultra-precision turning, Int. J. Mach. Tools Manuf. 73 (2013) 62–70.

[12] P. Sreejith, Machining of 6061 aluminium alloy with MQL, dry and flooded lubricant conditions, Mater. Lett. 62 (2008) 276–278.

[13] B.S. Kumar, G. Padmanabhan, P.V. Krishna, Multi response optimization for turning AISI 1040 steel with extreme pressure additive included vegetable oil based cutting fluids using grey relational analysis, J. Adv. Res. Mater. Sci. 23 (2016) 1–14.

[14] S. Anton, S. Andreas, B. Friedrich, Heat dissipation in turning operations by means of internal cooling, Proc. Eng. 100 (2015) 1116–1123.

[15] D. Adler, W.-S. Hii, D. Michalek, J. Sutherland, Examining the role of cutting fluids in machining and efforts to address associated environmental/health concerns, Mach. Sci. Technol. 10 (2006) 23–58.

[16] B.S. Kumar, G. Padmanabhan, P.V. Krishna, Performance assessment of vegetable oil based cutting fluids with extreme pressure additive in machining, J. Adv. Res. Mater. Sci. 19 (2016) 1–13.

[17] I. Asiltürk, H. Akkuş, Determining the effect of cutting parameters on surface roughness in hard turning using the Taguchi method, Measurement 44 (2011) 1697–1704.

[18] A.S. More, W. Jiang, W. Brown, A.P. Malshe, Tool wear and machining performance of cBN–TiN coated carbide inserts and PCBN compact inserts in turning AISI 4340 hardened steel, J. Mater. Process. Technol. 180 (2006) 253–262.

[19] H. Kishawy, M. Dumitrescu, E.-G. Ng, M. Elbestawi, Effect of coolant strategy on tool performance, chip morphology and surface quality during high-speed machining of A356 aluminum alloy, Int. J. Mach. Tools Manuf. 45 (2005) 219–227.

[20] A. Diniz, J. Ferreira, Influence of refrigeration/lubrication condition on SAE 52100 hardened steel turning at several cutting speeds, Int. J. Mach. Tools Manuf. 43 (2003) 317–326.

[21] J. Lima, R. Avila, A. Abrao, M. Faustino, J.P. Davim, Hard turning: AISI 4340 high strength low alloy steel and AISI D2 cold work tool steel, J. Mater. Process. Technol. 169 (2005) 388–395.

