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EXPERIMENTAL INVESTIGATION OF EFFECT OF USAGE OF NANO-FLUIDS ON COOLING IN MACHINING

M.Sc. Thesis by

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M.Sc. THESIS EXAMINATION RESULT FORM

We have read the thesis entitled "**EXPERIMENTAL INVESTIGATION OF EFFECT OF USAGE OF NANO-FLUIDS ON COOLING IN MACHINING**" completed by **HAKAN ZAFER KIZILKAYA** under supervision of **ASSOC. PROF. DR. KEMAL BİLEN** and **PROF. DR. ABDULMECİT GÜLDAŞ** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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EXPERIMENTAL INVESTIGATION OF EFFECT OF USAGE OF NANO-FLUIDS ON COOLING IN MACHINING

ABSTRACT

In various areas of the industry, especially in the machining sector, mineral-based boron oil and water mixture is used to prevent cutting tool wear by evacuating the heat generated during cutting, reduce thermal stresses on the workpiece surface, and improve friction at the tool and chip interface. There are studies showing that nano-particles added to fluids improve the thermo-physical properties of the fluids such as density, viscosity, and thermal diffusivity in literature. In this experimental study, nano-fluids were obtained by adding aluminum dioxide (Al_2O_3), multi-walled carbon nanotube (MWCNT) or titanium dioxide (TiO_2) nano-particles at 0.5 percent, 1.0 percent, and 1.5 percent by volume to a low viscosity boron oil and water mixture containing 7 percent boron oil and 93 percent water. The thermo-physical properties of the obtained nano-fluids were measured with various sensors and rheometers.

In addition, a turning machining experiment was carried out on Ti-6Al-4V material using these nano-fluids with fixed cutting parameters and the temperature distribution at the tool and chip interface were observed with the help of a thermal camera and the effect of the use of nano-fluids on surface roughness was also measured. As a result of the study, it was observed that increasing the concentration of nano-particles, naturally, continuously increases the density of the nano-fluid at a constant temperature of 24.5 celsius, but this is not the case for dynamic viscosity and thermal diffusivity, and there is a tendency to decrease the properties from 1 percent concentration by volume, which is due to precipitation and sedimentation. Approximately 18 percent temperature reduction was observed when using the nano-fluid containing 0.5 percent MWCNT nano-particles by volume at the cutting tool and workpiece interface. It was also found that values of cutting temperature and surface roughness did not improve with increasing the concentration of nano-particles due to precipitation and sediment formation, but on the contrary, deteriorated. With the using of nano-particles at optimum values, an improvement of approximately 25 percent in surface roughness was also detected. As a result, it has been determined that when the rate of nano-particles exceeds a certain value, nano-fluids do not provide the desired improvements in machining but they can provide the desired improvements when used at optimum admixtion rates.

Keywords: Machining, cutting, boron oil, Al_2O_3, MWCNT, TiO_2, nano-fluid, thermo-physical property, cutting insert, surface temperature, surface roughness.

NANO-AKIŞKAN KULLANIMININ TALAŞLI İMALATTA SOĞUTMAYA ETKİSİNİN DENEYSEL OLARAK ARAŞTIRILMASI

ÖZ

Talaşlı imalat sektörü başta olmak üzere endüstrinin çeşitli alanlarında mineral esaslı bor yağı ve su karışımı; kesme sırasında oluşan ısıyı ortamdan tahliye ederek kesici takımın aşınmasını engellemek, iş parçası yüzeyindeki ısıl gerilmeleri azaltmak ve takım ile talaş ara-yüzeyindeki sürtünmeyi iyileştirmek için kullanılmaktadır. Literatürde, akışkanlara eklenen nano-parçacıkların, ilgili akışkanların yoğunluk, viskozite ve ısı iletim katsayısı gibi termo-fiziksel özeliklerinde iyileştirmeler yaptığına dair çalışmalar mevcuttur. Bu hususlar dikkate alınarak bu deneysel çalışmada; alüminyum dioksit (Al_2O_3), çok duvarlı karbon nanotüp (MWCNT) veya titanyum dioksit (TiO_2) nano-parçacıkları, hacimsel olarak yüzde 7 bor yağı ve yüzde 93 su içeren ve düşük viskozitede olan bor yağı ve su karışımına hacimsel olarak yüzde 0.5, yüzde 1.0 ve yüzde 1.5 oranlarında eklenmesiyle nano-akışkanlar elde edilmiştir. Elde edilen nano-akışkanların belirtilen termo-fiziksel özelikleri, çeşitli sensörler ve reometre ile ölçülmüştür.

Ayrıca, bu nano-akışkanlar kullanılarak Ti-6Al-4V malzemesi üzerinde, sabit kesme parametreleri yardımıyla tornalama ile talaşlı imalat deneyi yapılmış ve takım ile talaş ara-yüzeyindeki sıcaklık dağılımı bir termal kamera yardımıyla gözlemlenmiş ve ayrıca nano-akışkan kullanımının yüzey pürüzlülüğüne etkisi ölçülmüştür. Çalışma sonucunda; nano-parçacık derişiminin artmasının, 24.5 santigrat sabit sıcaklıktaki nano-akışkan yoğunluğunu doğal olarak sürekli artırdığı, ancak dinamik viskozite ve ısı iletim katsayısında durumun böyle olmadığı ve hacimce yüzde 1 derişimden itibaren özeliklerde azalma eğilimi oluştuğu gözlemlenmiş, bu durumun, çökelme ve tortu oluşumundan kaynaklandığı tespit edilmiştir. Kesici takım ve iş parçası ara-yüzeyinde, hacimce yüzde 0.5 MWCNT nano-parçacığı içeren nano-akışkan kullanıldığında yaklaşık yüzde 18 sıcaklık düşüşü gözlemlenmiştir. Ayrıca, çökelme ve tortu oluşumlarından dolayı nano-parçacıkların derişiminin artırılmasıyla kesme sıcaklığı ve yüzey pürüzlülüğündeki değerlerin iyileşmediği, tam aksine kötüleştiği tespit edilmiştir. Optimum değerlerde nano-parçacık kullanımıyla, yüzey pürüzlülüğünde de yaklaşık yüzde 25'lik bir iyileşme tespit edilmiştir. Sonuç olarak, nano-parçacıkların oranı belirli bir değeri aştığında, nano-akışkanların talaşlı imalatta istenen iyileşmeleri sağlamadığı, ancak optimum karışım oranlarında kullanıldığında istenen iyileştirmeleri sağlayabildiği tespit edilmiştir.

Anahtar Kelimeler: Talaşlı imalat, kesme, bor yağı, Al_2O_3, MWCNT, TiO_2, nano-akışkan, termo-fiziksel özelik, kesici uç, yüzey sıcaklığı, yüzey pürüzlülüğü.

CONTENTS

NOMENCLATURE

$\boldsymbol{\Delta T}$	: Temperature difference, K or °C
$\boldsymbol{F}$	: Force, N
$\boldsymbol{f}$	: Feed, $\frac{\mathrm{mm}}{\mathrm{rev}}$
Ø	: Diameter, mm
$\boldsymbol{\varphi}$	: Volumetric ratio of nano-particle, %
$\boldsymbol{h}$	: Convective heat transfer coefficient, $\frac{\mathrm{W}}{\mathrm{m^2 \cdot K}}$
$\boldsymbol{k}$	: Thermal diffusivity, $\frac{\mathrm{W}}{\mathrm{m \cdot K}}$
$\boldsymbol{\dot{m}}$	: Mass flow rate, $\frac{\mathrm{g}}{\mathrm{s}}$
$\boldsymbol{\mu}$	: Dynamic viscosity, mPa·s or cP
$\boldsymbol{q}$	: Heat transfer, W
$\boldsymbol{Ra}$	: Surface roughness, µm
$\boldsymbol{\rho}$	: Density, $\frac{\mathrm{g}}{\mathrm{cm^3}}$
$\boldsymbol{t}$	: Process time, s
$\boldsymbol{t_h}$	: Heating time, s
$\boldsymbol{\theta}$	: Environment temperature, K
$\boldsymbol{V_c}$	: Cutting speed, $\frac{\mathrm{mm}}{\mathrm{s}}$
$\boldsymbol{Y_f}$	: Flow stress, MPa

ABBREVIATIONS

Acronyms

Al_2O_3	**:** Aluminum dioxide
CNC	**:** Computer numerical control
CNT	**:** Carbon nanotube
CNTs	**:** Carbon nanotubes
CO_2	**:** Carbon dioxide
FPS	**:** Fluid property sensor
LN_2	**:** Liquified nitrogen
MoS_2	**:** Molybdenum disulfide
MQL	**:** Minimum quantity lubrication
MWCNT	**:** Multi-walled carbon nanotube
MWCNTs	**:** Multi-walled carbon nanotubes
TiO_2	**:** Titanium dioxide

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CHAPTER 1

INTRODUCTION

1.1 Historical Review of Machining

The historical development of machining, which human beings use by nature to shape their world, covers a long period. Wood drilling and cutting, wood turning methods obtained from a rope stretched on a branch date back to B.C. The Industrial Revolution (between 1760 and 1830) had a great impact on production in various ways. This sign has transformed from an economy based on agriculture and animal husbandry and handicrafts to a structure based on industry and production. Some of the inventions of the Industrial Revolution contributed greatly to the development of manufacturing; Watt's steam engine is a new power-generating technology for industry; machine tools starting with John Wilkinson's boring machine built around 1775 can be shown as an example [1].

During the period of 1770-1850, machine tools were developed for most of the traditional material removing operations, such as boring, turning, drilling, milling, forming, and planning. Improving of the cutting tool materials used, the machining method has also undergone development. Machining is the complete shaping process in which excess material is removed from the workpiece by cutting it with cutting tools on suitable machine tools and the targeted final geometry is obtained [2].

The machining method is used more often than other manufacturing methods due to its applicability to almost all materials, easy implementation of different geometries, reaching precise surface and dimensional tolerances, development of original cutting tools and short operation times. The ability of a material to be shaped using machining methods is called machinability. Machinability is also the whole of the outputs that reveal the efficiency of machining in one respect [3].

The forces generated during the shaping of the material and the related energy consumption, the surface quality of the workpiece, the life of the tools used in the cutting process, the high heat energy released during cutting, etc. many outputs determine the machinability of the material. Low machinability characteristics mean that the machining costs are high, or the product quality is low. This also reduces the efficiency of the operation.

1.2 Coolant Applications

In machining applications, different cooling methods are used to facilitate machinability and increase operation efficiency. The application of coolants in machining operations was first carried out on the turning process in the 1860s. The main tasks of the cooling process can be listed as cooling the cutting tool and the workpiece, creating a lubricating surface by reducing the contact of the tool with the workpiece and the chip, effectively removing the chip, preventing or minimizing the chip adhering to the tool (built up edge/BUE), reducing power requirements, preventing corrosion and increasing the tool life [4].

Coolants, on the one hand, should carry out these tasks, while on the other hand, they should also carry some desired properties. For an effective cooling process, coolants must have cooling and lubricating properties. It should be able to maintain these properties for a long time, should not lead to corrosion, should not damage machine equipment, should not be volatile and flammable, should not disrupt the chemical structure of the workpiece, should be environmentally friendly and should not pose a danger to human health. Considering all these characteristics, different coolants are used depending on the material and processing methods [5].

The coolants and cooling applications used to effectively solve the different problems encountered during the cutting process are also changing. As coolants, pure cutting oils, water-based oils, gases (for cryogenic), and nano-particle additive oils can be defined as. The appropriate cooling technique is to ensure the good machinability of the metal, reduce the cutting temperature, improve the properties of the tools, increase the material removal rate, reduce energy consumption, etc. it results in [6].

1.3 Aim of the Study

A mixture of mineral-based boron oil and water is used in various areas of industry. The first of these areas is the machining/manufacturing sector. The mixture of boron oil and water prevents the wear of the cutting tool by evacuating the heat generated during cutting from the environment and reduces the thermal stresses on the workpiece surface. In addition, it decreases the friction on the cutting tool and chip interface. In this thesis, in the light of current studies in the literature, adding of nano-particles in various proportions to the boron oil + water mixture which is commonly used in aerospace industry will be examined in the aspects of thermal efficiency, surface roughness, and thermo-physical improvements.

CHAPTER 2

LITERATURE REVIEW

When the studies in the literature are examined from general to specific, it is seen that there are studies which draw attention to the tribological features. Tribological properties can be classified as friction, wear, and lubrication. Improvements of these features will directly affect cutting performance. It is necessary to improve the parameters which are affecting the quality such as tool life, cutter consumption, stresses in the cutting zone, and surface quality. When looking at the literature that will shed light on these issues, which will also be discussed in this study, the parameters of the cutting theory with complex effects will be understood.

Machining is a general term describing a group of processes that consist of the removal of material and modification of the surfaces of a workpiece after it has been produced by various methods. Thus, machining involves secondary and finishing operations [6]. Machining, which is one of the oldest methods, is theoretically made as a result of movements with shear stress on the workpiece. With these movements, metal pieces called as chip are broken off and new surfaces are obtained. Thanks to the relative movement at the contact surfaces, which is obtained by shear forces between the cutting tool and the workpiece, cutting is done.

While the chip removal operation is carried out with the resulting cutting force, frictional heating occurs on the cutting tool and workpiece surface. This warm-up causes abrasions on the cutting tool and deformities on the workpiece. The heat generated by friction can be removed from the cutting environment during the removal of chips [7]. This is more evident when cutting operation on hard materials.

Especially in materials with a hardness above 45 HRC, wear is a big problem due to cutting tool movements. These wears can be tried to be solved by methods such as cutting parameters optimization [8]. Another solution method is to reduce the stresses as a result of heat and chip evacuation in the cutting zone.

In machining operations, the extra heat generated in the cutting zone causes tool wear, which directly affects the cutting efficiency of the operation. In dry machining operations, the chip occurs very close to the tool-workpiece interface, which causes high heat generation in the relevant area and thus tool wear. For this reason, air cooling, liquid-based cooling, liquid phase cooling, etc. are used in machining in order to remove the heat from the cutting zone [9].

Cutting fluids are used to remove the heat generated during the cutting process on the related hard materials. Cutting fluids provide effective lubrication by forming a film layer that will reduce friction between the cutting tool and the workpiece during machining. With the reduction of the heat generated by friction between the tool and the workpiece, the tool life is extended, the manufacture processing with the desired surface quality and the costs of the mass production are also minimized. While cutting fluid positively affects the machining performance with its effective lubrication, high thermal conductivity coefficient and cooling feature, it also has negative aspects in terms of environmental pollution and human health [10].

Cutting fluids help to keep the heat under control by removing the heat generated in the cutting area together with the chips during machining. In machining processes, cutting fluids play an active role for high performance and low-cost production. The use of cutting fluids mixed with water in concentrated proportions causes evaporation of water at high temperatures and decomposition of additives at low temperatures [11].

