DEVELOPMENT OF MINIMUM QUANTITY LUBRICANT DEVICE FOR TURNING PROCESS

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MEng/SEET/2017/6910

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A THESIS SUBMITTED TO THE POSTGRADUATE SCHOOL FEDERAL UNIVERSITY OF TECHNOLOGY, MINNA, NIGERIA IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF MASTER OF ENGINEERING IN MECHANICAL ENGINEERING

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ABSTRACT

Minimum quantity lubrication (MQL) uses a very small lubricant flow (ml/h instead of l/min) and directly sprayed the lubricant on the cutting zone which guarantee a good level of lubrication and the chip removal mechanism; besides the economic benefits, one other important advantage is being environmentally friendly. This study developed an 80 % local content MQL device and carried out a performance evaluation by investigating the effect of flow characteristics, cutting velocity, feed rate and machining time on surface finishing for turning AISI 1018 mild steels. The developed MQL device was adapted with Harrison M400 lathe for the turning operation in which high speed steel (HSS) was used as the cutting tool and groundnut oil (vegetable oil) was used as the cutting fluid. Different ratios of air to oil (A/O) were used within the range of 1 to 5 bar. The result showed that the surface roughness R_a, progressively decreases with increase in A/O ratio at relatively low A/O value but this phenomenon ceased at a critical value of A/O of 1.5 and an increase in A/O resulted to an increase in R_a. Thus, A/O ratio of 1.5 (air compressor fixed at 3 bar and micropump at 2 bar) achieved the best surface finish having R_a of 0.95 μm and taken as optimum A/O value for MQL turning operation for mild steel. Further findings showed that the surface roughness, R_a increases with the increase in feed rate and decreases with the increase in cutting velocity V_c. Also, surface roughness gradually increases with the machining time. Therefore, A/O ratio of 1.50 is recommended as an optimum value for MQL turning operation for mild steel.

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CHAPTER ONE

1.0 INTRODUCTION

1.1 Background to the Study

The economic strength of a country is measured or judged from the development of manufacturing industries and productivity is always the main concern in this sector. Machining processes represent a cornerstone of manufacturing industries and crucial to their productivity (Yassin & Teo, 2015). Machining processes such as turning is commonly used to obtain the desired size, shape, and surface of a material through the removal of material from a workpiece. In other words, turning is a form of machining, a material removal process, which is used to create rotational parts by cutting away unwanted material, the process which requires a turning machine or lathe, workpiece, fixture, and cutting tool. The workpiece is a piece of pre-shaped material that is secured to the fixture, which itself is attached to the turning machine, and allowed to rotate at high speeds. The cutter is typically a single-point cutting tool that is also secured in the machine, although some operations make use of multi-point tools. The cutting tool feeds into the rotating workpiece and cuts away material in the form of small chips to create the desired shape (Patil &Potdar, 2014).

Moreover, turning is used to produce rotational, typically axis-symmetric, parts that have many features, such as holes, grooves, threads, tapers, various diameter steps, and even contoured surfaces. Parts that are fabricated completely through turning often include components that are used in limited quantities, perhaps for prototypes, such as custom designed shafts and fasteners. Turning is also commonly used as a secondary process to add or refine features on parts that were manufactured using a different process. Due to the high tolerances and surface finishes that turning can offer, it is ideal for adding precision rotational features to a part whose basic shape has already been formed (Yassin & Teo, 2015).

During the turning operation, significant amount of heat is generated at the tool-chip interface due to friction and stresses generated from the shearing of chips. The heat generated at the cutting zone contributes to the tool wear of the cutting tool and has a negative effect on the surface roughness and surface finish (Islam *et al.,* 2017). Chip formation is a machining criterion that is important in order to assess the cutting performance, thus the workpiece cooling is necessary to remove the heat generated during the chip formation by the friction between tool and workpiece (Attanasio *et al.,* 2006). In order to lower the temperatures at the cutting zone, lubricants or cutting fluids are widely used in the manufacturing industry for cooling and lubricating the tool-workpiece interface. To reach the cutting surface is not easy, in fact the high cutting pressure in the contact area and the small space between chip and tool do not allow the cutting fluid to access this zone. In order to obtain a good cooling action, the cutting area is generally flooded by lubricant. Finally, the cutting fluid flow can be used to avoid the chip remaining in the cutting zone, so reducing the possibility of damaging the workpiece. Many application methods have been used in which each application method is selected depending on the advantages that it can give.

Furthermore, the main types of application are:

(i) Hand application which is used only in small batch production and at the same time guarantees a low level of lubrication, cooling and chip removal (Kendall, 1998);

(ii) Flooding, this is the most commonly used application and guarantees a very good level of lubrication, cooling and chip removing; and

(iii) Minimum quantity lubrication (MQL), this application uses a very small lubricant flow (ml/h instead of l/min) and the lubricant is directly sprayed on the cutting area. MQL guarantees a good level of lubrication and the chip removal mechanism is obtained by air flow used to spread the lubricant (Attanasio *et al.*, 2006).

The concept of near dry machining is based on the principle of less lubrication with dry surface after the machining process. MQL is an efficient method of supplying lubrication in machining to achieve both environmental and economic benefits (Hwang and Lee, 2010). Typically, an MQL system supplies 0.3~0.5 ml/min of a metal working fluid (MWF) with pressurized air or other supplemental gases, whereas a conventional system supplies about several thousand ml/min of MWF. The conventional flood supply system demands more resources for operation, maintenance, and disposal, and results in higher environmental and health problems whereas MQL machining has many advantages in this regard (Barua, 2014).

In MQL, it uses an atomiser as an injector in which the energy of compressed gas, usually air is used to atomise the oil. Oil is then conveyed by the air in a low-pressure distribution system to the machining zone.

There are two major delivery methods for MQL - one is an external application and the other is an internal application. In the case of the external application, a mixture of compressed air and oil is fed via an external nozzle to the cutting zone from a chamber. On the other hand, the internal delivery system of MQL is also known as a through-tool application, where the delivery of MQL is made through the spindle.

MQL depends on the lubricant getting to the interface of the cutting tool and the workpiece. In some situations, an external nozzle is sufficient. In others the cutting interface is not easily accessible and it is desirable to apply internal, or thru-the-tool, lubrication. This differentiation is important because the cost and difficulty of fully implementing an internal system is much higher than that of an external. With an external nozzle, the lubricant is applied to the outer surface of the tool. This system is good for open machines, intermittent cutting operations where the tool is not always buried in the work, and on machines that were not made with an internal coolant system (Yassin & Teo, 2015).

Implementing MQL in a turning operation can provide numerous benefits when done properly. When relying on minute amounts of lubricant to reduce friction, proper nozzle placement is critical for ensuring lubricant is applied to the correct spot in the cutting application. In a turning operation, where the cutting tool can be embedded in the workpiece, this can be challenging.

1.2 Statement of the Research Problem

A change in environmental awareness and increasing cost on industrial enterprises have led to a critical consideration of conventional cooling lubricants used in most machining processes. Depending on the workpiece, the production structure, and the production location, the costs related to the use of cooling lubricants accounts for 7 - 17% of the total costs of the manufactured workpiece (Paulo *et al.,* 2007). The most common method of applying cutting fluids in turning process is by flood cooling. However, the usage of flood coolant has several harmful effects, namely environmental pollution if mishandled and high costs associated with flood machining (Huang *et al.* 2018). Thus, it is vital to find a way of manufacturing products using more sustainable techniques, which would minimize the use of cutting fluids and promote a healthy and safe working environment. By abandoning conventional cooling lubricants and using the technologies of dry machining or minimum quantity lubrication (MQL), this cost component can be reduced significantly. Besides an improvement in the efficiency of the production process, such a technology change contributes to the protection of labour (Chen *et al.,* 2000) and the environment (Rossmoore, 1995). The reduction of substantial exposure to cooling lubricants at the work place raises job satisfaction and improves the work result at the same time. Furthermore, an enterprise can use economically-friendly production processes for advertising purposes, which leads to a better image in the market (Goel & Gupta, 2017).

Dry cutting is preferred in the field of environmentally friendly manufacturing but causes high friction force, accelerated tool wear and poor surface finish owing to the absence of lubrication and cooling (Huang *et al.,* 2018). Minimum quantity lubrication (MQL) is suitable for this machining (Jang *et al.,* 2016). MQL involved the application of a very small amount of biodegradable lubricants, which are dispensed into the cutting zone by compressed air flow (Mao *et al.,* 2012). Compared with dry cutting, MQL is found to lower the friction coefficient and cutting temperatures. The reduction in the consumption of cutting fluids and the minimal lubricant residue on the chips, work-piece, and tool holder result in an economical benefit and industrial hygiene (Rahim and Sasahara, 2011).