[22] J. Arsecularatne, L. Zhang, C. Montross, P. Mathew, On machining of hardened AISI D2 steel with PCBN tools, J. Mater. Process. Technol. 171 (2006) 244–252.
[23] D. Umbrello, F. Micari, I. Jawahir, The effects of cryogenic cooling on surface integrity in hard machining: a comparison with dry machining, CIRP Ann. Manuf. Technol. 61 (2012) 103–106.
[24] M. Biček, F. Dumont, C. Courbon, F. Pušavec, J. Rech, J. Kopač, Cryogenic machining as an alternative turning process of normalized and hardened AISI 52100 bearing steel, J. Mater. Process. Technol. 212 (2012) 2609–2618.
[25] A. Srithar, K. Palanikumar, B. Durgaprasad, Experimental investigation and surface roughness analysis on hard turning of AISI D2 steel using coated carbide insert, Proc. Eng. 97 (2014) 72–77.
[26] M.H.S. Elmunafi, M. Noordin, D. Kurniawan, Tool life of coated carbide cutting tool when turning hardened stainless steel under minimum quantity lubricant using castor oil, Proc. Manuf. 2 (2015) 563–567.
[27] S. Sahu, B. Choudhury, Optimization of surface roughness using Taguchi methodology & prediction of tool wear in hard turning tools, Mater. Today: Proc. 2 (2015) 2615–2623.
[28] S. Debnath, M.M. Reddy, Q.S. Yi, Influence of cutting fluid conditions and cutting parameters on surface roughness and tool wear in turning process using Taguchi method, Measurement 78 (2016) 111–119.
[29] E. Ezugwu, J. Bonney, Effect of high-pressure coolant supply when machining nickel-base, Inconel 718, alloy with coated carbide tools, J. Mater. Process. Technol. 153 (2004) 1045–1050.
[30] V. Gaitonde, S. Karnik, J.P. Davim, Selection of optimal MQL and cutting conditions for enhancing machinability in turning of brass, J. Mater. Process. Technol. 204 (2008) 459–464.
[31] Y. Isik, An Experimental investigation on effect of cutting fluids in turning with coated carbides tool, J. Mech. Eng. 56 (2010) 195–201.
[32] P.C. Priarone, M. Robiglio, L. Settineri, V. Tebaldo, Effectiveness of minimizing cutting fluid use when turning difficult-to-cut alloys, Proc. CIRP 29 (2015) 341–346.
[33] A.K. Sahoo, B. Sahoo, Experimental investigations on machinability aspects in finish hard turning of AISI 4340 steel using uncoated and multilayer coated carbide inserts, Measurement 45 (2012) 2153–2165.
[34] S. Chinchanikar, S. Choudhury, Investigations on machinability aspects of hardened AISI 4340 steel at different levels of hardness using coated carbide tools, Int. J. Refract. Metal Hard Mater. 38 (2013) 124–133.
[35] S. Palanisamy, S.D. McDonald, M.S. Dargusch, Effects of coolant pressure on chip formation while turning Ti6Al4V alloy, Int. J. Mach. Tools Manuf. 49 (2009) 739–743.
[36] R. Avila, A. Abrao, The effect of cutting fluids on the machining of hardened AISI 4340 steel, J. Mater. Process. Technol. 119 (2001) 21–26.
[37] S. Dilbag, P. Rao, Performance improvement of hard turning with solid lubricants, Int. J. Adv. Manuf. Technol. 38 (2008) 529–535.
[38] V.G. Navas, D. Fernández, A. Sandá, C. Sanz, S. Suzon, T.F. de Mendiola, Surface integrity of AISI 4150 (50CrMo4) steel turned with different types of cooling-lubrication, Proc. CIRP 13 (2014) 97–102.
[39] J.P. Davim, L. Figueira, Machinability evaluation in hard turning of cold work tool steel (D2) with ceramic tools using statistical techniques, Mater. Des. 28 (2007) 1186–1191.
[40] V. Gaitonde, S. Karnik, L. Figueira, J.P. Davim, Analysis of machinability during hard turning of cold work tool steel (type: AISI D2), Mater. Manuf. Process. 24 (2009) 1373–1382.
[41] O. Çakīr, A. Yardimeden, T. Ozben, E. Kilickap, Selection of cutting fluids in machining processes, J. Achiev. Mater. Manuf. Eng. 25 (2007) 99–102.