According to their types, coolants can be classified as oil-based, gas-based, and water-based. Oil-based ones can be categorized as mineral oils and vegetable oils [9]. Mineral-based cutting oils are commonly used as refrigerants in most machining operations [12]. Mineral-based cutting oils are divided into two basic categories as naphthenic mineral oils and paraffinic mineral oils. If the paraffin-bonded carbon atoms are dominant, they are defined as ‘paraffin-based’ oils. If the fraction of naphthene is too large, the oil is named ‘naphthenic-based’. Oils containing high amounts of aromatic hydrocarbons are defined as ‘aromatic oils’ and that are not used as metal-working fluids because of their harm to the human health [13]. While these types of oils provide good lubrication and corrosion protection, they do not retain their properties at higher temperatures. For this reason, its usage area is limited in metals such as aluminum, magnesium, brass, and low carbon steels that can be easily processed [14].

The effects of cooling and lubrication depend on fluid flow parameters, fluid characteristics, and technique of fluid delivery to cutting region. So, choosing a correct cooling system is very difficult task. Researchers use water-based coolant in conventional cooling method, mixture of oil or water-based coolant with air passed thorough controllable flow in minimum quantity lubrication (MQL) and use of cryogenic coolant like carbon dioxide (CO_2), liquified nitrogen (LN_2) etc. in cryogenic technique. Researchers also use oxygen, helium, and nitrogen in air cooling, and multi-walled carbon nano tubes (MWCNTs), Ni nanowires, aluminum dioxide (Al_2O_3) nano-particles, mix of molybdenum disulfide (MoS_2) + carbon nanotube (CNT) in nano-machining of metals. For achieving good machinability of metals with suitable cooling technique is result of removed generated heat from the contact area [9].

Machining without any coolant is called dry cutting. During dry cutting, high temperature in the chip removal zone, high thermal shock, and geometrical deviations in the workpiece due to lubrication problems cause tool wear [15-18].

In dry machining operations, the high cutting temperature created at high cutting speed reduces the workpiece strength and low cutting force occurs. This changes the chemical properties of the workpiece, causing adhesions on the cutting tool and thus reducing the tool life with wear. However, dry machining with cutting tool design suitable for the workpiece is preferred for environmental sustainability and cost saving purposes. Appropriate cutting tool material can be selected by choosing those with low friction coefficient among the materials with high fracture and high temperature resistance. Some examples for appropriate cutting tool material are cubic boron nitride (CBN) and ceramic. However, the application is limited due to the geometric limitations of the cutting tools [14, 19].

There are some studies in literature on tribological efficiency provided by the use of cutting fluids in machining. Metal removal operations with the use of cutting fluids with water-based oils are classified as conventional metal removal operations [20]. One of the lubrication systems in conventional machining operations is the MQL system [9].

MQL system, which is studied to reduce the use of cutting oils, both reduces the heat on the contact surface of the cutting tool and the workpiece, and also reduces the consumption of excess cooling oil. Cooling liquid and compressed air are transmitted to the cutting area with the help of a pipe and nozzle in a controlled manner, providing cooling directly on the cutting contact surface. MQL also plays a role in reducing environmental pollution by preventing unnecessary use of cooling oil [9, 14, 20].

In the previous studies in the literature, it has been revealed that MQL method contributes to the improvement of tribological properties, especially in widely used metals. MQL method has positive effects such as surface finish quality and cutting force reduction in conventional machining operations [21, 22].

Recently, in addition to common metal materials, some nano-particles have been used in the cooling required in machining operations with hard materials. Nano-particles, which can be adapted to MQL or conventional cooling systems, offer an effective solution in terms of increasing cooling efficiency. Experimental results obtained from the previous studies on the improvement of tribological properties indicate that the cooling efficiency is increased.

The researchers examined both the thermophysical properties of nano-fluids and their effects on machining factors such as surface roughness and they analyzed the change in the amount of heat generated. Another different study is the selection of oils on this topic. In the light of all this, in this thesis, unlike the studies in the literature, the effects of changes in thermophysical properties, including viscous effects on a commonly used oil, on the tool were investigated.

When searching the literature, it is seen that there are some studies on usage of nano-particles in machining processes. According to this, in 2008, Krishna and Nageswara [23] conducted an experimental study on AISI 1040 (EN 8) steel using mineral oil and graphite in turning operations. As a result of the study, thermal conductivity and viscosity of mineral oil were increased. By the way, cutting force and tool flank wear were reduced because of the formation of lubricants and their bond characteristics. In the study, dry and wet machining conditions were examined. Also, the surface finish was improved according to the dry machining.

In 2008, Shen et al. [24] introduced an experimental study showing that the usage of Al_2O_3 nano-particles reduces the heat generated at the contact surface of cutting tool and workpiece and improves the surface roughness in grinding operations with cast iron samples.

In 2010, Prabhu and Vinagayam [25] conducted an experimental study improving the surface characteristics of AISI D2 steel using SAE20W40 mineral oil and MWCNTs in grinding operations. This improvement is achieved by using various samples such as water with soluble oil, SAE20W40 + MWCNTs etc.

In 2012, Sarhan et al. [26] conducted an experimental study on aluminum 6061 T6 material using mineral oil and SiO_2 nano-particles in milling operations. As a result of the study, reduction in cutting force, power, and specific power consumption were obtained.

In 2016, ManojKumar and Ghosh [27] implemented an experimental study containing MWCNTs nano-particles used with the sunflower oil by 1% volumetric concentration. By using AISI 52100 steel in grinding operation, the experiments were performed according to tribological focus. The results showed that tribological properties were improved. Also, the surface finish of workpiece was improved by comparation of nano-fluid and soluble oil cutting fluid.

In 2016, Sharma et al. [28] performed an experimental study using Al_2O_3 nano-particles for obtaining several types of nano-fluid with vegetable oil-water emulsion at the volumetric ratios of 0.25%, 0.5% 1.0%, 1.5%, 2%, and 3%. Experiments were carried out by using turning operations with AISI 1040 steel at constant machining parameters during dry, wet, and with MQL. The results showed that Al_2O_3 volumetric concentration of 1% gave better thermal conductivity, density, and viscosity. However, specific heat was decreased with the increase of nano-particle concentration. Additionally, cutting force and tool wear were reduced.

A similar study was conducted by Sharma et al. [29] in 2016, using titanium dioxide (TiO_2) nano-particles for obtaining several types of nano-fluid with vegetable oil-water emulsion at the volumetric ratios of 0.25%, 0.5% 1.0%, 1.5%, 2%, and 3%. In the study, experiments were performed by using turning operations with AISI 1040 steel at constant machining parameters during dry, wet, and with MQL. The results showed that thermal conductivity, density, and viscosity were improved with the increase of nano-particle concentration while specific heat was decreased. Also, machining performance was improved due to the reducing of flank tool wear.

In 2017, Uysal [30] conducted a study using graphene nano-particles with Eraoil KT/2000 commercial vegetable oil. The cutting fluid provides low temperature at cutting zone and forms small burr in milling operations of ferritic AISI 430 stainless steel. The experiments were carried out by changing the cutting tool coating and they compared the results of MQL, nano-MQL, and dry conditions. The best result was achieved in the use of 0.5% nano-particles by volume.

In 2018, Li et al. [31] performed an experimental study including graphene nano-particles added to vegetable oil in various volumetric ratios with MQL method and experiments were carried out on titanium alloy TC4 (Ti-6Al-4V) in milling operations. TC4 material is widely used in the aerospace and petrochemical industry. At the end of the study, it was shown that addition of graphene nano-particles reduces the milling force because they enhance anti-friction and load-bearing capacity of the oil film and improve the tool life.

In 2019, Sugiantoro et al. [32] conducted an experimental study using bio-nanofluids on high-hardness steel with MQL method at milling operations. In the study, fluid convective properties were tried to improve by using Al_2O_3, CuO, and TiO_2 nano-particles. Natural coolants used in the study are corn oil, sunflower oil, and water. As a result, significant effects to reduce surface roughness, cutting temperature, and power consumption were achieved. Also, using nano-fluids proof that it was able to apply in an environment-friendly manufacturing process.

In 2019, Jamil et al. [33] experimentally carried out a study using hybrid nano-particles of Al_2O_3 and carbon nanotubes (CNTs). In the study, cryogenic cooling with CO_2 and MQL-based hybrid nano-fluids were compared in turning operations. In the study also, vegetable oil was used as the base fluid and the coolant was applied to the Ti-6Al-4V material in the turning. Two different sustainable cooling/lubrication techniques were compared and it was detected that hybrid nano-fluids were better in average surface roughness, cutting force, and tool life factors. However, cryogenic cooling with CO_2 was better in terms of cutting temperature factor.

In 2019, Yıldırım et al. [34] performed an experimental study using hBN nano-particles in ester-based cutting oil. High tool life, low tool wear, and roughness in the turning process on Ni-based Inconel 625 material were achieved by using this nano-fluid. In the study, nano-MQL coolant compared with the pure-MQL and dry conditions. Investigated parameters of the study were tool life, surface roughness, tool wear, and tool-chip interface temperature. The usage of nano-MQL coolant with 0.5% hBN nano-particles produces the promising results in terms of the investigated parameters.

A summary of literature review on the studies using nano-fluids is given in Table 2.1.

Table 2.1 A summary of literature review on the studies using nano-fluids

Author(s)	Base lubricant	Nano-particle(s)	Operation type	Workpiece	Result(s)
Krishna and Nageswara [23]	SAE 40	Graphite	Turning	AISI 1040 (EN 8)	Thermal conductivity and viscosity were increased.
Shen et al. [24]	SAE 40	Al_2O_3	Grinding	Cast iron	Generated heat was reduced, and surface roughness was improved.
Prabhu and Vinagayam [25]	SAE20W40	MWCNTs	Grinding	AISI D2	Surface characteristics of AISI D2 tool steel was improved.
Sarhan et al. [26]	Mineral oil	SiO_2	Milling	Aluminum 6061 T6	Cutting force, power, and specific power consumption were reduced.
ManojKumar and Ghosh [27]	Sunflower oil	MWCNTs	Grinding	AISI 52100	Tribological properties and surface finish were improved.
Sharma et al. [28]	Vegetable oil	Al_2O_3	Turning	AISI 1040	Cutting force and tool wear were reduced. Thermal conductivity, density, and

					viscosity was improved.
Sharma et al. [29]	Vegetable oil	TiO_2	Turning	AISI 1040	Machining performance was improved due to the tool flank wear reduced. Also, thermal conductivity, density, and viscosity were improved.
Uysal [30]	Vegetable oil	Graphene	Milling	AISI 430	Temperature at cutting zone was reduced and small burr form was achieved.
Li et al. [31]	Vegetable oil	Graphene	Milling	Ti-6Al-4V	Reducing the milling force and improvement in tool life.
Sugiantoro et al. [32]	Natural oil	TiO_2, CuO, and Al_2O_3	Milling	High-hardness steel	Reducing surface roughness, cutting temperature, and power consumption.
Jamil et al. [33]	Vegetable oil	Al_2O_3 and CNT	Turning	Ti-6Al-4V	Nano-fluids were better in average surface roughness, cutting force, and tool life factors.
Yıldırım et al. [34]	Ester-based cutting oil	hBN	Turning	Inconel 625	Tool life, surface roughness, tool wear, and tool-chip interface temperature were investigated and promised results were obtained.

CHAPTER 3

THEORY OF COOLING IN MACHINING PROCESSES

In this section, the theory of the cooling process in the machining process is discussed. It is possible to say that the heat effect is an important factor on both the quality of the workpiece and the cutting tool in orthogonal cutting operations. In this context, starting from the heat transfer mechanism, this factor will be expanded theoretically.

3.1 Heat Transfer Mechanism

Heat transfer (or heat) is thermal energy in transit due to a spatial temperature difference [35]. Heat transfer mechanism occurs in three ways in nature as heat conduction, heat convection and heat radiation. Heat conduction mechanism occurs in media of less energetic molecules such as inside a wall or slab.

Heat convection occurs between a fluid in motion and a bounding surface when the two are at different temperatures [35]. Finally, the heat radiation mechanism is energy emitted by matter that is at a nonzero temperature and it does not require a material media like conduction or convection.

Cooling is removal of heat, usually resulting in a lower temperature and/or phase change [36]. This removal can be explained by Newton for convection phenomenon with the Newton's cooling law that formulated as in Eqn. (3.1):

$$q'' = h(T_\infty - T_s) \quad \textbf{(3.1)}$$

where, q'' is convective heat flux [W/m^2], h is convection heat transfer coefficient [W/(m^2·K)], T_∞ is fluid temperature and T_s is surface temperature.

Also, removal heat transfer between in a media such as cutting tool and workpiece can be denoted from 1st law of thermodynamics that shown in Eqn. (3.2):

$$q = \dot{m}\, c_p \Delta T \quad \textbf{(3.2)}$$

where, q is removal heat [W], $\dot{m}$ is mass flow rate [kg/s], c_p is specific heat at constant pressure [J/(kg·K)] and ΔT is temperature difference [K].

3.2 Temperature Effects in Machining

The removal heat directly affects the process quality in machining. As in all metalworking processes where plastic deformation is involved, the energy dissipated in cutting is converted into heat that, in turn, raises the temperature in the cutting zone [6]. This temperature rise plays vital role in machining such as the following:

- Extreme temperature in cutting zone lowers the strength of both workpiece and cutting tool. Thus, tools may soften, and deformation occur plastically. So, the change in tool shape can be observed.
- Ultimate temperature ensures the lower hardness and stiffness. Then the wear resistance can be observed.
- Excessive heat directly affects the irregularity in dimension of machined part. After that, the control of tolerances and dimensional accuracy cannot be made safely.
- Extreme temperature changes the microstructure of material due to thermal damage. These metallurgical changes, directly affects the mechanical properties and analysis limits of stock material. So, the machining quality is altered.

It is clearly seen the damage of heat in machining zone prevents the high-quality processes. The main sources of heat in machining are [6]:

- Due to the shearing effect in primary shear zone.
- Owing to friction at the tool-chip interference, energy dissipation occurs.
- Rubbing of tool against the machined surface generates heat.

In the orthogonal cutting that is the term has been coined to cover the case where the cutting tool generates a plane surface parallel to an original plane surface of the material being cut and is set with its cutting-edge perpendicular to the direction of relative motion of tool and workpiece [37], the expression for the mean temperature (T_{mean}) is [1]:

$$T = \frac{0.000665 Y_f}{\rho c} \sqrt[3]{\frac{V t_o}{\kappa}} \qquad \textbf{(3.3)}$$

where, T is the mean temperature of the tool-chip interface [K], Y_f is the flow stress of the workpiece material [MPa], V is the cutting speed [m/s], t_o is the depth of cut [m],

ρc is the volumetric specific heat of the workpiece [kJ/(m^3·K)] and κ is the thermal diffusivity (ratio of thermal conductivity to volumetric specific heat) of the workpiece material [m^2/s].