Analysing and understanding the cutting process mechanisms is a key issue in developing an economical and safe near-dry machining process. Beyond the adoption of minimum quantity lubrication (MQL) technology, the construction of machine tools and their peripheral equipment must also be considered (Weinert *et al.,* 2004). Industrial practitioners will only be willing to accept near-dry machining technology when comprehensive solutions exist. Thus, results for a large variety of workpiece materials and common production methods are essential to prove the superiority of this innovative machining technology (Daniel *et al.,* 1997).

1.3 Aim and Objectives of the Study

This research is aim at designing and developing a minimum quantity lubricant (MQL) delivery system based on injector nozzle and the key variable processes in turning operation.

The objectives are:

i. To design and fabricate MQL device

ii. To carry out performance evaluation of MQL device

1.4 Justification of the Study

The most credible bridging technology is minimum quantity lubrication (MQL). Turning operations can gain benefits from using limited cutting fluid volume. Avoiding sudden temperature reduction as in MQL reduces the chances for thermal cracks, which is predominantly caused by rapid cooling due to the use of flood coolant. However, further investigation still needs to be undertaken before full implementation on the shop floor can be achieved. It installation is low in cost compared to other existing machines. The system is used in order to concentrate small amounts of lubricant onto the cutting interface.

1.5 Scope of the Study

This study is to design and develop minimum quantity lubricant (MQL) delivery system based on injector nozzle. To deliver small amounts of lubricant onto the cutting interface during turning operation and to test the air/oil ratio required for good surface finishing.

1.6 Limitation of the Study

The study is limited at operating at a minimum level of volume of lubricant supplied to the reservoir, since it is used for small jobs.

CHAPTER TWO

2.0 LITETRATURE REVIEW

2.1 Theoretical Fundamentals

2.1.1 Machine tools and operations

Manufacturing is the industrial activity that changes the form of raw materials to create products. The derivation of the word manufacture reflects its original meaning: to make by hand. As the power of the hand tool is limited, manufacturing is done largely by machinery today. Manufacturing technology constitutes all methods used for shaping the raw metal materials into a final product. Manufacturing technology includes plastic forming, casting, welding, and machining technologies. Metals are produced in the form of bars or plates. Casting produces a large variety of components in a single operation by pouring liquid metals into moulds and allowing them to solidify. Parts manufactured by plastic forming, casting, sintering, and moulding are often finished by subsequent machining operations.

Youssef & El-Hofy (2008) defined machining as the removal of the unwanted material (machining allowance) from the workpiece, so as to obtain a finished product of the desired size, shape, and surface quality. The practice of removal of machining allowance through cutting techniques was first adopted using simple handheld tools made from bone, stick, or stone, which were replaced by bronze or iron tools. Water, steam, and later electricity were used to drive such tools in power-driven metal cutting machines (machine tools). The development of new tool materials opened a new era for the machining industry in which machine tool development took place. Non-traditional machining techniques offered alternative methods for machining parts of complex shapes in hard, stronger, and tougher materials that are difficult to cut by traditional methods. Machining technology is usually adopted whenever part accuracy and surface quality are of prime importance. The technology of material removal in machining is carried out on machine tools that are responsible for generating motions required for producing a given part geometry (Youssef &El-Hofy, 2008).

Machine tools are factory equipment used for producing machines, instruments, tools, and all kinds of spare parts. There are many types of machining tools, and they may be used alone or in conjunction with other tools at various steps of the manufacturing process to achieve the intended part geometry. The major categories of machining tools and operations include (Youssef & El-Hofy, 2008):

i. Turning tools: these tools rotate a workpiece on its axis while a cutting tool shapes it to form. Lathes are the most common type of turning equipment.
ii. Drilling tools: this category consists of two-edged rotating devices that create round holes parallel to the axis of rotation.
iii. Milling tools: a milling tool employs a rotating cutting surface with several blades to create non-circular holes or cut unique designs out of the material.
iv. Boring tools: boring is the machining process in which internal diameters are generated in true relation to the centerline of the spindle by means of single-point tools. Boring tools are typically used as finishing equipment to enlarge holes previously cut into the material.
v. Grinding tools: these instruments apply a rotating wheel to achieve a fine finish or to make light cuts on a workpiece
vi. Shaping, planning, and slotting tools: these processes are used for machining horizontal, vertical, and inclined flat and contoured surfaces, slots, grooves, and other recesses by means of special single-point tools. The difference between

these three processes is that in planning, the work is reciprocated and the tool is fed across the work, while in shaping and slotting, the tool is reciprocating and the work is fed across the cutting tool. Moreover, the tool travel is horizontal in shaping and planning and vertical in case of slotting. The essence of these processes is the same as of turning, where metals are removed by single point tools similar in shape to lathe tools. A similarity also exists in chip formation. However, these operations differ from turning in that the cutting action is intermittent, and chips are removed only during the forward movement of the tool or the work.

vii. Broaching tools: broaching is a cutting process using a multi-toothed tool (broach) having successive cutting edges, each protruding to a greater distance than the proceeding one in the direction perpendicular to the broach length. In contrast to all other cutting processes, there is no feeding of the broach or the workpiece. The feed is built into the broach itself through the consecutive protruding of its teeth. Therefore, no complex motion of the tool relative to the workpiece is required, where the tool is moved past the workpiece with a rectilinear motion.

2.1.2 Turning operation

Turning is one of the machining processes in which tool is fixed in tool holder and it require feed in linear motion to cut the metal and in other end workpieces is in rotating motion (Goel & Gupta, 2017). The turning processes are archetypally supported out on a lathe, painstaking to be the hoariest machine tools, and can be of four different types such as profiling, straight turning, external grooving or taper turning as illustrated in Figure 2.1. Those categories of turning processes can produce various shapes of materials such as straight, conical, curved, or grooved workpiece (Goel & Gupta, 2017). In general, turning uses simple single-point cutting tools. Each group of workpiece materials has an optimum set of tools angles which have been developed through the years. Turning is performed at various (1) rotational speeds, N, of the workpiece clamped in a spindle, (2) depths of cut, d, and (3) feeds rate, f (which is the movement of the tool cutting edge in millimetres per revolution of the workpiece (mm/rev)) as shown in Figure 2.2, depending on the workpiece materials, cutting-tool materials, surface finish and dimensional accuracy required, and characteristics of the machine tool (Youssef and El-Hofy, 2008).

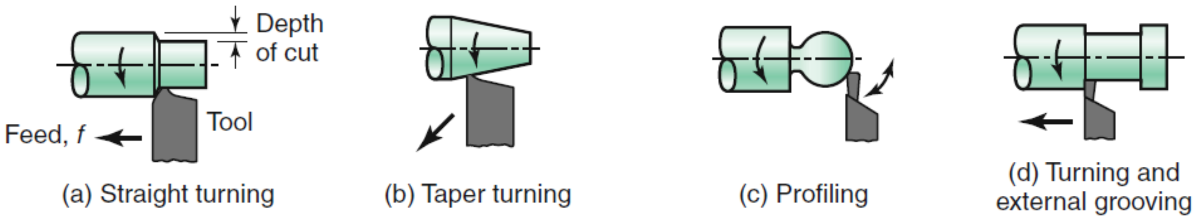

Figure 2.1: Basis turning operation performed on a lathe (Youssef and El-Hofy, 2008)

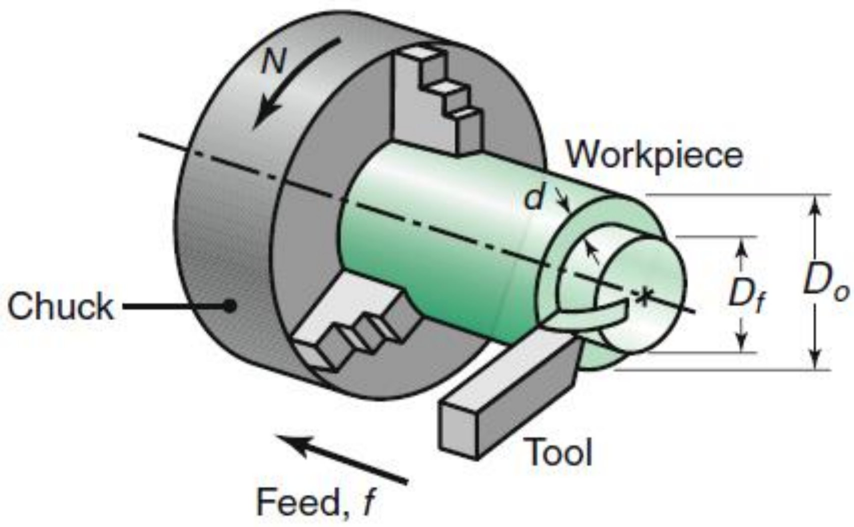

Figure 2.2: Schematic illustration of the basic turning operation, showing depth of cut, d; feed, f; and spindle rotational speed, N, in rev/min (Youssef and El-Hofy, 2008).