[42] R.B. da Silva, Á.R. Machado, E.O. Ezugwu, J. Bonney, W.F. Sales, Tool life and wear mechanisms in high speed machining of Ti–6Al–4V alloy with PCD tools under various coolant pressures, J. Mater. Process. Technol. 213 (2013) 1459–1464.
[43] R. Srikant, D. Rao, M. Subrahmanyam, V.P. Krishna, Applicability of cutting fluids with nanoparticle inclusion as coolants in machining, Proc. Inst. Mech. Eng., Part J: J. Eng. Tribol. 223 (2009) 221–225.
[44] M.A. Yallese, K. Chaoui, N. Zeghib, L. Boulanouar, J.-F. Rigal, Hard machining of hardened bearing steel using cubic boron nitride tool, J. Mater. Process. Technol. 209 (2009) 1092–1104.
[45] D.K. Das, A.K. Sahoo, R. Das, B. Routara, Investigations on hard turning using coated carbide insert: Grey based Taguchi and regression methodology, Proc. Mate. Sci. 6 (2014) 1351–1358.
[46] Z. Taha, H.-K. Lelana, H. Aoyama, R.A. Raja Ghazilla, J. Gonzales, N. Sakundarini, et al., Insert geometry effects on surface roughness in turning process of AISI D2 steel, J. Zhejiang Univ.-Sci. A 11 (2010) 966–971.
[47] J.G.A. Arulraj, K.L.D. Wins, A. Raj, Artificial neural network assisted sensor fusion model for predicting surface roughness during hard turning of H13 steel with minimal cutting fluid application, Proc. Mater. Sci. 5 (2014) 2338–2346.
[48] M. Khan, M. Mithu, N.R. Dhar, Effects of minimum quantity lubrication on turning AISI 9310 alloy steel using vegetable oil-based cutting fluid, J. Mater. Process. Technol. 209 (2009) 5573–5583.
[49] T. Özel, Y. Karpat, L. Figueira, J.P. Davim, Modelling of surface finish and tool flank wear in turning of AISI D2 steel with ceramic wiper inserts, J. Mater. Process. Technol. 189 (2007) 192–198.
[50] W. Grzesik, J. Rech, T. Wanat, Surface finish on hardened bearing steel parts produced by superhard and abrasive tools, Int. J. Mach. Tools Manuf. 47 (2007) 255–262.
[51] N.A.C. Sidik, S. Samion, J. Ghaderian, M.N.A.W.M. Yazid, Recent progress on the application of nanofluids in minimum quantity lubrication machining: a review, Int. J. Heat Mass Transf. 108 (2017) 79–89.
[52] A. Aggarwal, H. Singh, P. Kumar, M. Singh, Optimization of multiple quality characteristics for CNC turning under cryogenic cutting environment using desirability function, J. Mater. Process. Technol. 205 (2008) 42–50.
[53] D. Stephenson, M. Barone, G. Dargush, Thermal expansion of the workpiece in turning, Trans.-Am. Soc. Mech. Eng. J. Eng. Ind. 117 (1995) 542–550.
[54] D. O'sullivan, M. Cotterell, Temperature measurement in single point turning, J. Mater. Process. Technol. 118 (2001) 301–308.
[55] P. Sreejith, B. Ngoi, Dry machining: machining of the future, J. Mater. Process. Technol. 101 (2000) 287–291.
[56] B. Ozcelik, E. Kuram, M.H. Cetin, E. Demirbas, Experimental investigations of vegetable based cutting fluids with extreme pressure during turning of AISI 304L, Tribol. Int. 44 (2011) 1864–1871.
[57] M.A. Xavior, M. Adithan, Determining the influence of cutting fluids on tool wear and surface roughness during turning of AISI 304 austenitic stainless steel, J. Mater. Process. Technol. 209 (2009) 900–909.
[58] T. Leppert, Effect of cooling and lubrication conditions on surface topography and turning process of C45 steel, Int. J. Mach. Tools Manuf. 51 (2011) 120–126.
[59] S. Chinchanikar, A. Salve, P. Netake, A. More, S. Kendre, R. Kumar, Comparative evaluations of surface roughness during hard turning under dry and with water-based and vegetable oil-based cutting fluids, Proc. Mater. Sci. 5 (2014) 1966–1975.
[60] L. Liang, X. Liu, X.-q. Li, Y.-Y. Li, Wear mechanisms of WC–10Ni 3 Al carbide tool in dry turning of Ti6Al4V, Int. J. Refract. Metal Hard Mater. 48 (2015) 272–285.