According to the Eqn. (3.3), the mean temperature decreases with the increasing thermal conductivity and specific heat of workpiece material and increases with cutting speed, depth of cut and workpiece strength.

3.3 Temperature Distribution in Cutting Tools

Due to the heat generation at tool-chip interface, the temperature distribution may evaluate. Although it is pointed out in almost any book, temperatures in metal cutting affect the shear properties of the work material and chip-forming processes [38]. The generated heat limits the machining process and also affects directly to the tool wear mode. The primary purpose of considering heat in metal cutting is limiting the material removal rate due to the melting point of metals. Also, there is not directly relation between the cutting forces and the heat generation at the tool cutting edge [39]. In order to understand the temperature zones at the workpiece and chip interface, it may be necessary to refer to the 1st law of thermodynamics. Accordingly, due to the conservation of energy, the total temperature at the interface of the tool, workpiece and chip can be considered constant [40].

In this theory, it has been evaluated that the heat stored in the deformed chip constitutes 2-3% of the total heat at the interface, while that in the moving chip is 80-85%. The power component of the cutting force and the cutting speed directly affect the heat generated. In this case, the heat generated in the cutting zone can be formulated as Eqn. (3.4) [38]:

$$F_c v = \Sigma Q = Q_c + Q_w + Q_t \qquad \textbf{(3.4)}$$

where, F_c is power component of cutting force, v is cutting speed, Q_c is the thermal energy transported by the chip, Q_w is the thermal energy conducted into the workpiece, Q_t is the thermal energy conducted into the tool.

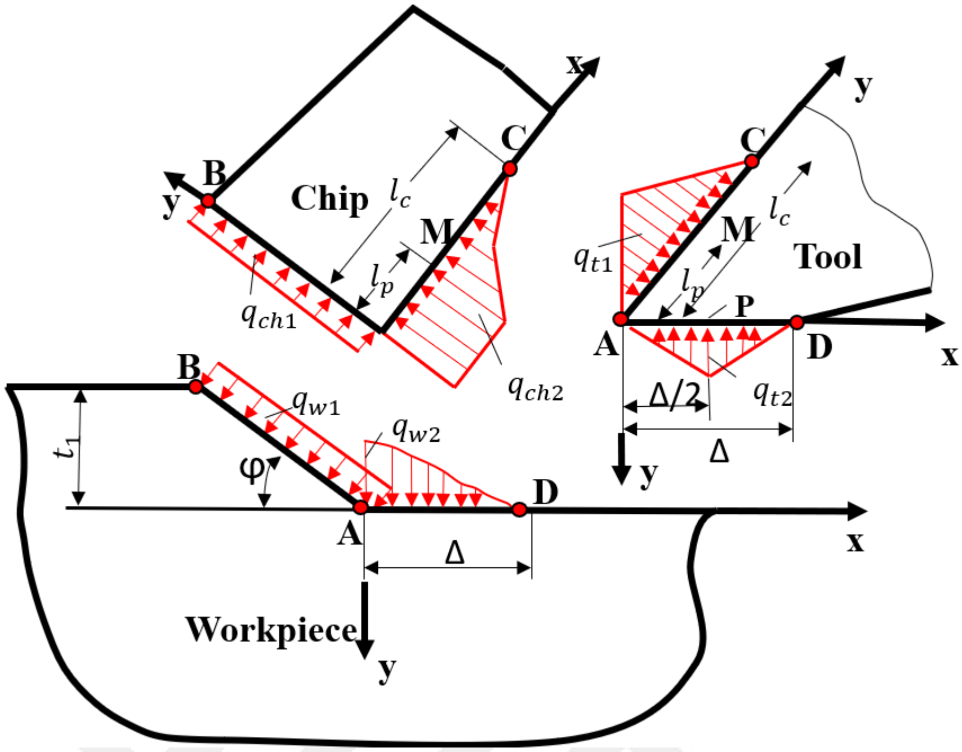

Figure 3.1 Heat generation regions on the tool, workpiece, and removed chip (adopted from Ref. 37)

Figure 3.1 shows the geometrical situation at the interface between cutting tool, chip, and workpiece, in other words, in the region where heat is generated. Accordingly, l_p is the length of the plastic part, AB is the length of the shear plane, AC is the tool-chip contact length, φ is the shear angle, t_1 is uncut chip thickness, Δ is the tool-workpiece contact length.

Table 3.1 shows the heat rates obtained in a study for AISI 1045 steel. Hereof, the following two features can be evaluated [38]:

- Most of the thermal energy generated during the cutting process is dissipated by the moving chip (80-85%).
- The higher the cutting speed, the higher the percentage of total heat recovered per chip.

Table 3.1 Heat energy balance rates in machining (for AISI 1045) [38]

v [m/s]	Q_c [W]	$Q_c/\Sigma Q$ [%]	Q_w [W]	$Q_w/\Sigma Q$ [%]	Q_t [W]	$Q_t/\Sigma Q$ [%]
0.10	47.9	50.2	38.4	40.2	9.2	9.6
0.20	93.7	55.7	63.7	37.8	11.0	66.6
0.5	272.3	70.3	100.3	25.9	14.7	3.8
1	501.6	76.2	136.9	20.8	19.7	3.0
2	1177.1	82.8	217.5	15.3	27.0	1.0
4	2306.2	86.3	336.7	12.6	29.4	1.1

A typical temperature distribution gradient is as follows. Material properties, cutting conditions, tool coating and cutting fluid are effective in the formation of gradients.

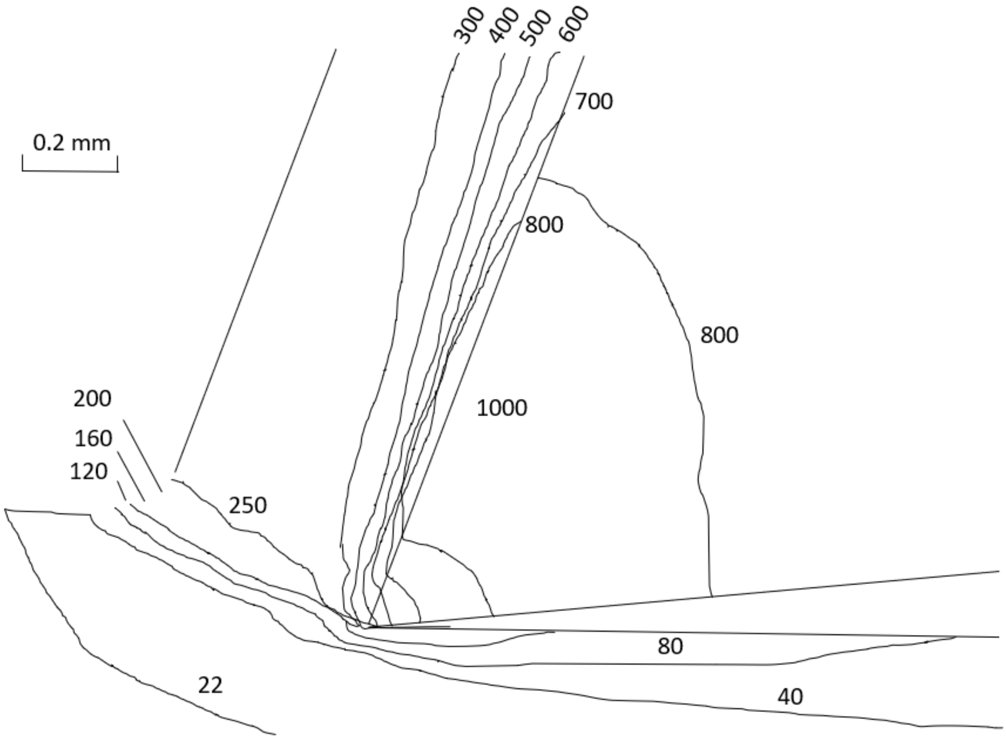

Figure 3.2 Typical temperature distribution for steel material in orthogonal dry cutting condition for 155 m/s cutting speed and 0.274 mm/rev feed (in °C unit) [41]

As shown in Figure 3.2, the temperatures in all °C unit and increases at cutting zone or cutting point at interface between cutting tool and workpiece. These values can be changeable with adding of cutting fluid or type of coolant and cooling processes directly.

Figure 3.3 shows the flank and tool-chip interface temperatures at the constant feed value and cutting speed values in the turning processes of AISI 52100 steel. Increase of cutting speed is directly proportional with surface temperature at same distances from the tool tip.

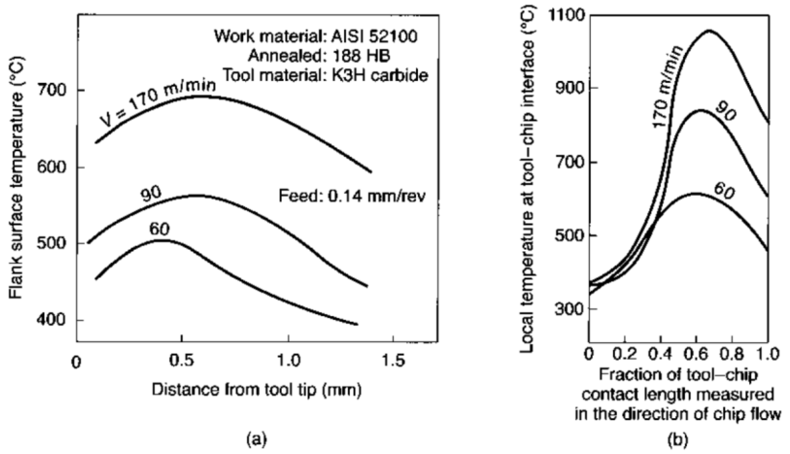

Figure 3.3 Temperature distribution in case of turning of AISI 52100 a) at the flank face b) at the tool-chip interface [6]

If the moving body can be modeled as one-dimensional, then one can define a control volume over which that can perform an energy balance in order to derive a conservation equation for thermal energy in terms of temperature [42].

The control volume has length of Δx, perimeter p and cross-sectional area of A_{ch}. The heat can be transferred in this control volume by means of conduction and advection. Advection is the horizontally energy transportation way due to the flow of a solid in horizontal direction (e.g. x-direction) through a control volume. The advected energy rate of the control volume can be different and is written as $\dot{m}e_x + \Delta x$, where $e_x$is specific enthalpy at x. Also, heat can be generated in the volume ($\dot{q}$) and also the heat can be lost due to the outside ambient convection [38].

Assume that the geometrical properties, volume, and material properties cannot be changed along the movement direction of fluid motion. Under these conditions the energy conservation equation can be written as Eqn. (3.5) by Bejan [42] which contains the temperature along the length of moving body, heat generation and heat loss due to the convection.

$$kA_{ch}\frac{d^2T}{dx^2} - \left(\dot{m}c_p\right)\frac{dT}{dx} - hp(\theta_{ch} - \theta_{ev}) + \dot{q}A_{ch} = 0 \quad \textbf{(3.5)}$$

where, k is the thermal conductivity of the material (e.g. chip), c_p is the specific heat of material, h is the convection heat transfer coefficient, θ_{ch} and θ_{ev} are the chip and environment temperatures. The parts of Eqn. (3.5) describe the axial conduction, advection, convection loss, and heat generation, respectively.

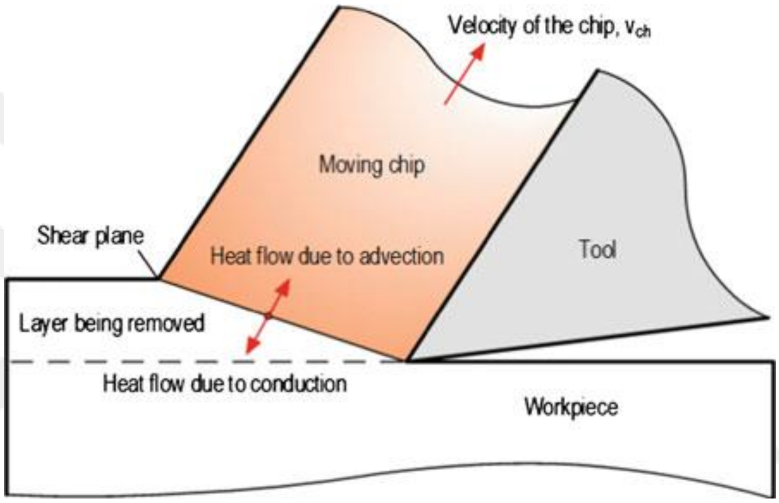

Figure 3.4 The simplified representation of chip formation during machining operations [38]

As shown in Figure 3.4, the moving chip carries the latent heat from the tool-workpiece interface. In metal cutting operations, this movement is adequately fast and due to this situation, the convection term of Eqn. (3.5) can be negligible. The heat transfer by means of conduction and convection is generally considered in the metal cutting literature but the advection affect also should be recognized because of the latent heat movement with moving chip.

3.4 Tool Life and Failure

Due to the reasons that listed below, the tool wear mechanism can be observed at cutting tools in metal cutting operations [6, 39].

- Highly localized stresses near or at the tip of cutting tool.
- Chip sliding along the rake face of the cutting tool.
- High temperatures at faces of cutting tool.

- Cutting tool sliding at the newest surfaces of workpiece in the metal cutting operation.

Tool wear and the changes in tool geometry during cutting manifest themselves in different ways, generally classified as flank wear, crater wear, nose wear, built-up edge and notching [6].

Flank wear: Flank wear is caused by friction between the flank face of the tool and the machined workpiece surface and leads to loss of the cutting edge [6].

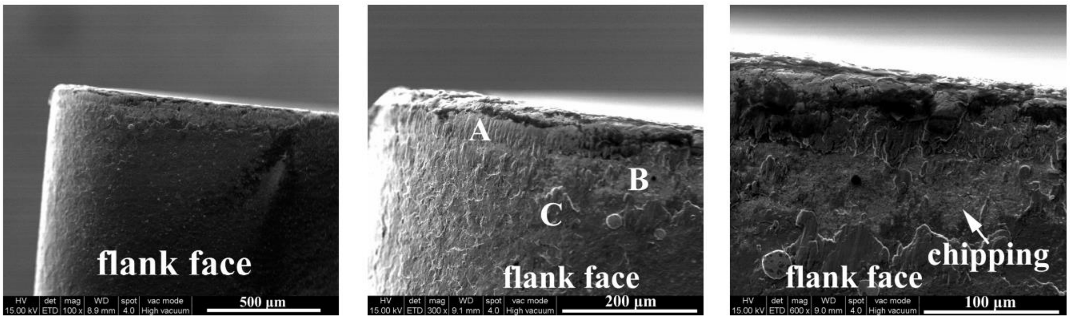

Figure 3.5 Tool wear mechanism at flank face (flank wear) [43]

Crater wear: The wear of the rake face is known as crater wear. The chip flows across the rake face, resulting in severe friction between the chip and rake face, and leaves a scar on the rake face which usually parallels the major cutting edge [44].