The basic machining parameters in turning that are mathematically related as expressed as follows (Youssef & El-Hofy, 2008):

Cutting speed (v)

$v = \pi D_o N$ m/min (maximum speed) (2.1)

where D_0 is initial diameter of the workpiece (mm)

N is rotational speed of the workpiece (rpm)

D_{avg} is Average diameter of workpiece, mm or inches = $\frac{D_o + D_f}{2}$

Rotational speed (spindle) (N)

$$N = \frac{v}{\pi D_0} \text{ rpm} \tag{2.2}$$

Feed *f*, which is the movement of the tool cutting edge in millimetres per revolution of the workpiece (mm/rev). Feed rate, *r* or linear speed of the tool along workpiece length, mm/min or inches/min

$$r = fN \tag{2.3}$$

Depth of cut d , which is measured in a direction perpendicular to the workpiece axis, for one turning pass.

$$d = \frac{D_0 - D_f}{2} \text{ mm} \tag{2.4}$$

where D_f , is the diameter of the machined surface.

The material-removal rate (MRR) in turning is the volume of material removed per unit time, with the units of mm^3/min or in^3/min. For each revolution of the workpiece, a ring-shaped layer of material is removed which has a cross-sectional area that equals the product of the distance the tool travels in one revolution (feed, *f*) and the depth of cut, *d*.

The volume of this ring is the product of the cross-sectional area (f) (d) and the average circumference of the ring, πD_{avg} where

$$\pi D_{avg} = \frac{D_o + D_f}{2} \tag{2.5}$$

The material removal rate per revolution is $(\pi)(d)(D_{avg})(f)$ Since there are N revolutions per minute, the removal rate is:

$$\text{MRR} = \pi D_{avg} dfN \tag{2.6}$$

The dimensional accuracy of this equation can be checked by substituting dimensions into the right-hand side. For instance, $(\text{mm})(\text{mm})(\text{mm/rev})(\text{rev/mm}) = \text{mm}^3/\text{min}$ which indicates volume rate of removal. Equation 2.6 also can be written as:

$$\text{MRR} = dfv \tag{2.7}$$

where v is the cutting speed and MRR has the same unit of mm^3/min.

The cutting time, t, for a workpiece of length l can be calculated by noting that the tool travels at a feed rate of $fN = (\text{mm/rev})(\text{rev/mm}) = \text{mm/min}$ Since the distance traveled is l mm, the cutting time is:

$$t = \frac{l}{fN} \tag{2.8}$$

The cutting time in equation 2.8 does not include the time required for tool approach and retraction. Because the time spent in noncutting cycles of a machining operation is unproductive and adversely affects the overall economics, the time involved in approaching and retracting tools to and from the workpiece is an important consideration (Youssef & El-Hofy, 2008).

2.1.3 Cutting fluids and applications

The process of machining involves a shearing mechanism to transform a workpiece to an end shape. This fundamental mechanism creates a high friction load between the cutting tool and the workpiece, which significantly increases the cutting temperature. In addition, friction dissipates energy thus generating heat, which if it is not properly controlled might have a detrimental effect on the cutting tool and machined component. Control of the heat generated can be achieved by reducing cutting temperature and friction. Cutting temperature has a positive and negative impact. A higher cutting temperature would be necessary, to some extent, to make the deformation process occur easily; as in hot machining processes. On the other hand, it generates excessive heat, which will affect tool life and in some cases the surface integrity of components (Mulyadi, 2013).

Many metallic and non-metallic materials can be machined without a cutting fluid, but in most cases the application of a cutting fluid can improve the operation significantly. Cutting fluids typically perform numerous functions simultaneously, including cooling and lubricating the tool-workpiece and tool-chip interfaces, minimizing the effect of built-up edge (BUE), protecting the workpiece from corrosion, and flushing away chips (Hasan& Dwivedi, 2014). However, a good cutting fluid must serve two important basic functions, namely cooling and lubrication (Sapian, 2012).

Depending on the type of machining operation, the cutting fluid needed may be a coolant, a lubricant, or both. The effectiveness of cutting fluids depends on a number of factors, such as the type of machining operation, tool and workpiece materials, cutting speed, and the method of application. Water is an excellent coolant and can effectively reduce the high temperatures developed in the cutting zone. However, water is not an effective lubricant; hence, it does not reduce friction. Furthermore, it can cause oxidation (rusting) of workpieces and machine-tool components. The need for a cutting fluid depends on the severity of the particular machining operation, which may be defined as the level of temperatures and forces encountered and the ability of the tool materials to withstand them, the tendency for built-up edge (BUE) formation, the ease with which chips produced can be removed from the cutting zone, and how effectively the fluids can be applied to the proper region at the tool–chip interface. The relative severities of specific machining processes, in increasing order of severity, are as follows: sawing, turning, milling, drilling, gear cutting, thread cutting, tapping, and internal broaching (Kalpakjian & Schmid, 2010).

As coolant, by flowing over the tool, chip and workpiece, a cutting fluid can remove heat and thus reduce temperature in the cutting zone. In order for a cutting fluid to function effectively as a coolant, two requirements must be met. The cutting fluid must gain an access to the source of heat, and the fluid must have the thermal capability of removing the heat. The properties of a cutting fluid which determine its ability to cool are its thermal conductivity, specific heat, heat of vaporization, and wet ability with metal surface (Sapian, 2012). Water fulfils this requirement and has the additional advantage of being inexpensive, but it is a poor lubricant and therefore is not effective in reducing friction between chip and tool face. In addition, it is corrosive to ferrous metals and so cannot be tolerated in high end machine tools. Moreover, it tends to wash the lubricating oil from the sliding and rotating the surfaces of the machine, thus reducing the smoothness of running and increasing wear (Baradie, 1996). Generally, a reduction in temperature results in a decrease in wear rate and an increase in tool life. This occurs because, first, the tool material is harder and so more resistant to abrasive wear at lower temperatures, and secondly, the diffusion rate of constituents in the tool material is less at lower temperatures (Baradie, 1996). Opposing these two effects, a reduction in the temperature of the workpiece will increase its shear flow stress, so that the cutting force and power consumption may be increased to some extent. Under certain conditions this can lead to a decrease in tool life. Particularly, to clarify the condition of decreasing in tool life, the cooling effect is important in reducing thermal expansion and distortion of the workpiece. The cooling action does not have a very significant effect on the surface finish produced. It can, however, bring about some small improvements in the surface finished at medium to low speeds. This is probably due to the chip formation which increase chip curl and reduce built-up edge formation (Sapian, 2012).

On the other hand, lubrication, as defined in most theories, considers two sliding surfaces, and it depends on the ability of the fluid to penetrate the interfaces of the cutting zone. If the lubricant can penetrate into the chip tool contact area, it will reduce the contact length and decrease the forces, heat generation, temperatures and tool wear. Its ability to improve surface finish is attributed to the fact that it can lubricate the rake face and avoid formation of built-up edge (BUE), by minimizing adherence. If the lubricant cannot penetrate the entire contact length it could at least lubricate part of the contact where there is no strong adherence (the sliding zone) reducing the shear stress distribution on the rake face, reducing the energy, as well as temperature.

There are operations, however, in which the cooling action of cutting fluids can be detrimental. It has been shown that cutting fluids may cause the chip to become curlier and thus concentrate the heat closer to the tool tip, reducing tool life. More importantly, in interrupted cutting operations, such as milling with multiple tooth cutters, cooling of the cutting zone leads to thermal cycling of the cutter teeth, which can cause thermal cracks by thermal fatigue or thermal shock. However, beginning with the mid-1990s, there has been a major trend toward near-dry machining, meaning a minimal use of cutting fluids, as well as toward dry machining (Kalpakjian and Schmid, 2010).

2.1.4 Types of cutting fluids

There are generally four types of cutting fluids commonly used in machining operations (Kalpakjian & Schmid, 2010):

i. **Oils** (also called straight oils), including mineral, animal, vegetable, compounded, and synthetic oils, typically are used for low-speed operations where temperature rise is not significant.

ii. **Emulsions** (also called soluble oils), a mixture of oil and water and additives, generally are used for high-speed operations because the temperature rise is significant. The presence of water makes emulsions highly effective coolants. The presence of oil reduces or eliminates the tendency of water to cause oxidation.

iii. **Semi - synthetics** are chemical emulsions containing little mineral oil, diluted in water, and with additives that reduce the size of oil particles, making them more effective.

iv. **Synthetics** are chemicals with additives, diluted in water, and containing no oil.

Because of the complex interactions among the cutting fluid, the workpiece materials, temperature, time, and cutting-process variables, the application of fluids cannot be generalized.