[61] V. Bhemuni, S.R. Chelamalasetti, S.P. Kondapalli, Effect of machining parameters on tool wear and nodal temperature in hard turning of AISI D3 steel, Open Access Library J. 1 (2014) 1.
[62] S.R. Das, A. Kumar, D. Dhupal, Effect of machining parameters on surface roughness in machining of hardened aisi 4340 steel using coated carbide inserts, Int. J. Innov. Appl. Stud. 2 (2013) 445–453.
[63] S.R. Das, D. Dhupal, A. Kumar, Experimental investigation into machinability of hardened AISI 4140 steel using TiN coated ceramic tool, Measurement 62 (2015) 108–126.
[64] R. Suresh, S. Basavarajappa, V. Gaitonde, G. Samuel, Machinability investigations on hardened AISI 4340 steel using coated carbide insert, Int. J. Refract. Metal Hard Mater. 33 (2012) 75–86.
[65] R.T. Coelho, E.-G. Ng, M. Elbestawi, Tool wear when turning hardened AISI 4340 with coated PCBN tools using finishing cutting conditions, Int. J. Mach. Tools Manuf. 47 (2007) 263–272.
[66] N.A.C. Sidik, S. Samion, J. Ghaderian, M.N.A.W.M. Yazid, Recent progress on the application of nanofluids in minimum quantity lubrication machining: a review, Int. J. Heat Mass Transf. 108 (Part A) (2017) 79–89.
[67] R. Da Silva, J. Vieira, R. Cardoso, H. Carvalho, E. Costa, A. Machado, et al., Tool wear analysis in milling of medium carbon steel with coated cemented carbide inserts using different machining lubrication/cooling systems, Wear 271 (2011) 2459–2465.
[68] B.A. Beatrice, E. Kirubakaran, P.R.J. Thangaiah, K.L.D. Wins, Surface roughness prediction using artificial neural network in hard turning of AISI H13 steel with minimal cutting fluid application, Proc. Eng. 97 (2014) 205–211.
[69] S. Zhang, J. Li, Y. Wang, Tool life and cutting forces in end milling Inconel 718 under dry and minimum quantity cooling lubrication cutting conditions, J. Clean. Prod. 32 (2012) 81–87.
[70] M.H.S. Elmunafi, D. Kurniawan, M. Noordin, Use of castor oil as cutting fluid in machining of hardened stainless steel with minimum quantity of lubricant, Proc. CIRP 26 (2015) 408–411.
[71] Z. Liu, Q. An, J. Xu, M. Chen, S. Han, Wear performance of (nc-AlTiN)/(a-Si 3 N 4) coating and (nc-AlCrN)/(a-Si 3 N 4) coating in high-speed machining of titanium alloys under dry and minimum quantity lubrication (MQL) conditions, Wear 305 (2013) 249–259.
[72] S. Chinchanikar, S. Choudhury, Hard turning using HiPIMS-coated carbide tools: wear behavior under dry and minimum quantity lubrication (MQL), Measurement 55 (2014) 536–548.
[73] Y. Yildiz, M. Nalbant, A review of cryogenic cooling in machining processes, Int. J. Mach. Tools Manuf. 48 (2008) 947–964.
[74] F. Pusavec, T. Lu, C. Courbon, J. Rech, U. Aljancic, J. Kopac, et al., Analysis of the influence of nitrogen phase and surface heat transfer coefficient on cryogenic machining performance, J. Mater. Process. Technol. 233 (2016) 19–28.
[75] Y. Kaynak, S. Robertson, H. Karaca, I. Jawahir, Progressive tool-wear in machining of room-temperature austenitic NiTi alloys: the influence of cooling/lubricating, melting, and heat treatment conditions, J. Mater. Process. Technol. 215 (2015) 95–104.
[76] Y. Sun, B. Huang, D. Puleo, I. Jawahir, Enhanced machinability of Ti-5553 alloy from cryogenic machining: comparison with MQL and flood-cooled machining and modeling, Proc. CIRP 31 (2015) 477–482.
[77] B.D. Jerold, M.P. Kumar, Experimental investigation of turning AISI 1045 steel using cryogenic carbon dioxide as the cutting fluid, J. Manuf. Process. 13 (2011) 113–119.
[78] D. Kramar, P. Krajnik, J. Kopac, Capability of high pressure cooling in the turning of surface hardened piston rods, J. Mater. Process. Technol. 210 (2010) 212–218.