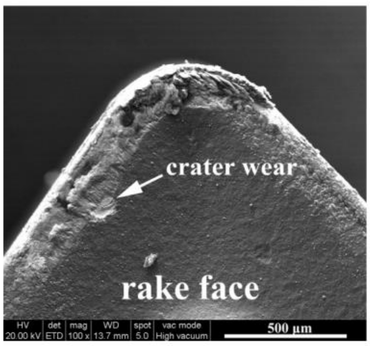

Figure 3.6 Tool wear mechanism at the rake face (crater wear) [43]

Nose wear: Nose wear is the rounding of a sharp tool due to mechanical and thermal effects. It dulls the tool, affects chip formation, and causes rubbing of the tool over the workpiece, raising its temperature and possibly inducing residual stresses on the machined surface [6].

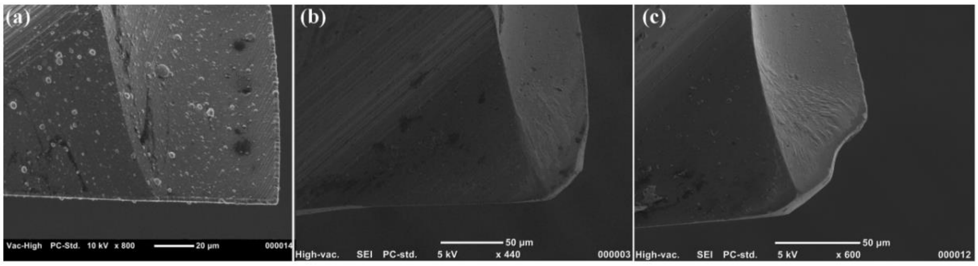

Figure 3.7 Tool nose wear for different tools a) for a fresh tool b) for tool A c) for tool B [45]

Built- up edge: At low cutting speed (*v*) values, the built-up edge (BUE) phenomenon appears, material tends to adhere to the cutting tool at the tool–chip interface, forming built-up edge, producing wear on the cutting tool as well contributing to the rough surface on the workpiece. [46, 47].

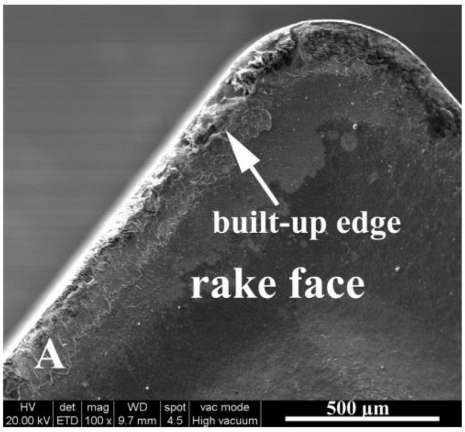

Figure 3.8 Tool wear mechanism at the rake face (built-up edge) [43]

Notching: Notches or grooves observed on cutting tools, have been attributed to the fact that the region they occupy is the boundary where the chip is no longer in contact with the tool.

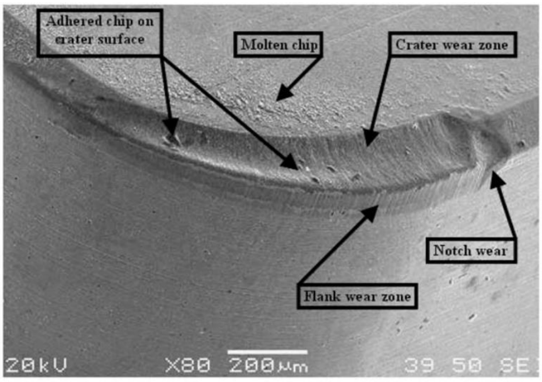

Figure 3.9 Tool wear mechanism (notching) [48]

Some of the factors that directly effects on tool life listed below:

- Material of machined workpiece.
- Required surface quality of the workpiece.
- Tool material.
- Tool geometry.
- Machining parameters such as cutting speed, feed, and depth of cut.
- Type of coolant.
- Condition of cutting tool with respect to vibrations.

Also, the high temperatures at the tool chip interface:

- Reduces strength of the tool and formation, so create wear.
- Shortens tool life.
- Causes thermal distortion.
- Caused dimensional change in workpiece.
- Causes dimensional change in workpiece, making difficult of controlling dimensional accuracy.

When the material and cutting tool parameters are kept constant according to the listed factors, there are two ways to increase the life of the cutting tool. The first of these is the optimization of cutting parameters. The other is coolant optimization. In this study, the path for optimization is coolants.

3.5 Cutting Fluids

Cutting fluids have been extensively utilized in machining operations to achieve the following outcomes:

- Enhancing the life domain of the tool and improving the surface finish of the workpiece by reducing friction and wear.
- Extending the tool life, minimizing temperature, and mitigating thermal distortion of the workpiece by cooling the cutting zone.
- Safeguarding the machined surface against environmental corrosion.
- Reducing forces and energy consumption.
- Particularly in drilling and tapping operations, preventing interference from chips and effectively removing them from the cutting zone.

The type of cutting fluid required varies depending on the machining operation, which may involve a coolant, a lubricant, or both. The efficacy of cutting fluids is influenced by several factors, including the type of machining operation, materials of the tool and workpiece, cutting speed, and the method of application [6].

Water serves as an effective coolant, efficiently reducing high temperatures within the cutting zone. However, it falls short as a lubricant and fails to minimize friction. Additionally, water can result in the oxidation (rusting) of both workpieces and machine tool-components. The necessity of a cutting fluid depends on the severity of the specific machining operation. Severity refers to the levels of temperatures and forces involved, as well as the capacity of tool materials to withstand them. It also considers the likelihood of built-up edge formation, and the appropriate application of fluids in the designated region at the tool-chip interface.

Nevertheless, there are instances where the cooling action of cutting fluids can have negative effects. Research has demonstrated that these fluids can cause chips to curl, leading to the concentration of heat near the tool tip and ultimately reducing the tool's lifespan. Additionally, cooling the cutting zone induces thermal cycling of cutter teeth, which can result in thermal cracks due to thermal fatigue or thermal shock.

Due to the limited dimensions of the capillary network, it is necessary for the cutting fluid to have a molecular size that is small and exhibit suitable wetting properties. For instance, when it comes to machining, grease is not a suitable lubricant, whereas low-molecular-weight oils mixed with water prove to be highly efficient.

3.6 Types of Cutting Fluids

There are several types of cutting fluids available for various machining operations. These include:

1. Oils: This category includes mineral, animal, vegetable, compounded, and synthetic oils. Oils are typically suitable for low-speed operations where there is minimal temperature rise.
2. Emulsions: Emulsions are a mixture of oil, water, and additives. They are commonly used in high-speed operations where significant temperature rise occurs. The presence of water in emulsions makes them effective coolants, while the oil component helps prevent oxidation caused by water.
3. Semisynthetics: Semisynthetics are chemical emulsions that contain a small amount of mineral oil, diluted in water, and supplemented with additives. These additives help reduce the size of oil particles, enhancing their effectiveness.
4. Synthetics: Synthetic cutting fluids are chemical formulations that do not contain oil. They are typically diluted in water and include various additives to enhance their performance.
5. Nano-fluids: Nano-fluids are a newer type of cutting fluid that incorporate nano-sized particles or additives. These fluids offer unique properties and enhanced performance compared to traditional cutting fluids.

These different types of cutting fluids are chosen based on factors such as the machining operation, speed, temperature rise, and desired cooling and lubricating properties.

3.7 Methods of Cutting-fluid Application

1. **Flooding:** Flooding is the most frequently employed method for applying cutting fluids. In this approach, flow rates vary depending on the specific application. For instance, flow rates may range from 10 L per minute for single-

point tools to 225 L per minute per cutter for multiple-tooth cutters, such as those used in milling [6].

2. **Mist:** This form of cooling delivers fluid to hard-to-reach regions and enhances the visibility of the object being processed [6].
3. **High-pressure systems:** High-pressure systems are highly beneficial for enhancing heat removal from the cutting zone. They effectively increase the rate at which heat is eliminated. These systems are also utilized to deliver cutting fluid using specifically designed nozzles that direct a forceful stream of fluid to the zone, particularly targeting the clearance or relief face of the tool [6].
4. **Through the cutting tool system:** To optimize the application process, narrow passages can be incorporated into cutting tools and toolholders. These passages allow high-pressure cutting fluids to be applied more effectively [38].
5. **Cryogenic machining:** Newer advancements in machining involve the utilization of cryogenic gases like nitrogen or CO_2 as coolants. LN_2, with a temperature as low as - 200 °C, is introduced into the cutting zone using small-diameter nozzles. This extreme cooling temperature helps maintain tool hardness and improves tool lifespan. Additionally, the chips produced during machining become more brittle, resulting in enhanced machinability [38].

3.8 Effects of Cutting Fluids

When choosing a cutting fluid, it is important to consider various factors, including its impact on:

- Workpiece material and machine tools: The cutting fluid should be compatible with the workpiece material to avoid any negative effects such as corrosion or damage. It should also be suitable for the machine tools used in the machining process.
- Biological considerations: The cutting fluid should be evaluated for any potential health hazards or risks to operators or other personnel who may come into contact with it. It should adhere to safety standards and regulations to ensure the well-being of individuals involved.

- The environment: Environmental factors should be taken into account when selecting a cutting fluid. This includes considerations such as the fluid's biodegradability, toxicity, and potential for pollution. Choosing environmentally friendly options can help minimize the impact on ecosystems and comply with environmental regulations.

Considering these aspects during the selection process can help ensure the appropriate cutting fluid is chosen, considering its effects on workpieces, machine tools, human health, and the environment.

When selecting a cutting fluid, it is crucial to consider whether the machined component will be exposed to stress and the potential for adverse effects like stress-corrosion cracking. This consideration becomes particularly important when dealing with cutting fluids containing sulfur and chlorine additives. For instance:

(a) Cutting fluids with sulfur should not be used with nickel-based alloys.

(b) Cutting fluids with chlorine should not be used with titanium.

Additionally, cutting fluids can have detrimental effects on machine tool components. Therefore, it is essential to evaluate their compatibility with various metallic and non-metallic materials in the machine tool.

Furthermore, since machine tool operators are typically in close proximity to cutting fluids, their health effects should be a primary concern. Some potential health risks associated with cutting fluids include:

Mist, fumes, smoke, and odors from cutting fluids can cause severe skin reactions and respiratory problems.

Cutting fluids can undergo chemical changes over time due to environmental factors or contamination from sources like metal chips, fine particles generated during machining, and tramp oil. These changes can lead to the growth of microbes, posing environmental hazards and adversely affecting the characteristics and effectiveness of the cutting fluids. To mitigate these adverse effects, various techniques are available for clarifying used cutting fluids. Recycling methods involve treating the fluids with additives, agents, biocides, deodorizers, and implementing water treatment processes.

These measures help maintain the quality and functionality of the cutting fluids while minimizing their environmental impact [6, 38].

3.9 Applications of Nano-fluids

A nano-fluid refers to a fluid that incorporates particles with nanometer-scale dimensions (0.000000001 m), known as nano-particles. These fluids consist of colloidal suspensions, where nano-particles are dispersed within a base fluid. The nano-particles employed in nano-fluids are commonly composed of metals, oxides, carbides, or carbon nanotubes. Base fluids used in nano-fluids include water, ethylene glycol, oils, and refrigerants [49, 50].

Nano-fluids are created by incorporating nanometer-sized particles into base fluids such as water, ethylene glycol, or refrigerants. This method is utilized to enhance heat transfer. Lately, there have been advancements in dispersing innovative solid particles at the nanoscale into base fluids, resulting in the development of heat transfer fluids known as 'nano-fluids'.

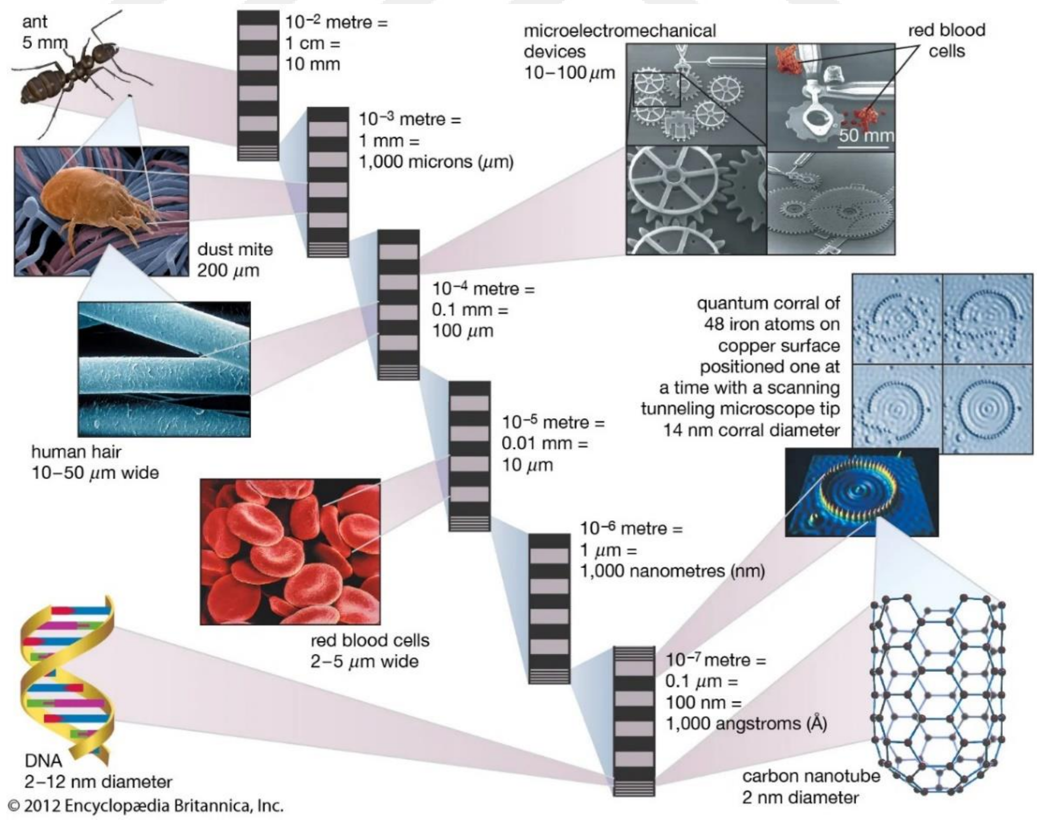

Figure 3.10 Size of carbon nanotube nano-particles [51]

The following diagram summarizes the areas of use of nano-fluids:

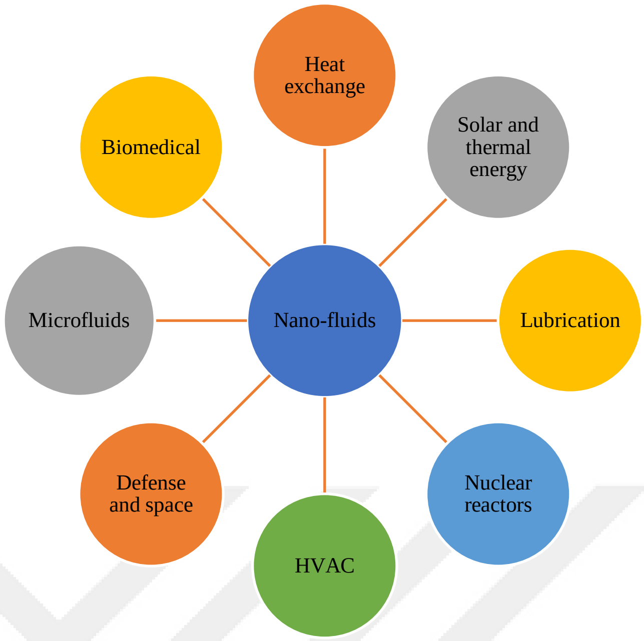

Figure 3.11 A diagram of usage areas of nano-fluids

Due to their high thermal efficiency, [52] nano-fluids stand out in heat transfer applications. In 1997, Pak B. Choi developed a newly innovative class of heat transfer fluids that depends on suspending nano-scale particles of metallic origin with an average particle size of less than 100 nm into conventional heat transfer fluids and gave such type of fluids the term ‘nano-fluids’.