2.1.5 Methods of cutting-fluid application

The main types of cutting fluid application processes are:

2.1.5.1 Hand application

This is used only in small batch production and at the same time guarantees a low level of lubrication, cooling and chip removal (Kendall, 1998).

2.1.5.2 Flooding

This is the most common method with flow rates typically range from 10 L/min (3 gal/min) for single-point tools to 225 l/min (60 gal/min) per cutter for multiple-tooth cutters, as in milling. In some operations, such as drilling and milling, fluid pressures in the range from 700 to 14,000 kPa (100 to 2000 psi) are used to flush away the chips produced, to prevent interfering with the operation (Huang *et al.*, 2018).

Cutting fluids generally in flooded application are employed in machining to reduce friction, cool the tool and work piece and to wash away the chips from cutting area. Their application minimises the tool wear and improves the surface integrity of machined surface. These also minimise the cutting forces thus decrease power consumptions thereby saving precious energy (Ezugwu *et al.*, 2003). When used effectively, cutting fluids remove the extra heat from cutting area generated in machining operation resulting in only longer tool life along with achieving close dimensional control (Ezugwu, 2005). However, the usage of flood coolant has several harmful effects, namely environmental pollution if mishandled and high costs associated with flood machining (Huang *et al.*, 2018).

2.1.5.3 Dry machining

In the recent past lots of efforts have been made to do away the use of cutting fluid or use minimal amount of cutting fluid. When no cutting fluid is used during machining, it is referred to as dry machining. The dry cutting (DC) is always preferred in the era of environment friendly machining, which involves higher cutting forces, higher power and requires special cutting tools like PCBN, PCD and ceramic, etc. along with prudent design of tool geometry (generally negative rake tools, honed and chamfered edges are used). But DC is not always feasible as there are materials, which are sticky in nature like nickel-chromium and titanium base alloys and stainless steel, etc., these materials when machined dry tend to stick to tool surface leading to tool failure and poor surface finish on machined surface. Conventionally, these sticky materials are machined under flooded coolant conditions, which involves higher manufacturing cost on one hand and poses serious environmental and health hazards on the other hand (Adler *et al.*, 2006). In such cases, it is not altogether possible to do away with the use of cutting fluids but attempts can be made to minimise their use. It is here machining with minimum-quantity lubrication (MQL) finds its application (Singh *et al.*, 2016).

2.1.5.4 Near-dry machining (NDM)

For economic and environmental reasons, there has been a continuing worldwide trend since the mid-1990s to minimize or eliminate the use of metalworking fluids. This trend has led to the practice of near-dry machining (NDM), with major benefits such as alleviating the environmental impact of using cutting fluids, improving air quality in manufacturing plants, and reducing health hazards; reducing the cost of machining operations, including the cost of maintenance, recycling, and disposal of cutting fluids; and further improving surface quality. When a minimal amount of cutting fluid is used during machining, it is referred as near dry machining (NDM) with minimum quantity lubrication (MQL) (Singh *et al.*, 2016).

2.1.6 Minimum Quantity Lubrication (MQL)

The concept of minimum quantity lubricant (MQL), sometimes referred to as near dry machining (NDM) refers to the use of a small amount of cutting fluid, typically in the order of 100 ml/hr or less, which is about ten-thousandth of the amount of cutting fluid used in flood-cooling machining (Singh *et al.*, 2016). The concept of near dry machining is based on the principle of less lubrication with dry surface after the machining process. MQL is an efficient method of supplying lubrication in machining to achieve both environmental and economic benefits (Hwang and Lee, 2010). Typically, an MQL system supplies 0.3~0.5 ml/min of a metal working fluid (MWF) with pressurized air or other supplemental gases, whereas a conventional system supplies about several thousand of ml/min of MWF. The conventional flood supply system demands more resources for operation, maintenance, and disposal, and results in higher environmental and health problems whereas MQL machining has many advantages in this regard (Barua, 2014).

The best machining option is always: dry machining which eliminates adverse effect of flooded cooling including environmental and health hazards. However, under certain machining application when dry cutting is not feasible, compressed air may be used for direct cooling. Although, air is less effective for cooling than a liquid coolant, but it also does not thermally shock hot tools like a liquid coolant. Moreover, pressurised air supply in cutting zone removes cut chips. Air absorbs sensible heat only, thus heat carrying capacity is limited. The heat removal capacity of air blast can be improved by mixing lubricant into it in tiny amounts which is directed in the cutting area in mist form using nozzles having the benefit of greater access to tool-work-chip interface under air pressure. This aerosol when comes in contact with red hot areas in the cutting zone absorbs its latent heat and vaporises, thereby improves heat removal from cutting zone. Whereas in flooded cooling, metal working fluids (MWFs) are not able to penetrate into the tool-chip and tool-workpiece contact surfaces even when supplied at high pressure (Singh *et al.*, 2016).

In MQL system, a lubricant instead of coolant is employed and that too in tiny amounts. Whereas in flooded system coolant floods the cutting zone to cool things down, MQL applies a coating of thin film of lubricant at tool-chip-work interface to transfer the heat of friction in the cutting zone effectively into cut chips. Lubrication of interfaces and transfer of heat into chips relatively cools the cutting thereby reducing tool wear (Singh *et al.,* 2016). The friction and heat in the interface vaporise the small amount of lubricant and leaves cutting tools, parts, equipment, and floors dry and clean. The swarf or chips from cutting with MQL are virtually dry and can be recycled without cleaning thus reducing overall machining cost. With MQL, parts often do not require any cleaning prior to secondary operations. Because the lubricant is consumed, there is no disposal required and no extra equipment is necessary for fluid reclamation. Many MQL lubricants are essentially highly refined bio-based (plant) oils and are completely safe for skin contact as well as having the extra benefit of coming from renewable, environmentally-friendly material (Astakhov, 2012).

In MQL, the cooling/lubricating medium is supplied as a mixture of air and an oil in the form of an aerosol (often referred to as a mist). An aerosol is a gaseous suspension (hanging) in air of solid or liquid particles. Aerosols are generated using a process called atomisation. An atomiser is an injector in which the energy of compressed gas, usually air is used to atomise the oil. Oil is then conveyed by the air in a low-pressure distribution system to the machining zone (Astakhov, 2012).

2.1.6.1 Types of MQL supply systems

Aerosol in MQL system can be supplied in the cutting zone either externally through a set of nozzles fitted separately in the machine area or by supplying aerosol internally via channels built into the tool (Singh *et al.*, 2016). The selection between external and internal supply channel is made based on application. Based on selected literature (Boubekri *et al.*, 2010) a summary of different types of MQL delivery systems has been presented in Figure 2.3.

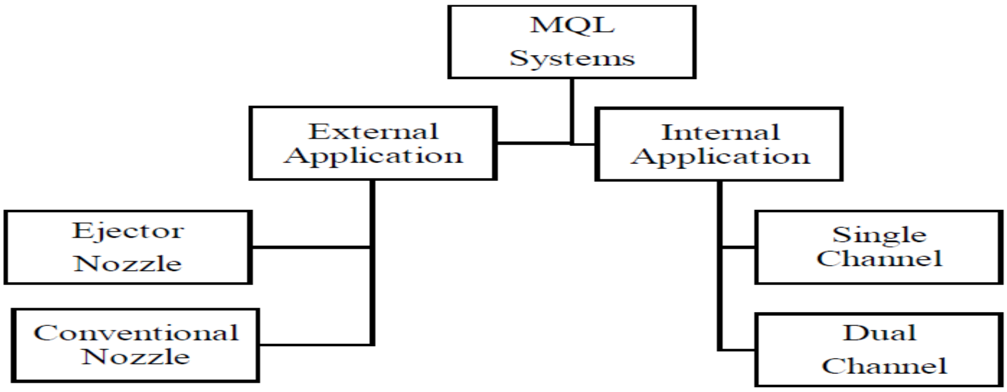

Figure 2.3: MQL supply systems (Source: Boubekri *et al.*, 2010)

There are two major delivery methods for MQL - one is an external application and the other is an internal application.

2.1.6.2 MQL external application process

The applications involving external supply, the aerosol is sprayed onto the tool from outside via one or more nozzles shown in Figure 2.4. The number and direction of the nozzles in conjunction with the spray pattern, which depends on the nozzle arrangement, play an important role in the final surface quality of machined surface. This technique finds application in operations: sawing, end and face milling, and turning. In the case of machining operations, such as drilling, reaming, or tapping, external supply of the medium is appropriate only up to length/diameter ratios of $l/d < 3$. When the l/d ratio is larger than this, the tool may have to be withdrawn several times so that it can be wetted again, resulting in a considerable increase in the overall machining time. The external supply of aerosol is not suitable during machining operations requiring the use of multiple tools with widely varying lengths and diameters. But this system is critical, when the tools involved in the operation do not have any internal cooling channels (Singh *et al.,* 2016).