[79] R. Saidur, K. Leong, H. Mohammad, A review on applications and challenges of nanofluids, Renew. Sustain. Energy Rev. 15 (2011) 1646–1668.
[80] C.S. Nor Azwadi, O.A. Alawi, Computational investigations on heat transfer enhancement using nanorefrigerants, J. Adv. Res. Des. 1 (2014) 35–41.
[81] C.S. Nor Azwadi, I. Adamu, M. Jamil, Preparation methods and thermal performance of hybrid nanofluids, J. Adv. Rev. Sci. Res. 24 (2016) 13–23.
[82] Y.K. Lee, The use of nanofluids in domestic water heat exchanger, J. Adv. Res. Appl. Mech. 3 (2014) 9–24.
[83] O. Mahian, A. Kianifar, S.Z. Heris, D. Wen, A.Z. Sahin, S. Wongwises, Nanofluids effects on the evaporation rate in a solar still equipped with a heat exchanger, Nano Energy 36 (2017) 134–155.
[84] O. Mahian, A. Kianifar, S.A. Kalogirou, I. Pop, S. Wongwises, A review of the applications of nanofluids in solar energy, Int. J. Heat Mass Transf. 57 (2013) 582–594.
[85] O. Mahian, A. Kianifar, S.Z. Heris, S. Wongwises, First and second laws analysis of a minichannel-based solar collector using boehmite alumina nanofluids: effects of nanoparticle shape and tube materials, Int. J. Heat Mass Transf. 78 (2014) 1166–1176.
[86] S.S. Meibodi, A. Kianifar, H. Niazmand, O. Mahian, S. Wongwises, Experimental investigation on the thermal efficiency and performance characteristics of a flat plate solar collector using SiO 2/EG–water nanofluids, Int. Commun. Heat Mass Transfer 65 (2015) 71–75.
[87] M. Khattak, A. Mukhtar, S.K. Afaq, Application of nano-fluids as coolant in heat exchangers: a review, J. Adv. Rev. Sci. Res. 22 (2016) 1–11.
[88] M. Khairul, K. Shah, E. Doroodchi, R. Azizian, B. Moghtaderi, Effects of surfactant on stability and thermo-physical properties of metal oxide nanofluids, Int. J. Heat Mass Transf. 98 (2016) 778–787.
[89] M. Pryazhnikov, A. Minakov, V.Y. Rudyak, D. Guzei, Thermal conductivity measurements of nanofluids, Int. J. Heat Mass Transf. 104 (2017) 1275–1282.
[90] B. Wei, C. Zou, X. Yuan, X. Li, Thermo-physical property evaluation of diathermic oil based hybrid nanofluids for heat transfer applications, Int. J. Heat Mass Transf. 107 (2017) 281–287.
[91] S. Halelfadl, T. Maré, P. Estellé, Efficiency of carbon nanotubes water based nanofluids as coolants, Exp. Therm. Fluid Sci. 53 (2014) 104–110.
[92] Y. Zhang, C. Li, D. Jia, B. Li, Y. Wang, M. Yang, et al., Experimental study on the effect of nanoparticle concentration on the lubricating property of nanofluids for MQL grinding of Ni-based alloy, J. Mater. Process. Technol. 232 (2016) 100–115.
[93] S. Murshed, K. Leong, C. Yang, A combined model for the effective thermal conductivity of nanofluids, Appl. Therm. Eng. 29 (2009) 2477–2483.
[94] J. Yan, Z. Zhang, T. Kuriyagawa, Effect of nanoparticle lubrication in diamond turning of reaction-bonded SiC, Int. J. Autom. Technol. 5 (2011) 307–312.
[95] G. Ny, N. Barom, S. Noraziman, S. Yeow, Numerical study on turbulent-forced convective heat transfer of Ag/Heg water nanofluid in pipe, J. Adv. Res. Mater. Sci. 22 (2016) 11–27.
[96] M. Faizal, R. Saidur, S. Mekhilef, M. Faizal, Potential of size reduction of flat-plate solar collectors when applying Al2O3 nanofluid, Adv. Mater. Res.: Trans. Tech. Publ.; 2014. p. 149–53.