The thermal conductivity comparison of several types of nano-additives can be shown in Figure 3.12. According to the figure, metal oxides have 500 times higher thermal conductivity compared to mineral oils.

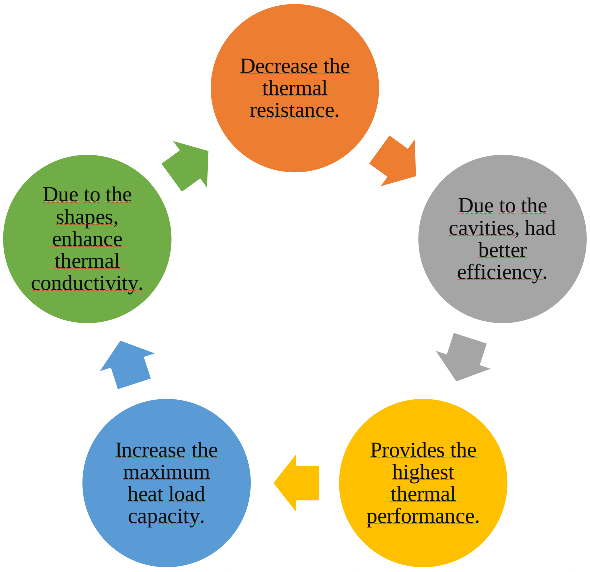

Figure 3.12 Some characteristics of the nano-particles [49, 50]

Nano-fluids can consist of a single-element. It can also consist of single or multiple oxides. Some examples are below:

Single-element:

- Cu (Copper)
- Fe (Iron)
- Ag (Silver) etc.

Single-element oxide:

- CuO (Copper (I) oxide)
- Cu_2O (Copper (II) oxide)
- Al_2O_3 (Aluminum (III) oxide) etc.

Multi-element oxide:

- $CuZnFe_4O_4$ (Copper zinc iron oxide nano-powder)
- $NiFe_2O_4$ (Nickel ferrite)
- $ZnFe_2O_4$ (Zinc ferrite)

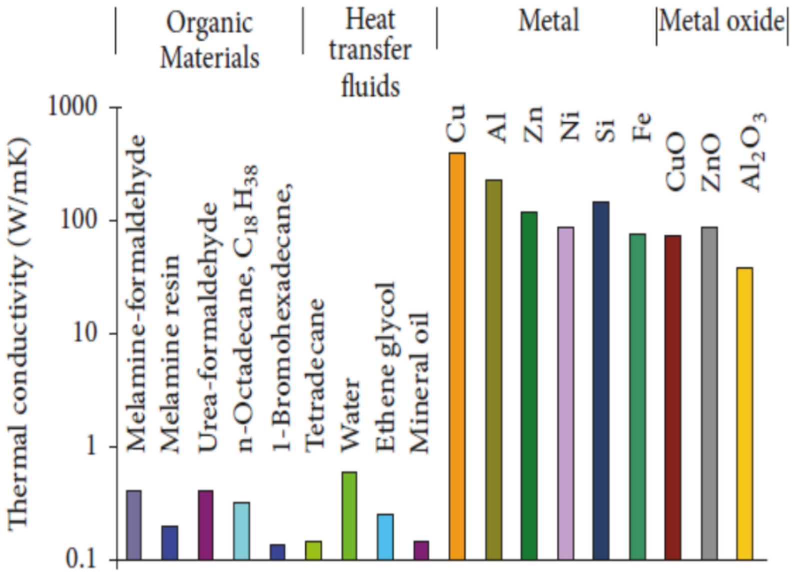

Figure 3.13 Comparison of thermal conductivity values of some organic materials, heat transfer fluids, metals, and metal oxides (nano-particles) [53]

As shown in Figure 3.13, nano-particles that cause a change in the thermal characterization of the liquid to which they are added can be used effectively in thermal processes. This is achieved both by changes in parameters such as density, viscosity, specific heat capacitance, heat conduction coefficient, thermal diffusivity, classified as thermo-chemical changes, and by parametric changes such as shape change, cavity formation, homogenization, classified as physical changes.

The fluid obtained by the process of adding nano-particles is included in a new property group by being called nano-fluid. Therefore, a mixture is obtained whose viscosity and temperature change gradients can behave differently. Therefore, behavior characterization can be solved by making individual measurements. Contrary to what is generally expected, the precipitation effect causes much greater damage. For example, it has formed lumpy structures exceeding 100 nm in diameter in organic oils [27].

As can be seen in the literature [22-31], the usability of machining in cooling applications is also being tested. The important issue here is the amount of nano-particles added. A continuous increase in the amount of particles, passing the saturation point, has negative effects on the thermal properties of the mixture. In this context, it is necessary to add nano-particles up to the saturation point for effective thermal efficiency [54].

In addition, most of the nano-particles obtained are metal-nonmetal compounds and in a sense, ceramic structures. These structures are micro-structurally used as cutting tools, workpieces, workbench metal structures, etc. considering the effect on it, the intensive use of nano-particles can cause damage to the cumulative system [31, 49, 50, 54].

CHAPTER 4

EXPERIMENTAL SETUP

The main purpose of this thesis is to study the cooling effect of nano-particle doped coolant on Ti-6Al-4V workpiece. For this purpose, a three-stage experimental systematics has been applied. According to this,

- Measurements to be conducted with the help of fluid property sensor (FPS) and rheometer used for measuring the dynamic viscosity to study the density and viscosity of nano-fluids.
- Measurements to be applied to determine the thermal conductivity of nano-fluids.
- A turning process that will be performed to study the effects of cutting in machining and the study of the cooling state with the help of MQL at this time.

All these measurements within the scope of the study were carried out in order. The process has also ensured that the results of the measurements are compatible with each other.

The nano-fluid preparation process was carried out before all the measurements were performed. Accordingly, the nano-particles were added to the mixture of FUCHS ECOCOOL S 761 B boron oil and water at a concentration of 7% under the boundary conditions given in Table 4.1 and mixed with the ultrasonic mixer shown in Figure 4.3. Nano-particles have been selected in such a way that they are widely used and easy to compare in the literature. In addition, the effect of the selection of nano-particles entering the ceramic class on the workpiece can also be observed to some extent.

Table 4.1 Conditions of the experiments

Nano-particles and conditions	
Nano-particles	Al_2O_3, MWCNT, TiO_2
Concentration percentages	0.5%, 1%, 1.5%
Ultrasonic mixer maximum temperature limit	30 °C
Mixing time	60 min
Mixing frequency	20-25 kHz (via Ø8 apparatus)
Boron mineral oil + water mixture pH interval	8.9 – 9.8
Boron mineral oil + water mixture electrical conductivity interval	1500-2000 µS/cm

4.1 Preparation of Nano-fluids

The nano-fluid preparation process starts with the preparation of the base fluid first. The base fluid will be kept constant throughout all measurements. FUCHS ECOCOOL S 761 B boron oil is mixed by adding 7% by volume to water with the help of beakers. In this way, boron oil, which is a white colored and slippery liquid, is obtained. The pH and conductivity degrees of the obtained liquid are measured with the help of reference rulers.

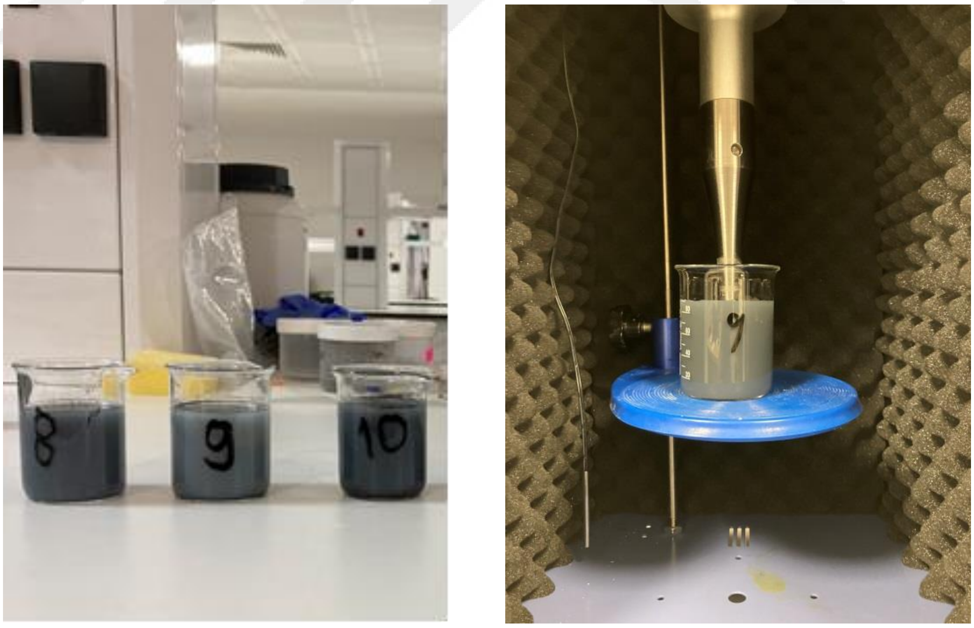

Figure 4.1 A general view of the nano-fluid samples before the mixing process and the ultrasonic mixer

The boron mineral oil + water mixture has a structure that can dissolve when it waits motionless. It can be maintained for an average of up to fourteen days. This situation depends on factors such as ambient temperature, humidity, and organic material/substance contact. A similar situation may also be the case for nano-fluids when appropriate or optimal conditions are maintained. In addition, regulatory liquids should be used for both these situations, as bacterial production or pH change situations may occur during long-term use. If the liquids are dynamic (i.e. in a closed-loop cycle with a pump system), both boron oil and nano-particle addition can be performed by executing necessary checks at certain periods.

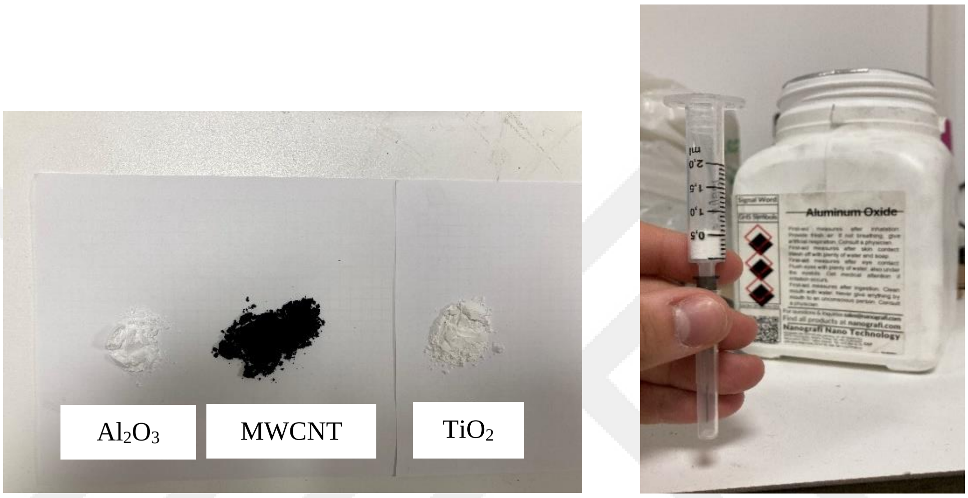

Figure 4.2 A photograph of nano-fluid preparation process

In the measurements in this study, although the liquids were stationary, there was no need for regulator liquid because fresh mixtures were used. The recommended range for pH value is between 8.9-9.8. Liquids were formed to fall within this range, and the pH regulator was kept ready to add liquid (BASF brand) if necessary.

After the boron oil + water mixture is prepared, solid nano-particles are prepared at 0.5%, 1%, and 1.5% by volume. Then, they are combined separately as 99.5% base fluid + 0.5% nano-particles, 99% base fluid + 1% nano-particles, and 98.5% base fluid + 1.5% nano-particles, respectively. During the combining process, attention should be paid to volumetric ratios and care should be taken to prevent nano-particles from fliting.

After the combining process, the mixtures are mixed sequentially in an ultrasonic mixer for one hour in accordance with the boundary conditions. During mixing process, the temperature is constantly measured and kept within the range of 24.5-30

°C. When mixing process is completed, it is left to cool to 24.5 °C. Liquids with decreasing temperature are proceeded to the FPS measurements, respectively.

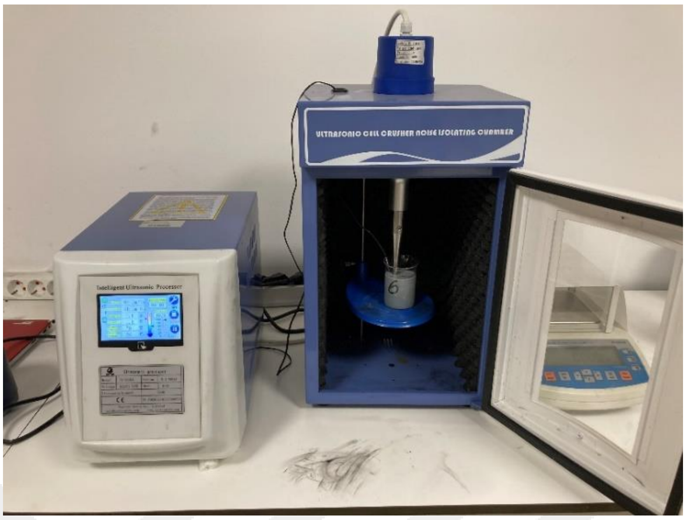

Figure 4.3 A view of nano-fluid preparation process in the ultrasonic mixer

Prepared mixtures were named according to the type of nano-particle they contained and their volumetric amount. The mixtures are shown in Table 4.2.