In the case of the external application, there are two possible methods for the external application of oil and air or aerosol namely:

i. Injector nozzle: The compressed air and oil are supplied to the injector separately and mixing occurs just after the nozzle shown in Figure 2.4. In other words, the nozzle itself serves as the atomizer and thus the means of controlling air/oil concentration ratios are provided by the nozzle design. One possible design for an injector nozzle is shown in Figure 2.5. As can be seen, it has two air passages. The first one is external and creates the airenvelope that served as the mixing chamber. The second one provides the atomizing air supply. The oil to be atomized is supplied through the central passage.

ii. Conventional nozzle: The aerosol is prepared in an external atomizer and then transported to a conventional nozzle shown in Figure 2.4.

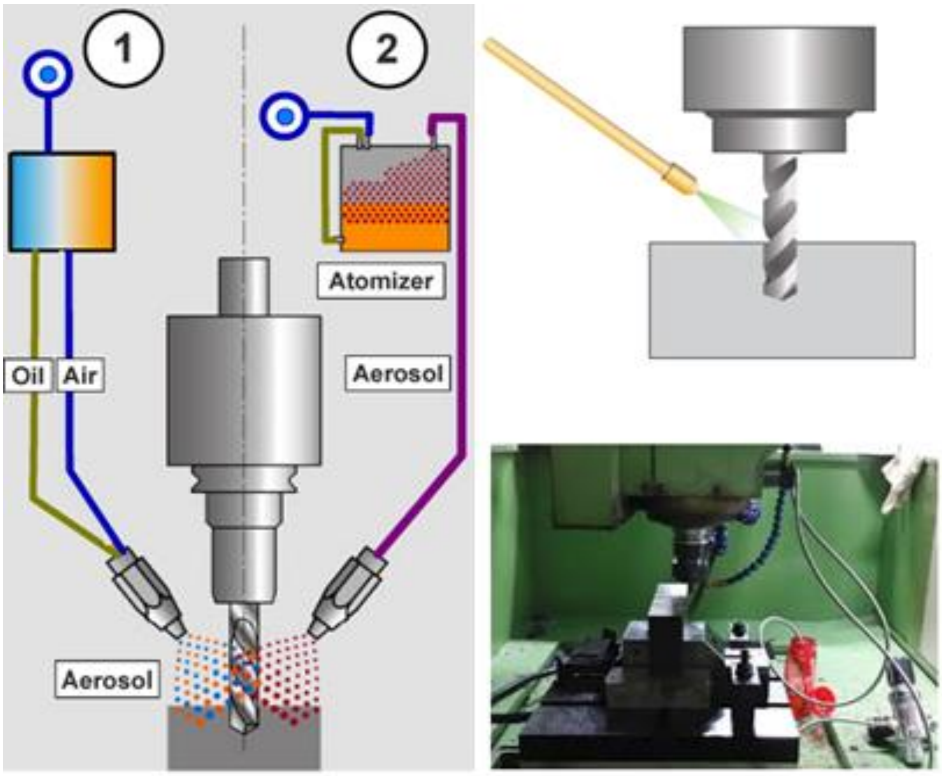

Figure 2.4: The principles of injector nozzle and conventional nozzle in MQL external applications as illustrated (Source: Astakhov, 2012)

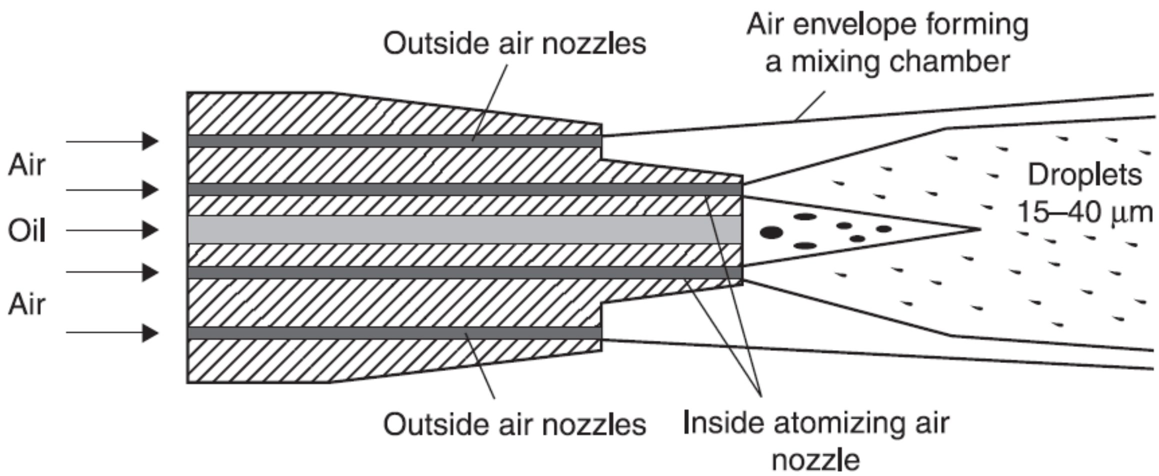

Figure 2.5: Nozzle design for MQL with injector nozzle (Source: Astakhov, 2012)

MQL with injector nozzle is probably the cheapest and simplest method. The parameters of the aerosol can be adjusted over a wide range in terms of droplet size and oil flow rate by setting the appropriate air and oil flow rates and by adjusting the pressure in the oil reservoir. Moreover, such a device prevents oil spills as it shuts down the oil supply line when the air supply is not available (Astakhov, 2012). In reality, however, adjustments are not that simple. If no special precautions are taken, the unit generates a dense mist that covers everything in the workshop, including the operator's lungs. To prevent this from happening and to gain the full control on the parameters of aerosol, one needs to have a hydraulic unit similar to that shown in Figure 2.6.

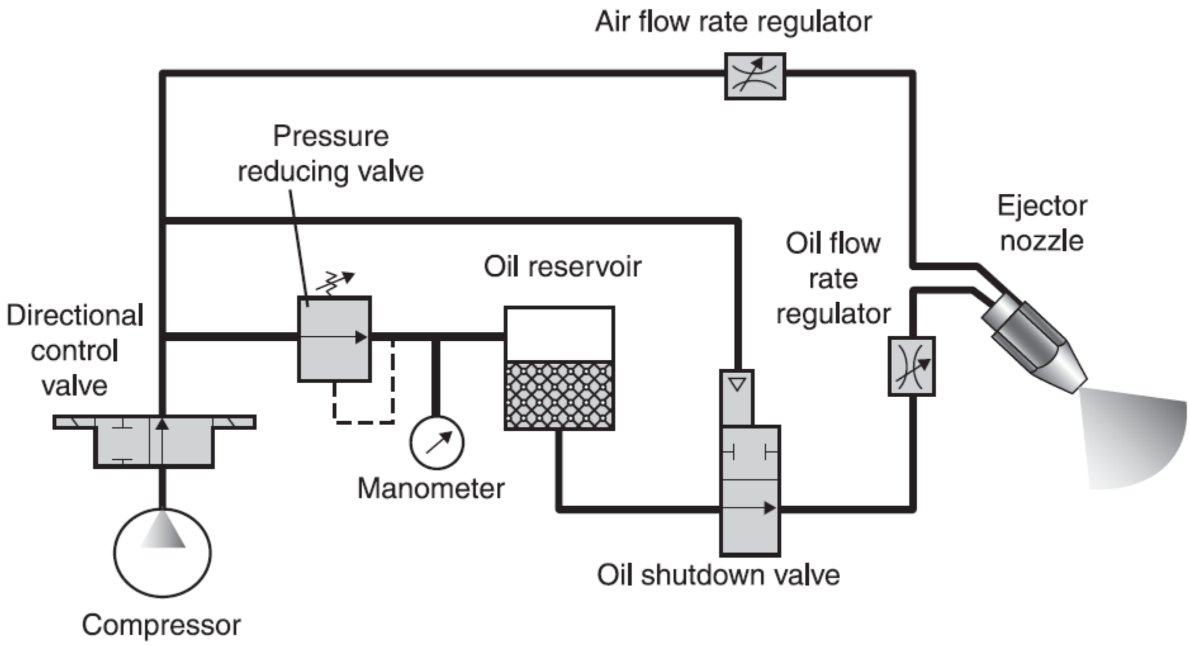

Figure 2.6: Aerosol control unit (Astakhov, 2012)

The important technologies that are widely used in external feed system are devices with metering pumps, devices with pressure tank and targeted bombardment with oil droplets.

i. Devices with metering pumps: In this device the lubricant is transported by a pneumatic micro-pump. Lubricant dosage is regulated by means of the stroke and frequency of the pump plunger. The key advantages of the micro-pump system are the exact dosage volume settings and modular design, which, in addition to the decentral assembly of the pump elements, makes it possible to install nearly any number of pump elements (Madhukar *et al.,* 2016).