[97] M. Jamil, C.S. Nor Azwadi, M.M. Yazid, Thermal performance of thermosyphon evacuated tube solar collector using $TiO_2$/water nanofluid, J. Adv. Res. Fluid Mech. Therm. Sci. 20 (2016) 12–29.
[98] S. Abubakar, C.S. Nor Azwadi, A. Ahmad, The use of Fe3O4-H2O4 nanofluid for heat transfer enhancement in rectangular microchannel heatsink, J. Adv. Res. Mater. Sci. 23 (2016) 15–24.
[99] H. Ay, W.-J. Yang, Heat transfer and life of metal cutting tools in turning, Int. J. Heat Mass Transf. 41 (1998) 613–623.
[100] T.-P. Teng, Y.-H. Hung, T.-C. Teng, H.-E. Mo, H.-G. Hsu, The effect of alumina/water nanofluid particle size on thermal conductivity, Appl. Therm. Eng. 30 (2010) 2213–2218.
[101] A.K. Sharma, R.K. Singh, A.R. Dixit, A.K. Tiwari, Characterization and experimental investigation of $Al_2O_3$ nanoparticle based cutting fluid in turning of AISI 1040 steel under minimum quantity lubrication (MQL), Mater. Today: Proc. 3 (2016) 1899–1906.
[102] A.M. Hussein, R. Bakar, K. Kadirgama, K. Sharma, Heat transfer enhancement using nanofluids in an automotive cooling system, Int. Commun. Heat Mass Transfer 53 (2014) 195–202.
[103] H. Jiang, Q. Zhang, L. Shi, Effective thermal conductivity of carbon nanotube-based nanofluid, J. Taiwan Inst. Chem. Eng. 55 (2015) 76–81.
[104] P.V. Krishna, R. Srikant, R. Padmini, J. Viswaditya, Application of nanomaterials as coolants/lubricants in machining, in: Advanced Nanomaterials and Emerging Engineering Technologies (ICANMEET), 2013 International Conference on: IEEE; 2013. p. 674–82.
[105] A.K. Sharma, A.K. Tiwari, A.R. Dixit, Progress of nanofluid application in machining: a review, Mater. Manuf. Process. 30 (2015) 813–828.
[106] R. Padmini, P.V. Krishna, G.K.M. Rao, Effectiveness of vegetable oil based nanofluids as potential cutting fluids in turning AISI 1040 steel, Tribol. Int. 94 (2016) 490–501.
[107] A. Khalil, M. Ali, A. Azmi, Effect of Al2O3 nanolubricant with SDBS on tool wear during turning process of AISI 1050 with minimal quantity lubricant, Proc. Manuf. 2 (2015) 130–134.
[108] Y. Su, L. Gong, B. Li, Z. Liu, D. Chen, Performance evaluation of nanofluid MQL with vegetable-based oil and ester oil as base fluids in turning, Int. J. Adv. Manuf. Technol. 83 (2016) 2083–2089.
[109] P. Sharma, B.S. Sidhu, J. Sharma, Investigation of effects of nanofluids on turning of AISI D2 steel using minimum quantity lubrication, J. Clean. Prod. 108 (2015) 72–79.
[110] S.K. Das, S.U. Choi, W. Yu, T. Pradeep, Nanofluids: Science and Technology, John Wiley & Sons, 2007.
[111] R. Srikant, M. Prasad, M. Amrita, A. Sitaramaraju, P.V. Krishna, Nanofluids as a potential solution for minimum quantity lubrication: a review, Proc. Inst. Mech. Eng., Part B: J. Eng. Manuf. 228 (2014) 3–20.
[112] S. Zainal, C. Tan, C. Sian, T. Siang, ANSYS simulation for Ag/HEG hybrid nanofluid in turbulent circular pipe, J. Adv. Res. Appl. Mech. 23 (2016) 20–35.
[113] H. Mohammed, O.A. Alawi, C.S. Nor Azwadi, Mixed convective nanofluids flow in a channel having forward-facing step with baffle, J. Adv. Res. Appl. Mech. 24 (2016) 1–21.