Table 4.2 Nano-particle concentrations used in the nano-fluid samples

Sample no	Content
1	7% boron mineral oil + 93% water mixture
2	99.5% boron mineral oil + water mixture + 0.5% Al_2O_3
3	99% boron mineral oil + water mixture + 1% Al_2O_3
4	98.5% boron mineral oil + water mixture + 1.5% Al_2O_3
5	99.5% boron mineral oil + water mixture + 0.5% MWCNT
6	99% boron mineral oil + water mixture + 1% MWCNT
7	98.5% boron mineral oil + water mixture + 1.5% MWCNT
8	99.5% boron mineral oil + water mixture + 0.5% TiO_2
9	99% boron mineral oil + water mixture + 1% TiO_2
10	98.5% boron mineral oil + water mixture + 1.5% TiO_2

4.2 Nano-fluid Density and Viscosity Measurements

The obtained nano-fluids are respectively placed in the FPS2800B12C4 model FPS assembly. FPS measures the density and dynamic viscosity of the mixture with the help of sensor waves. Here, it is necessary to wait for the stabilization of the sensor waves for both values. When the waves stabilize, the results can be monitored instantly via the 'CAN Viewer' software as shown in Figure 4.4.

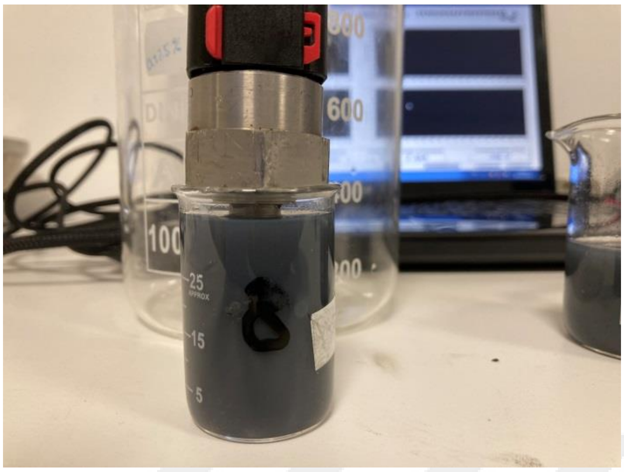

Figure 4.4 A view from the measurements made with FPS

Dynamic viscosity measurements were also performed with the help of Anton Paar brand MCR 702-e model modular compact rheometer available at UNAM in Bilkent University.

Figure 4.5 The photograph of Anton Paar brand MCR 702-e compact rheometer [55]

Rheometer measurements were made for three minutes each under a constant shear rate of 50 [1/s] with the help of a parallel sliding plate and dynamic viscosity results were obtained.

4.3 Nano-fluid Thermal Conductivity Measurements

The measurements of thermal conductivity, one of the thermophysical properties, were carried out by means of the KD-2 Pro apparatus located in the infrastructure of Erciyes University and shown in Figure 4.6.

Figure 4.6 A view of measurements made with KD-2 Pro thermal conductivity measurement device

A KD-2 Pro probe was used for the thermal conductivity measurements. The measuring probe consists of a needle with a heater and a temperature sensor inside. A current flow through the heater and the system monitors the temperature of the sensor over time. Analysis of the sensor temperature determines the thermal conductivity.

In order to make a measurement, a probe suitable for the sample to be measured is selected. The recommended probe for liquid samples is the KS-1 coded sensor.

The KS-1 sensor is designed to measure the thermal conductivity and thermal resistance of both low viscosity and high viscosity liquids. However, it is difficult to measure the heat transfer coefficient due to natural or forced convection. If the liquid moves, the error rate will increase due to convection heat transfer within the liquid itself.

Convective heat transfer in liquids can be divided into two categories: forced and free convection. Forced convection occurs when the fluid is agitated or stirred by mechanical forces. Free convection can occur when an object of higher or lower temperature is present in a fluid. The temperature difference between the object and the fluid forms density gradients in the fluid and these density gradients cause the fluid to better mix. From a practical point of view, some steps can be taken to minimize both forced and free convective heat transfer.

To eliminate forced convection, the liquid sample and sensor must be absolutely still during the measurements. Even very small vibrations in the sample are often enough to compromise the thermal compliance measurement.

The KD-2 Pro with KS-1 sensor is designed to add a very small amount of heat through the heater to the sample during measurements which minimizes the problems with free convection. In high viscous liquids (e.g. oils, glycerin) free convection is usually not a problem. However, for low viscous liquids such as water or aqueous solutions, the followings are recommended by the manufacturer (Decagon inc.) to obtain more accurate measurements [56]:

- When working with low viscous liquid samples, the reading time should be as short as possible to minimize the amount of heat added to the sample. The default reading time for the KS-1 sensor is one minute. Use this reading time if you are studying with liquids with low viscosity.
- For liquid samples, the KS-1 sensor needle should be oriented vertically during measurements to help prevent free convection.
- Never use the KS-1 sensor in liquids in high power mode. The sensor should be configured in low power mode to avoid free convection.

The working algorithm of the sensor is as follows:

Heating is applied to a single needle for the time of t_h. The temperature in the region is monitored during and after the heating. Since it is a measurement for a liquid, a KS-

1 needle with a diameter of 1.2 mm and a length of 6 cm is vertically inserted into the liquid sample [56]. Temperature during heating is calculated from Eqn. (4.1).

$$T = m_0 + m_2 T + m_3 \ln t \qquad \textbf{(4.1)}$$

Where, m_0 is the ambient temperature during heating (which may include some offset due to contact resistance and the fact that the heating element is adjacent to the temperature sensor inside the needle), m_2 is the background temperature drift rate, m_3 is the slope of a line connecting the temperature rise to the logarithm of the temperature, and t is the total elapsed measurement time.

Eqn. (4.2) represents the model during cooling.

$$T = m_1 + m_2 t + m_3 \ln\left(\frac{t}{t - t_h}\right) \qquad \textbf{(4.2)}$$

Where, m_1 is the contact temperature when heating starts and t_h is the heating time. Thermal conductivity of the sample is calculated from Eqn. (4.3).

$$k = \frac{q}{4\pi m_3} \qquad \textbf{(4.3)}$$

4.4 Machining Experiments with Nano-fluids

The machining experiments were carried out using ACCUWAY brand JT-150 model computer numerical control (CNC) lathe and other equipment available in the laboratory of Düzce University. The process of the machining experiments is as follows:

Ti-6Al-4V workpiece is connected to the lathe chuck. The tool and workpiece setup is completed by connecting the selected cutting insert (YG brand WNMG080408-SM coded) to the appropriate cutting tool holder (AKKO brand MWLNR2020K08 coded). Then, OPTRIS brand PI450 model thermal camera and SKF brand Vario model MQL system are connected.

The prepared setup is started with the appropriate NC Program and instantaneous temperature measurements are made via the thermal camera. The average values taken from the thermal camera are noted and the experiment is terminated for temperature measurement. Afterwards, surface roughness values for the cut part are measured with the Mahr Marsurf brand PS10 model surface quality measurement device and the effect of the use of nano-fluid on the surface quality of the workpiece is also observed.

The CNC lathe, the equipment used in the experimental setup and the whole setup are shown in Figure 4.7.

Figure 4.7 A photograph of the experimental setup for the machining

The experiment was carried out using the test parameters in Table 4.3. The cutting parameters were selected from catalogs in accordance with the cutting tool and tool holder. The other parameters are the optimum values of the devices used.

Table 4.3 Machining experiments parameters

Parameter	Input value
Cutting speed (V_c)	60 m/min
Feed rate (f)	0.20 mm/min
Diameter of workpiece ($Ø_w$)	47.6 mm
Volumetric flow rate (Q)	75 mL/h
Pressure (P)	8 bar
Nozzle diameter ($Ø_n$)	2 mm

Nozzle distance from tool rake face (*l*)	30 mm
Emissivity of thermal camera	0.6

The machining experiments were completed by processing the parameters specified in Table 4.3 into the following NC Program and using different insert faces for each nano-fluid.

NC PROGRAM:

```
T000081;

G54 G90;

G96 S60 M03; //CYCLE START

G00 X50. Z5.;

G01 X46. F0.2;

G01 Z-15.;

G00 X200. Z0.; //HOME POSITION

M30;

%
```

Emissivity value is taken from the ‘OPTRIS brand PI450 model thermal camera data sheet’ for a distance of 1 μm. According to the data sheet, the typical emissivity value for 1 μm is in the range of 0.5-0.7 for Ti-6Al-4V material. By choosing 0.6 as the average value, the temperature during the experiments was analyzed through the thermal camera. A sample data taken from the thermal camera is shown in Figure 4.8. The cutting insert and cutting tool holder used in the experiments are shown in Figure 4.9.

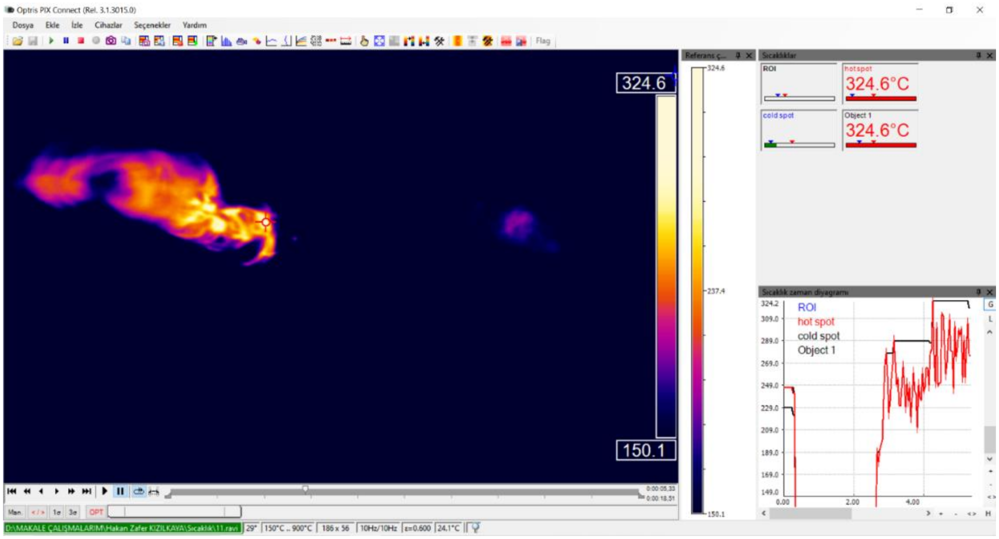

Figure 4.8 A sample thermal camera output image from OPTRIS PIX Connect software

Figure 4.9 A photograph of cutting insert and cutting tool holder used in the machining experiments

CHAPTER 5

RESULTS AND DISCUSSIONS

The results of the measurements described in Chapter 4 are given in this section. Thermo-physical property measurements and then cutting experiments were performed on the prepared nano-fluids, respectively. All nano-fluids were prepared and subjected to the experiments in accordance with the grouping in Table 4.2.

5.1 Results of FPS Measurements

The prepared samples were subjected to density and dynamic viscosity measurements using FPS. The graphs containing the results of the measurements are given in Figure 5.1 and Figure 5.2.

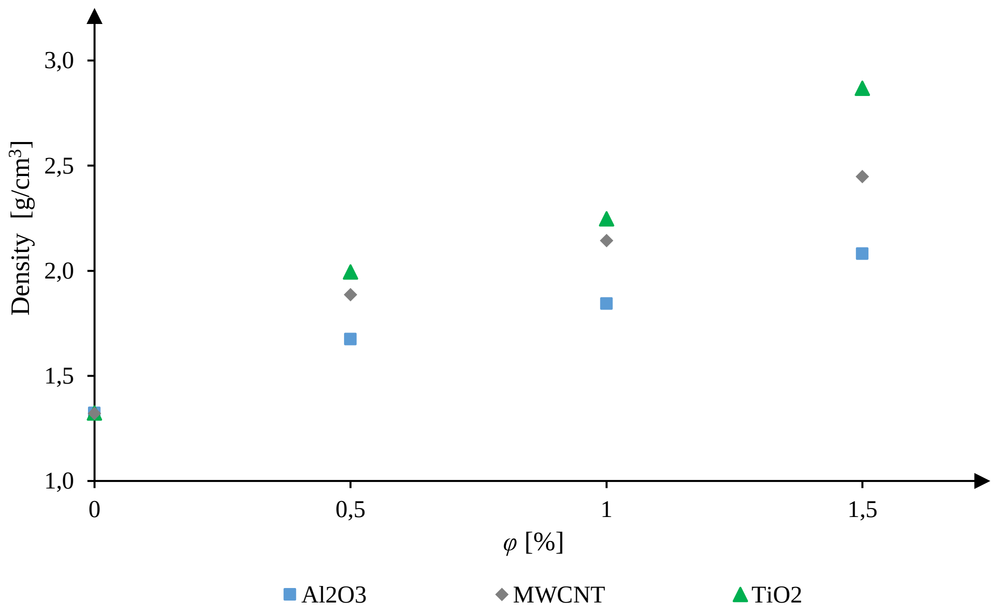

Figure 5.1 Density measurement results by using FPS ($T = 24.5$ °C and at atmospheric pressure)

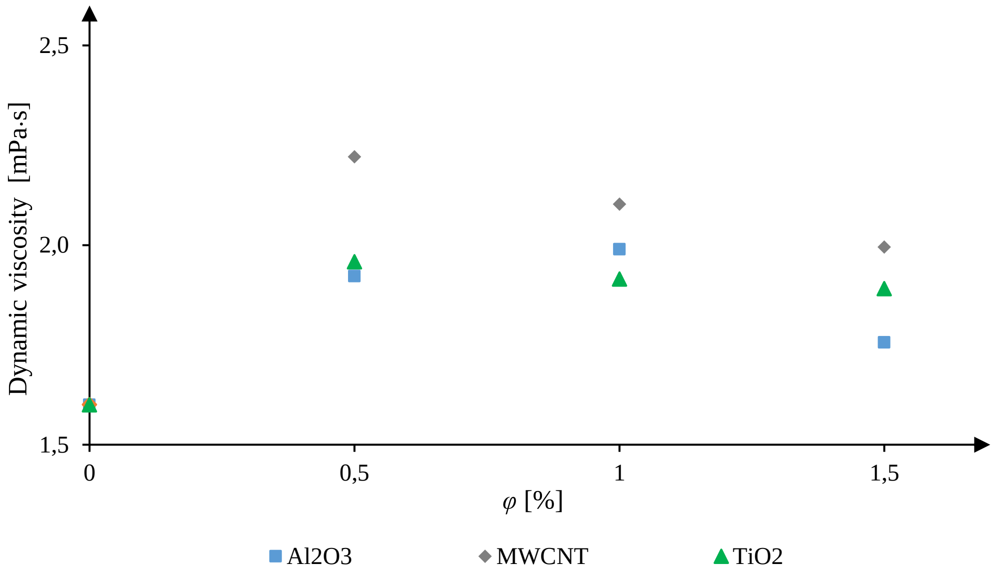

Figure 5.2 Dynamic viscosity measurement results by using FPS ($T = 24.5$ °C and at atmospheric pressure)

According to the results in Figure 5.1, the highest density was observed in Sample 10, 98.5% boron mineral oil + water mixture and 1.5% TiO_2, while the lowest density was observed in Sample 1, 100% boron mineral oil + water mixture. It was also observed that the density tends to increase in all nano-fluids as the amount of nano-particles increases. The natural reason for this circumstance is that each nanoparticle is denser than the base fluid.