ii. Devices with pressure tank: In this device the lubricant tank is pressurized. Lubricant is forced out of the tank with pressure. Metering is done with supply pressure settings and with throttle elements in the pipework for air and oil atomization. To guarantee optimum use of these systems, it should be possible to adjust tank pressure, atomization air, and oil quantity separately (Madhukar *et al.,* 2016).

iii. Targeted bombardment with oil droplets: This type device shoots single droplets of lubricant at the machining contact point via a high-speed valve. There can be a distance of up to 800 mm between valve and tool without air mixing in or atomization taking place. This metering principle makes it to break through the boundary-layer air that builds up during the turning movement.

iv. MQL external application process is characterized with several benefits such as inexpensive and simple retrofitting of the existing machines; the same cutting tools used for flood metal working fluids will work; easy to use and maintain equipment; the NDM equipment can be moved from one machine to another; and relative flexibility of the device as the position of nozzle relative to the machining zone can be adjusted for the convenience of operator. As such, the parameters of the aerosol do not depend on the particular nozzle location. However, this process is without drawbacks such as the device does not work well with drills and boring tools, as an aerosol cannot penetrate into the hole being machined and thus cannot provide any help in the cooling and lubrication of the machining zone and removing chip from the hole being machined (Madhukar *et al.,* 2016).

2.1.6.3 MQL internal application process

On the other hand, the internal delivery system of MQL is also known as a through-tool application, where the delivery of MQL is made through the spindle. The internal supply of aerosol through spindle and tool finds applications in drilling, reaming, and tapping operations with larger l/d ratios, ensuring the supply close to the cutting edge, regardless of the tool position. This system is also applicable for tools with very different dimensions. In deep hole drilling operations, the large l/d ratio makes an internal aerosol supply indispensable. Internal supply of aerosol eliminates the errors associated with incorrect nozzle positioning, and frees machine area of piping system. The internal supply system may be: 1-channel and 2-channel systems as shown in Figure 2.7 and 2.8 (Weinert *et al.,* 2004). In 1-channel system, the aerosol mixture is formed outside the spindle, and the single channel acts as a feed route for the mixture. In 2-channel systems, oil and air are fed separately through the spindle. The air-oil mix is then produced directly ahead of the tool. Both the systems, however, ensure sufficient availability aerosol in cutting zone (Singh *et al.,* 2016).

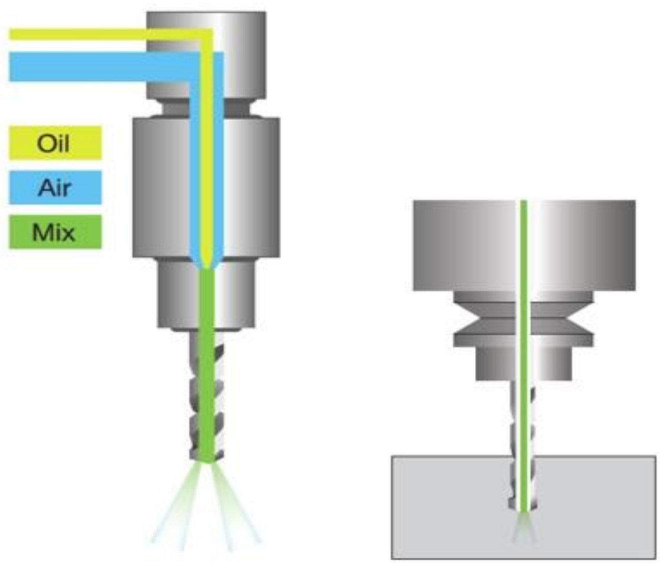

Figure 2.7: Internal application (Source: Walker, 2013)

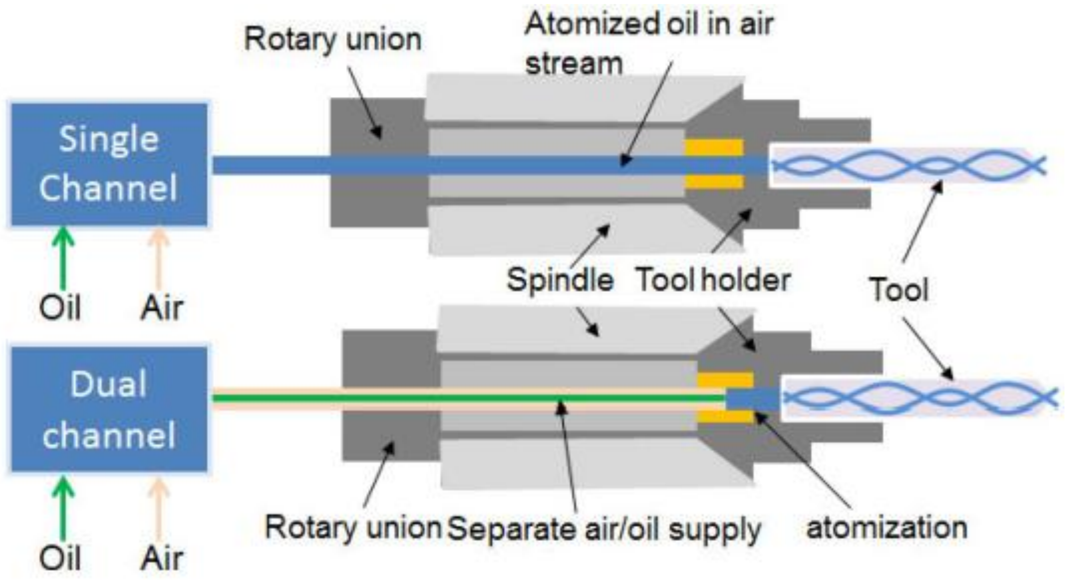

Figure 2.8: The principles of single channel and dual channel in MQL internal applications (Source: Walker, 2013)

i. Single-channel: The oil and compressed air are mixed before being supplied through the cutting tool to the workpiece/tool zone.

ii. Dual-channel: The oil and compressed air are delivered in different channels and are only mixed before the holder of the cutting tool i.e. the lubricant and air are carried separately and mixed at the point of application.

Single-channel systems have only one hose with no separate structure to carry the fluid. Dual-channel hoses have separate paths for the air and oil or may be two tubes side by side or one tube inside of another (coaxial) shown in Figure 2.9 (Walker, 2013).

Figure 2.9: Coaxial and single-line hose (Source: Walker, 2013)

MQL depends on the lubricant getting to the interface of the cutting tool and the work piece. In some situations, an external nozzle is sufficient. In others the cutting interface is not easily accessible and it is desirable to apply internal, or thru-the-tool, lubrication. This differentiation is important because the cost and difficulty of fully implementing an internal system is much higher than that of an external. With an external nozzle, the lubricant is applied to the outer surface of the tool. This system is good for open machines, intermittent cutting operations where the tool is not always buried in the work, and on machines that were not made with an internal coolant system (Huang *et al.,* 2018).

2.1.7 Cutting Fluids for MQL

The cutting fluids are basically of two types: oil-based cutting fluids and chemical cutting fluids. Oil-based cutting fluids comprise of: straight oil, soluble oil, whereas chemical cutting fluids can be further categorised as synthetic and semi synthetic cutting fluids. Straight oils are non-emulsifiable and are used in an undiluted form. These comprise of a base mineral or petroleum oil and additives such as fats, vegetable oils and esters, or extreme pressure additives such as chlorine, sulphur and phosphorus. Straight oils provide the best lubrication and the poorest cooling characteristics among cutting fluids. Synthetic fluids contain no petroleum or mineral oil base and instead are formulated from alkaline inorganic and organic compounds along with additives for suppressing of corrosion phenomenon. They cannot be used in pure form, but used in a diluted form (concentration = 3 to 10%) (Dixit *et al.,* 2012).

For best cooling under extreme cutting conditions, synthetic fluids preferred as these provide best cooling among all cutting fluids. Soluble oil cutting fluids are used in emulsification with water. These comprise of a base mineral oil and emulsifier to help produce a stable emulsion. They are used in a diluted form and provide good lubrication and heat transfer performance. They are widely used in industry and are the least expensive among all cutting fluids. Semi-synthetic fluids are essentially combination of synthetic and soluble oil fluids and have characteristics common to both types. The cost and heat transfer performance of semi-synthetic fluids lies between those of synthetic and soluble oil fluids. Extremely cold (cryogenic) fluids (often in the form of gases) like liquid CO_2 or N_2 are used in some special cases for effective cooling without creating much environmental pollution and health hazards. The selection of cutting fluid depends on parameters such as work piece material and nature of machining process (Sluhan, 1994). For instance, cutting fluids containing sulphur and chlorine additives should not be used with nickel-based alloys and titanium, respectively. Cutting fluids with high lubricity ability are generally used in low-speed machining such as screw cutting, broaching and gear cutting and on difficult-to-cut materials, whereas cutting fluids with high cooling ability are generally used in high-speed machining. Generally, cutting fluids are employed in liquid form but occasionally also employed in gaseous form.

The selection of cutting fluids for a machining application is mainly based on two factors (Baradie, 1996): (i) type of machining processes, (ii) type of machined work piece material apart from other factors like: fluid cost, environmental impact and health hazards. In turning, milling and grinding, water-based cutting fluids are more commonly used due to material being hard involving higher cutting speeds and feeds thereby minimising contact period between cutting tool and work piece material small. The applications of synthetic cutting fluids are possible in drilling and broaching operations (Ebbrell *et al.,* 2000). Water-based cutting fluids reduce heat generation in the cutting zone and its effect on cutting tool wear. For grinding, some emulsion oils and chemical cutting fluids are prepared specially having concentration between 1:25 and 1:60 with water. Material removal rate in grinding is higher when higher concentration (2.5% to 10%) cutting fluids are used. This would also provide a better surface finish quality. Moreover, the required grinding power would decrease (Ebbrell *et al.*, 2000). Grinding which is predominantly carried out under flood cooling, the potential of MQL in grinding is being explored by various researchers. MQL grinding of 100Cr6 hardened steel and AISI 4140 hardened steel in comparison to dry grinding significantly enhances grinding performance in terms of improving surface quality of the groundwork piece and reducing grinding temperature and forces (Mao *et al.*, 2012). Synthetic ester oil is a better cutting fluid in grinding of Ti-6Al-4V titanium alloy under MQL conditions (Sadeghi *et al.*, 2009). Drilling with under MQL can be carried out externally only in the cases where the surface quality of the holes can be compromised, but for best results, the internally allied MQL is the most suitable technique.

The selection of cutting fluid is also based on work piece material (Baradie, 1996). For machining of steel, cutting fluids with some additive are used at high pressure and for stainless steel, high pressure cutting oils are generally selected. Work-hardening properties in some steels may cause some problems during machining operation. For machining of heat resistant and difficult-to-cut steel alloys, water-based cutting fluids are preferred, due to higher cutting zone temperature. The concentration for water-based cutting fluids lies between 1:20 to 1:40. However, sulphur added mineral cutting oils can also be used in such applications (Ebbrell *et al.*, 2000). During MQL milling, the tool life as well as the cutting force values can be improved by using vegetable oil, especially in machining of Inconel 718.

In machining of nickel and chromium base alloys, generally sulphured mineral oil is the preferred cutting fluid. In machining of the difficult-to-cut materials such as titanium alloys, generally machined at higher cutting speeds, high temperature becomes an influential factor for selection of cutting fluid. The selected cutting fluid must have both cooling and lubricating characteristics. The cooling factor is more important in machining of titanium alloys due to high heat generation during machining operation. It is observed that lubrication properties of selected cutting fluids are preferred when low cutting speeds are selected. Emulsion oil can be selected in the machining of titanium alloys when low cutting speeds are used; chlorine additive cutting oils are preferred when higher cutting speed are used (Ezugwu *et al.*, 2003). With the environmental factor in mind, the synthetic esters could well be replaced by palm oil, thus the cost reduction could be made possible as well, while drilling Inconel and titanium alloys. Machining under MQL shows significant reduction in maintenance and cleaning work and better surface quality during turning and milling of high strength material like tool steel, aluminium, forged alloys and Cr-Ni steels. Likewise, during the machining of magnesium and its alloys, MQL led to a lowered adhesion rate and built up edge formation (Bhowmick & Alpas, 2011), thus resulting in a better surface quality and tool Life.

2.2 Review of Past Work

AISI-1040 steel under different speed-feed combinations was investigated by Dhar *et al.* (2006). Fratila and Caizar (2012) investigated the influence of process parameters and cooling/lubrication method during finish turning of AISI 1045 steel on tool performance and surface quality of machined surface. Tests were performed in dry conditions (DC), using the minimal quantity lubrication (MQL) conditions, and also in flood coolant (FC) conditions, using carbide inserts. Numerical and graphical optimisations show that the minimal level of depth of cut, the maximum cutting speed, and the maximum lubricant flow rate resulted in a better quality of machined surface. Dhar *et al.*(2006) investigated the role of MQL on tool wear and surface roughness in turning AISI-4340 steel with uncoated carbide inserts. The results indicated a reduction in tool wear rate and surface roughness under MQL environment, mainly through reduction in the cutting zone temperature and favourable change in the chip-tool and work-tool interaction.

Hadad and Sadeghi (2013) presented a new method to calculate average temperatures and the heat partition to the tool, work piece and chip during MQL turning of AISI 4140 steel. It was observed that if the oil mist be supplied only to rake face, the tool temperature could be reduced by 200°C lower than that achieved under dry turning. The results were compared with dry machining and machining with soluble oil as coolant. The experimental results indicated that MQL enables substantial reduction in the cutting zone temperature, dimensional inaccuracy depending upon the levels of the cutting velocity and feed rate. It was also observed that the chip formation and chip-tool interaction become more favourable under MQL conditions.

The effect of cutting speed, feed rate and different amount of MQL on machining performance during turning of brass using K10 cemented carbide tools was investigated by Gaitonde *et al.* (2012). It was revealed that amount of lubricant has no impact on surface finish of machined surface; however, it increases sharply with increase in feed rate.

Davim *et al.* (2007) investigated turning performance of brasses with different amounts of MQL. Various parameters studied include the feed rate, cutting power, specific cutting power, and surface roughness. Results of the study suggest that with proper selection of the MQL system, results similar to flooded lubricant conditions can be achieved. The effect of different lubricant environments during machining of aluminium alloy 6061 with diamond-coated carbide tools was investigated by Sreejith (2008). Machining performance under dry machining, MQL, and flooded coolant conditions was analysed with respect to the cutting forces, surface roughness of the machined work-piece and tool wear. It was observed that MQL conditions provide a very good alternative to flooded coolant/lubricant conditions, in addition to improving the machinability characteristics.

Yazid *et al.* (2011) experimentally investigated the effect of cutting parameters and machining conditions on surface integrity in finish turning of Inconel 718 under three cutting conditions (dry, MQL 50 ml/h and MQL 100 ml/h) and observed that MQL possibly improve surface integrity of machined surfaces. Kamata and Obikawa (2007) applied MQL in finish-turning of Inconel 718, with super lattice (PVD) and Ti/AlN (PVD) and TiCN/Al_2O_3/TiN coatings. It was observed that carbide tools coated with TiN/AlN gives best performance under MQL.

Arunachalam *et al.* (2004) examined the residual stresses and surface integrity of components when machining (facing) age hardened Inconel 718 using two grades of coated carbide cutting tools specifically developed for machining heat resistant super alloys (HRSA). This investigation, suggested that coated carbide cutting tool inserts of round shape, chamfered cutting edge preparation, negative type and small nose radius (0.8 mm) and coolant generate primarily compressive residual stresses.

Rahman *et al.* (1997) examined the effect of cutting conditions on the machinability of Inconel 718. Various combinations of side cutting edge angles (SCEAs), cutting speeds and feed rates were tested at a constant depth of cut. Cutting results indicate that SCEA, together with cutting speed and feed rate, do play a significant role in increasing the tool life of an insert.

Costes *et al*. (2007) investigated wear mechanisms on the rake and flank faces of different tool grades during finish machining of Inconel 718. It was found that a low CBN content tool with a ceramic binder and small grains gives the best results.

Thakur *et al.* (2013) during investigation of machinability characteristics of Inconel 718 under dry and MQL conditions with respect to cutting forces, surface roughness and tool wear using K20 tungsten carbide cutting tool, observed that machining of Inconel 718 under MQL conditions has outperformed as compared to dry machining.

Cantero *et al.* (2013) examined tool wear mechanisms in finishing turning of Inconel 718, both under wet and DC conditions. It was observed from experimental analysis that SCEA has strong influence in the tool wear evolution. Results indicate that with increase in SCEA, the cutting aggressiveness of the tool decreases.

2.3 Research Gap

The most common method of applying cutting fluids in turning process is by flood cooling. However, the usage of flood coolant has several harmful effects, namely environmental pollution if mishandled and high costs associated with flood machining (Huang *et al.* 2018). Thus, it is vital to find a way of manufacturing products using more sustainable techniques, which would minimize the use of cutting fluids and promote a healthy and safe working environment. By abandoning conventional cooling lubricants and using the technologies of dry machining or minimum quantity lubrication (MQL), this cost component can be reduced significantly. Besides an improvement in the efficiency of the production process, such a technology change contributes to the protection of labour (Chen *et al.*, 2000) and the environment (Rossmoore, 1995).