According to the results in Figure 5.2, the highest dynamic viscosity was observed in Sample 5, 99.5% boron mineral oil + water mixture and 0.5% MWCNT, while the lowest dynamic viscosity was observed in Sample 1, 100% boron mineral oil + water mixture. It was also observed that the dynamic viscosity of all nano-fluids tended to decrease as the amount of nano-particles increased. The reason for this situation is precipitation and sediment formation [54]. In other words, it was determined that the samples became fluidized as the amount of nano-particles increased.

5.2 Results of Rheometer Measurements

Prepared samples were subjected to dynamic viscosity measurements by using the rheometer. The graphs containing the results of the dynamic viscosity measurements are given in Figure 5.3.

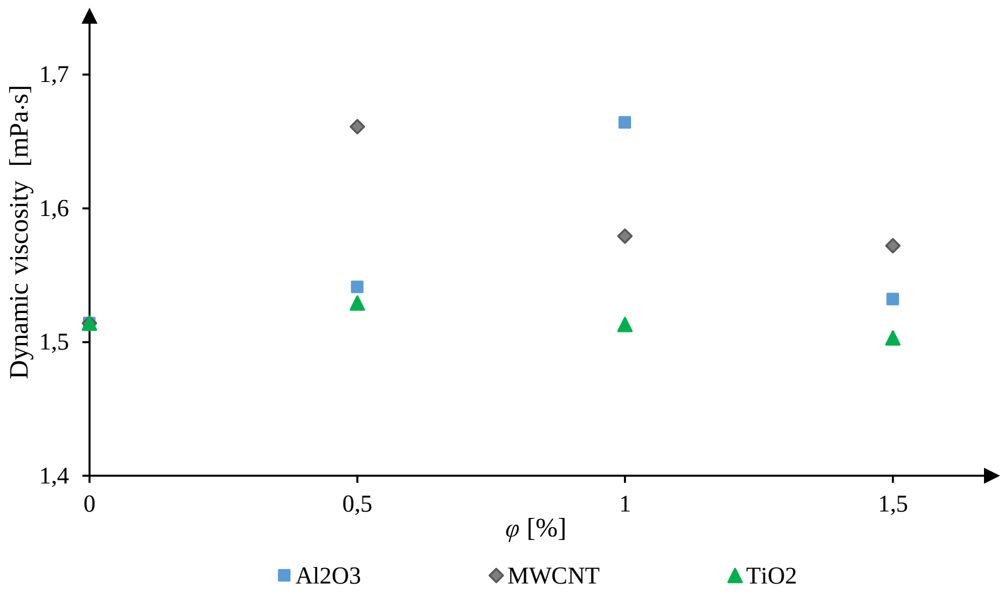

Figure 5.3 Dynamic viscosity measurement results with the rheometer (T = 24.5 °C and at atmospheric pressure)

According to the results in Figure 5.3, the highest dynamic viscosity was observed in Sample 3, 99% boron mineral oil + water mixture and 1% Al_2O_3, while the lowest dynamic viscosity was observed in Sample 1, 100% boron mineral oil + water mixture. The trend of the results is similar to that of the FPS measurements. In a sense, measurements obtained by FPS and the rheometer confirmed each other. Similarly, as the amount of nano-particles increased, it was found that the samples became fluidized.

5.3 Results of Thermal Conductivity Measurements

The prepared samples were subjected to thermal conductivity measurements by using KD-2 Pro device as described in Chapter 4. The graphs containing the results of the measurements are given in Figure 5.4.

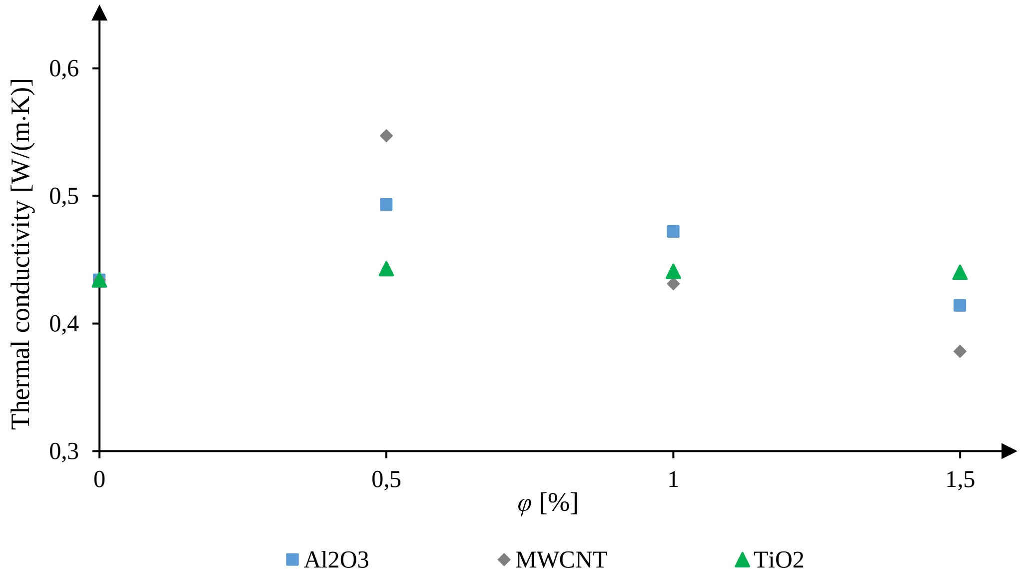

Figure 5.4 Thermal conductivity measurement results ($T = 24.5$ °C and at atmospheric pressure)

According to the results in Figure 5.4, the highest thermal conductivity was observed in Sample 5, 99.5% boron mineral oil + water mixture and 0.5% MWCNT, while the lowest thermal conductivity was observed in Sample 7, 98.5% boron mineral oil + water mixture and 1.5% MWCNT. When evaluated separately for each nano-particle, it was determined that the increase in the amount of nano-particles did not increase the thermal conductivity, but decreased it after the optimum value. This circumstance can be understandable considering the fact of changing in the fluid form.

5.4 Results of Machining Experiments

In the machining experiments, both the temperature at the contact surface of the cutting tool and workpiece and surface roughness value at the end of the operation were measured. The results of the experiments are given in Figure 5.5 and Figure 5.6.

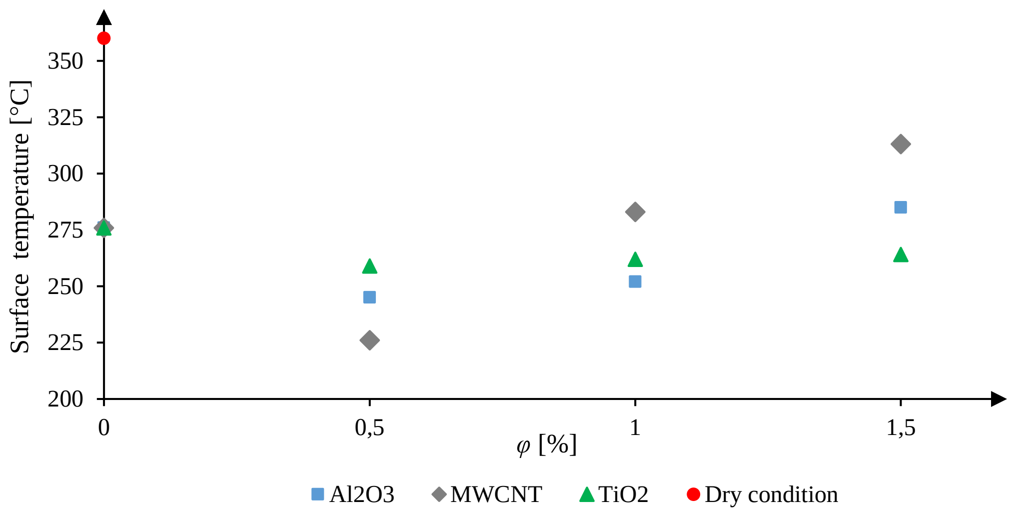

Figure 5.5 Temperature measurement results at the contact surface of the cutting tool and workpiece

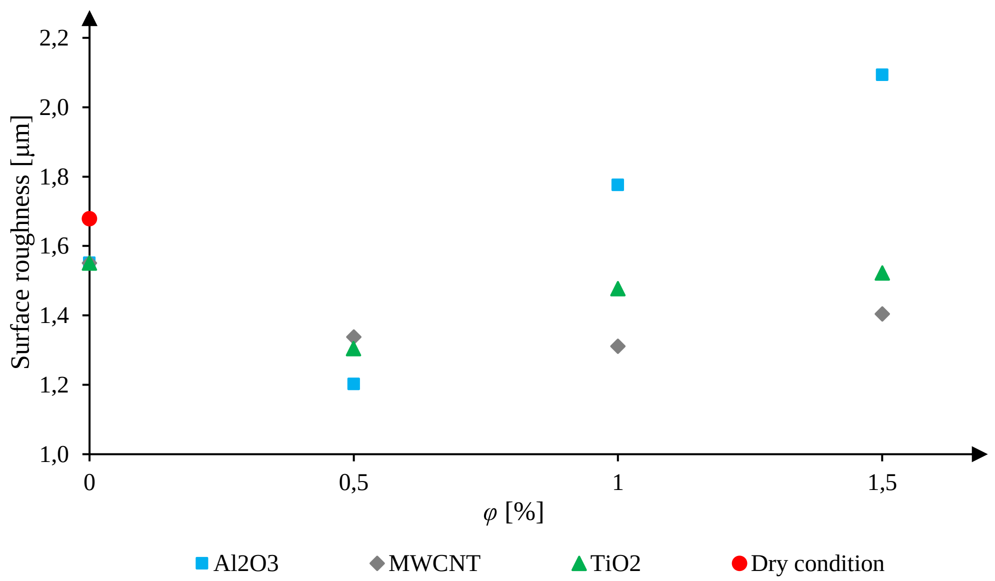

Figure 5.6 Workpiece surface roughness measurement results

According to the results in Figure 5.5, the lowest temperature was observed in Sample 5, 99.5% boron mineral oil + water mixture and 0.5% MWCNT, while the highest temperature was observed in Sample 11, dry condition. Increasing the amount of nano-particles did not decrease the temperature, which is again due to precipitation and changing in fluid form. It can be seen that the use of nano-fluids is beneficial both compared to the base fluid and compared to dry condition. In the best condition, 37.2%

temperature reduction was achieved compared to dry condition and 18.08% compared to Sample 1, 100% boron mineral oil + water mixture.

According to the results in Figure 5.6, the lowest surface roughness was observed in the Sample 2, 99.5% boron mineral oil + water mixture and 0.5% Al_2O_3, while the highest surface roughness was observed in the Sample 4, 98.5% boron mineral oil + water mixture and 1.5% Al_2O_3. The nano-fluids obtained with the use of nano-particles at the appropriate ratio also improved the surface quality compared to both base fluid and dry condition. According to the results, when the concentration of nano-fluids exceeds the required level, degradation in surface quality can be seen [26, 34]. This circumstance can be understandable with the facts of changing in fluid form, abrasive effects of nano-particles on the workpiece, difficulty for entering tool-workpiece interface (this is also understandable with film thickness) at high concentrations and precipitation.

The results of this study and the results of similar studies in the literature seem to be close to each other. In the literature, it is explained that vegetable oils, mineral oils, etc. can be used instead of direct boron oil + water mixture. The comparison of this study and Sharma et al.'s studies [28, 29] with vegetable oils is given in the Figure 5.7 - Figure 5.13.

In the study by Sharma et al. [28], Al_2O_3 nano-particles were added to vegetable oil at various concentrations and their effects on the cutting force in turning AISI 1040 steel using the MQL method were investigated. The methods used to determine thermo-physical properties are similar to those used in this study. According to this, comparison of this study and Sharma et al.'s study [28] for density measurement results, dynamic viscosity measurement results, and thermal conductivity measurement results are shown in Figure 5.7, Figure 5.8, and Figure 5.9, respectively.

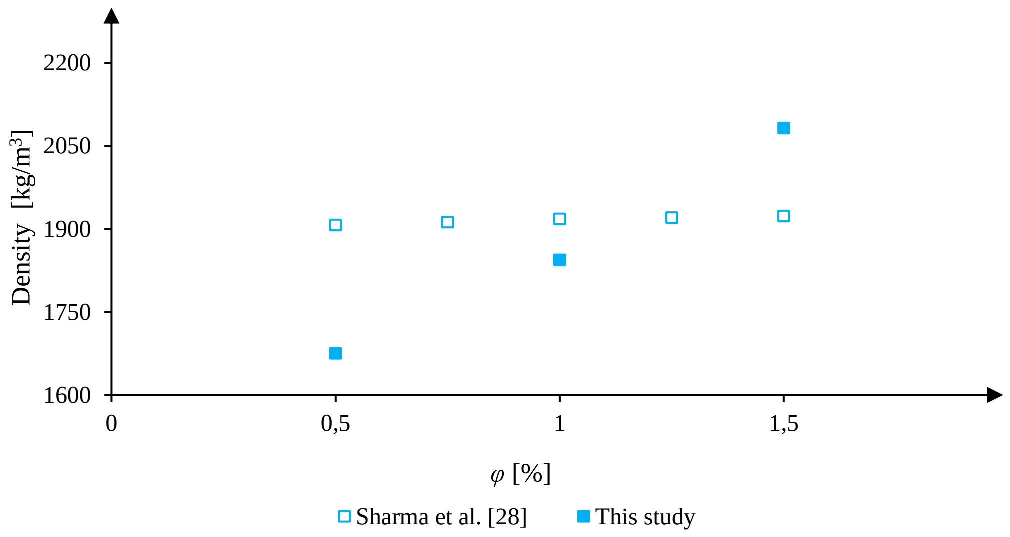

Figure 5.7 Comparison of density measurement results in case of using Al_2O_3 nano-particles

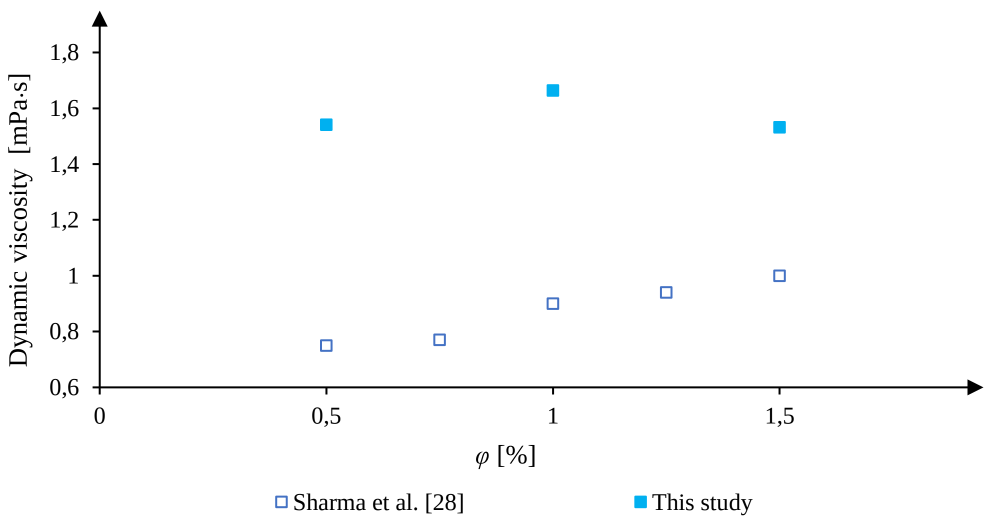

Figure 5.8 Comparison of dynamic viscosity results in case of using Al_2O_3 nano-particles

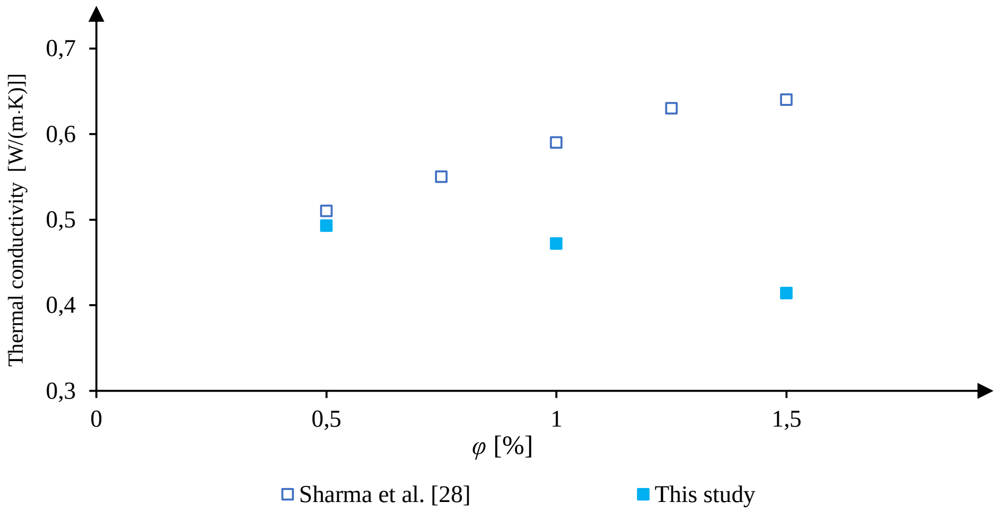

Figure 5.9 Comparison of thermal conductivity results in case of using Al_2O_3 nano-particles

When Figure 5.7 - Figure 5.9 are examined, it is seen that the general proportional trend of the results is similar for thermo-physical properties. The difference between the results is due to the different base fluids. However, measurement conditions such as temperature and pressure are the same in both studies.

In another study by Sharma et al. [29], TiO_2 nano-particles were added to vegetable oil at various concentrations and their effect on the cutting force in turning AISI 1040 steel using the MQL method were investigated. The methods used to determine thermo-physical properties are similar to those used in this study. According to this, comparison of this study and Sharma et al.'s study [29] for density measurement results, dynamic viscosity measurement results, and thermal conductivity measurement results are shown in Figure 5.10, Figure 5.11, and Figure 5.12, respectively.

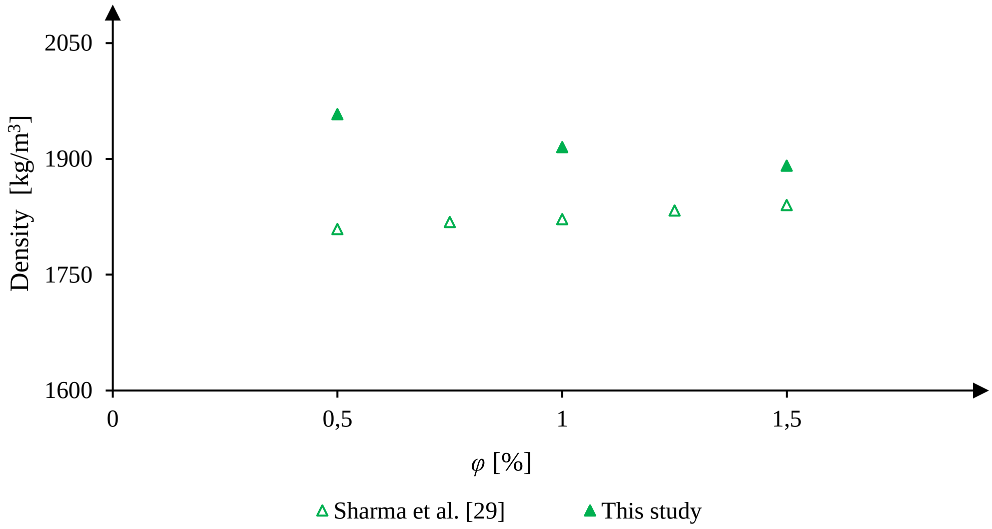

Figure 5.10 Comparison of density results in case of using TiO_2 nano-particles

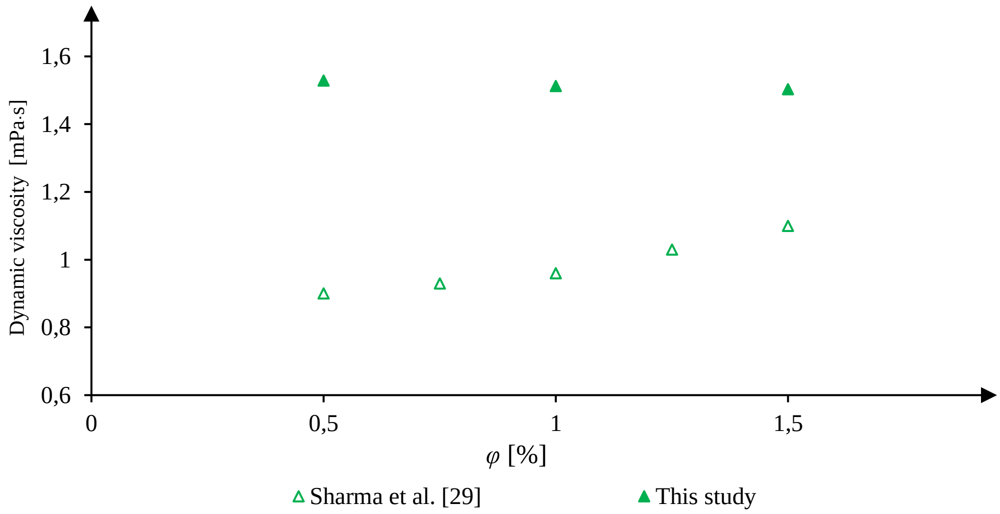

Figure 5.11 Comparison of dynamic viscosity results in case of using TiO_2 nano-particles

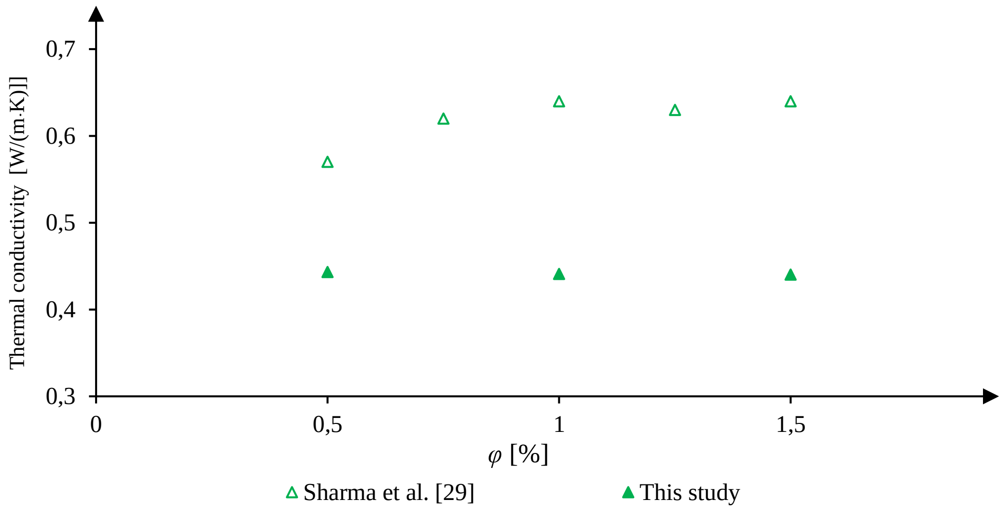

Figure 5.12 Comparison of thermal conductivity results in case of use TiO_2 nano-particles

When Figure 5.10 - Figure 5.12 are examined, it is seen that the proportional trend of the results is similar in general for thermo-physical properties. The difference between the results is again due to the different base fluids. However, measurement conditions such as temperature and pressure are the same in both studies.

CHAPTER 6

CONCLUSIONS

In this thesis, the effect of nano-fluids obtained by adding nano-particles to the boron oil and water mixture used in machining in the cooling of contact surface of the cutting tool and workpiece has been investigated experimentally. The experimental studies can be categorized into two groups: determining thermo-physical properties of the nano-fluids used in the study and machining experiments, respectively. Within the measurements of thermo-physical properties, density, dynamic viscosity, and thermal conductivity were determined. Within the machining experiments, temperature distribution at the tool-chip interface and surface roughness at the contact surface of the cutting tool and workpiece were examined by using nano-fluids.

In the study, Al_2O_3, MWCNT, and TiO_2 were selected as nano-particles and nano-particle volumetric ratios of 0.5%, 1%, and 1.5% were used. The results of the study, which aimed to reduce the temperature at the workpiece and cutting tool interface and to improve the surface roughness, showed that some enhancements can be reached at the suitable volumetric ratios of nano-particles as expected.

In the literature, relatively high viscous fluids have been used compared to this thesis. In this study, it has been determined that the desired improvements can be obtained in relatively low viscous fluids. In the study, a decrease of approximately 18% in the contact surface temperature was obtained by using 99.5% boron mineral oil + water mixture and 0.5% MWCNT nano-fluid represented as Sample 5. In the literature [31, 33], similar gains were obtained with relatively high viscous oils. Especially for using hard materials such as the Ti-6Al-4V in the aerospace industry. In this study, some economic gains can also be achieved with this temperature reduction. These economic gains include the reduction of cutting insert consumption due to increased cutting tool life, the ability to achieve the same amount of heat transfer using less cutting fluid with the help of nano-fluids, and the reduction of heat-induced problems in front of the cutting parameters.

In the experiments, it was also found that the use of large amounts of nano-particles does not have a positive effect, because of changing in the fluid form, precipitation, and sedimentation have a negative effect on the cutting parameters to be improved. In addition, in order to maintain the form of the nano-fluids, the cooling system must also be effectively agitated. In the experiments by using MQL, this aim was achieved due to the pressure drive, but there is always a risk of not achieving the desired aim in case of using only the centralized or conventional cooling systems.

The circumstance is the similar in view of thermo-physical properties. For all nano-particles, increasing the volume fraction has a negative effect on thermo-physical properties such as dynamic viscosity and thermal conductivity. According to dynamic viscosity measurement results obtained by rheometer, 99.5% boron mineral oil + water mixture + 0.5% TiO_2 nano-fluid provided an increase in dynamic viscosity is about 2% compared to 100% boron mineral oil + water mixture fluid. On the other hand, a decrease about 1.3% in dynamic viscosity was observed for 98.5% boron mineral oil + water mixture + 1.5% TiO_2 nano-fluid compared to the 100% boron mineral oil + water mixture fluid.

The case is the similar for the thermal conductivity measurement results. For example, 99.5% boron mineral oil + water mixture + 0.5% Al_2O_3 nano-fluid provided an increase in thermal conductivity is about 13.5% compared to 100% boron mineral oil + water mixture fluid. On the other hand, a decrease about 5.4% in thermal conductivity was observed for 98.5% boron mineral oil + water mixture + 1.5% Al_2O_3 nano-fluid compared to 100% boron mineral oil + water mixture fluid.

The similar case was observed for surface roughness measurements as in the thermo-physical properties. While a decrease in surface roughness was observed in the appropriate form of the nano-fluids, an increase in surface roughness was observed when the amount of nano-particles was increased. For example, an improvement of approximately 25% was obtained in surface roughness in case of using 99.5% boron mineral oil + water mixture + 0.5% Al_2O_3 nano-fluid compared to 100% boron mineral oil + water mixture fluid. On the other hand, an increase of approximately 27% was observed in surface roughness in case of using 98.5% boron mineral oil + water mixture + 1.5% Al_2O_3 nano-fluid compared to 100% boron mineral oil + water mixture fluid.

As a result of the study, it is observed that the use of nano-fluids increases the thermal efficiency and improves both the cutting tool and the cooling process at appropriate volumetric ratios. It is also evaluated that this effect can be better in hard materials such as Ti-6Al-4V or steel, because thermal problems are more crucial in the machining of these materials. When appropriate chemical conditions and cooling installations are provided, an increase for thermal efficiency in the machining can be achieved.

In the future, some studies investigating biological factors such as boron oil and water mixture and easy use in appropriate cooling installations can be carried out. Also, effects of using hybrid nano-fluids on the thermal efficiency, surface roughness, and cutting force in the machining can be investigated.

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Bachelor's Degree Ankara Yıldırım Beyazıt University/Mechanical Engineering Department, 2020

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Senior Numerical Control and Automation Engineer (2021 - Continued)
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INFORMATIONS OF COURSES AND CERTIFICATES

Participation Certificate of TEKNOFEST Rocket Competition, ROKETSAN, 2019

Participation Certificate of UAV Competition, TUBITAK, 2018 & 2019

Graduation Certificate of CATIA Course, Gazi University, 2018

Graduation Certificate of CNC Programming Course, Gazi University, 2018

Educational Certificate about UAVs, TUBITAK, 2017 & 2018

English Level Certificate, PEARSON, 2017

PROJECTS

Competition Design and Manufacturing of 10000 ft. Ranged Solid Propellant Rocket, 2020

Competition Design and Manufacturing of 5000 ft. Ranged Solid Propellant Rocket, 2019

Competition Design and Manufacturing of Autonomous UAV, 2019

Competition Design and Manufacturing of Autonomous UAV, 2018