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Materials

The materials used for the body fabrication and the design includes the following:

1. Mild steel sheet: It was used to fabricate the body of the MQL device and support stand for the reservoir.
2. D.C. Power supply: It Supply 220 V to 12 V and 12.5 A with 150 W and it primary function of the DC Power Supply is to supply power to the Miro Pump and Air Compressor.
3. Air compressor: It was used to compress air and to deliver it for end use. The air compressor used in the study was Car Mini Inflatable Pump Air Compressor with a pressure of 0-8 bars and voltage input of 12 V.
4. Air pressure regulator/gauge: It was used to measure/control the air pressure. It used Air Pressure Regulator with adjustment gauge pressure regulating valve pneumatic tool accessory with pressure range of 0-10 bars.
5. Micro pump: It was used to pump the lubricant. The type of Micro Pump used is Brushless Micro Pump. The primary function of Brushless pump is to pump the lubricant from the lubricating oil reservoir to the Mixing Chamber where it is mixed with pressurised air.
6. Plastic oil reservoir: It was calibrated to monitor the oil flow rate in which the volume of the oil reservoir is 2 litres; the radius is 20 cm and height is 35 cm. The oil reservoir has one inlet and one outlet; the inlet is used to refill the reservoir with the lubricating oil, and the outlet is connected to the Micro Pump and supply oil to the mixing chamber embedded in the nozzle.

7. Nozzle: It was used to control the direction or characteristics of a fluid flow as it exits (or enters) an enclosed chamber or pipe which is made up of brass and a hole outlet diameter of 0.5 mm. The nozzle is attached to the mixing chamber.
8. Connecting pipes and pipe nipple: It was used to pass the lubricating oil from the oil reservoir to the pump and then to the mixing chamber.

The following equipment was used to carry out the experiment include:

1. Lathe: The late was used to carry out cutting of the metal sample to test the MQL device. The lathe model which M400 was Manufactured in 2004 made by Harrison.
2. Lubricant: The major lubricating oil used was treated vegetable oil (groundnut oil) which was used to reduce friction.
3. Workpiece (AISI 1018 Mild/Low Carbon Steel): It was available in the form of cylindrical rod of diameter 38mm was used for the turning test on the lathe to determine the surface roughness of the metal.
4. Cutting tool (M2 high speed steel): It was used to cut the metal sample which was inserted in the lathe with the size 14 x 200.
5. Test meter (SRT 6200S Digital): Is used to measure the surface roughness of the workpiece.

3.2 METHODS

The method used is subdivided into three categories; the design, development and evaluation performance of the MQL.

3.2.1 Design Analysis

i. Design considerations
ii. The volume of fluid used and time taking for discharged

iii. The area of the nozzle

iv. The velocity of fluid discharged

v. The discharge from the nozzle

(a) Design considerations

The design consideration for the MQL includes the following:

(i) The energy source to power the pump

(ii) The viscosity of the fluid being pumped

(iii) The pump size

(iv) The fluid flow process incorporated with a MQL design

(v) Availability of the material to be used

(vi) Installation and Operation are kept simple

(vii) The design of a MQL and designing it for single operator.

(b) Volume of the fluid and time for discharge

The MQL device was design to hold a volume of fluid and discharge at a given period of time. The reservoir tank of fluid held 1L and the discharge time was 3600 seconds. the output from the pump is 240 l/hr and the diameter of the nozzle is 0.5 mm

(c) Velocity of fluid discharge

We can use Bernoulli's Equation to calculate velocity of a fluid from head. Head is the distance from outlet to top of water.

$$\text{Velocity} = \sqrt{2gh} \tag{3.1}$$

g = Gravity 9.81 m/sec^2

h = head metres

The volume of fluid holds 1 L and has an outlet 0.4 m from the bottom of the reservoir. The reservoir is full and is 0.9 m high.

Head = 0.9 m – 0.4 m = 0.5 m

$V = 4.43\sqrt{h}$

$V = 4.43\sqrt{0.5}$

= 3.133 m/ s

The pressure specification of the injector nozzle is 500kpa

(d) Discharge from the nozzle

$$Q = AV \qquad (3.2)$$

Q = quantity of fluid per unit of time

A = area of nozzle outlet (metres^2) A = $1.96 \times 1010^{-7}\ m^2$

V = velocity of fluid (metres per second)

Q = $1.96 \times 10^{-7}\ m^2$ x 32.62 m/s

= $6.4 \times 10^{-6} m^3/s$

3.2.2 Fabrication of MQL

The MQL is composed of two (2) structural units which consist of: MQL housing and installation of the pumping unit, these were fabricated and connected together in a single unit in a rectangular form.

3.2.2.1 Fabrication of the MQL housing

The MQL was fabricated as a rectangular container where all the component where installed and has a support for holding the reservoir. The MQL device housing was made of 1.5 mm mild steel sheet, hinges, dampers, and bolts and nuts. The pictures of the housing construction process are presented in Plate I. The housing construction process involved marking-out, cutting, punching, drilling, folding, welding, filling, painting and assembly. The assembly involved fitting all the components together in the housing.

Plate I: MQL Housing construction

3.2.2.4   Installation of the pumping unit and the air compressor

The pump of 12 V was installed connected to the power source for pumping air and oil at the same time. The unit which comprise of the air compressor and the pressure guage to regulated the air and oil flow shown in Plate II.

Plate II: Installation of pumping unit and the air compressor

3.3.2 Experimental Procedure

The machining test was carried out by turning the workpeice on the lathe by high speed steel (HSS) cutting tool at different cutting velocities (Vc) and feeds rate (So) at constant depth of cut under dry and MQL cutting condition all the values were recorded shown in the Table 3.1.

Table 3.1: Experimental parameter

Parameter	Condition
Cutting velocity	100, 150 and 200 m/min
Feed rate	0.50 mm/rev, 0.55 mm/rev, and 0.60 mm/rev,
Depth of cut	0.8 mm

The workpeice was machined using the parameter in Table 3.1. The MQL fabricated was introduced to lubricate the workpeice and the air/oil ratio. The data were collected between the range of 1 and 5 bar for AFR and OFR, analyzed and results were presented and designated as AO1, AO2, AO3, AO4 and AO5 as indicated in Table 3.2.

Table 3.2: Parameter for Air/Oil ratio used

Air pressure (bar)	Oil guage (bar)	A/O ratio	Designate
1.0	1.0	1.00	
1.0	2.0	0.50	
1.0	3.0	0.33	AO1
1.0	4.0	0.25	
1.0	5.0	0.20	
2.0	1.0	2.00	
2.0	2.0	1.00	AO2
2.0	3.0	0.67	
2.0	4.0	0.50	
2.0	5.0	0.40	
3.0	1.0	3.00	
3.0	2.0	1.50	
3.0	3.0	1.00	AO3
3.0	4.0	0.75	
3.0	5.0	0.60	
4.0	1.0	4.00	
4.0	2.0	2.00	
4.0	3.0	1.33	AO4
4.0	4.0	1.00	
4.0	5.0	0.80	
5.0	1.0	5.00	
5.0	2.0	2.50	
5.0	3.0	1.67	AO5
5.0	4.0	1.25	
5.0	5.0	1.00	

Surface roughness R_a was measured using testing meter, SRT 6200S Digital at regular intervals of 2 minutes with the progress of machining. This was performed at a fixed A/O ratio of 1.5, cutting velocity of 100 m/min, feed rate of 0.5 mm/rev and depth of cut of 0.8 mm. The variation of R_a is with machining time.

The surface roughness values of each of the ratio were measured at three different locations on the machined surface. The measurements were taken at distance of 40 mm from the nozzle exit which was considered as close as practically possible to the cutting zone. Average surface roughness (R_a) was obtained by taking average of the three surface roughness readings for each experiment under the experimental conditions of 50 m/min cutting velocity; 0.5 mm/rev feed rate; 0.8 mm depth of cut, and vegetable oil (groundnut oil) as cutting fluid.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 Result of the Surface Finishing

Good surface finishing was achieved using different air/oil ratio shown in Table 4.1, the test reading is in Appendix A and it was plotted against air/oil ratio shown in Figure 4.1.

Table 4.1: Surface finishing results

Designate	Air/Oil ratio	Surface Finishing (μm)
AO1	1	3.43
	0.5	4.41
	0.33	5.09
	0.25	7.71
	0.20	8.53
AO2	2.00	3.63
	1.00	3.44
	0.67	4.91
	0.50	5.01
	0.40	6.67
AO3	3.00	4.13
	1.50	0.95
	1.00	3.42
	0.75	4.42
	0.60	5.56
AO4	4.00	6.64
	2.00	3.62
	1.33	1.77
	1.00	3.45
	0.80	4.56
AO5	5.00	7.92
	2.50	3.92
	1.67	2.46
	1.25	1.53
	1.00	3.41

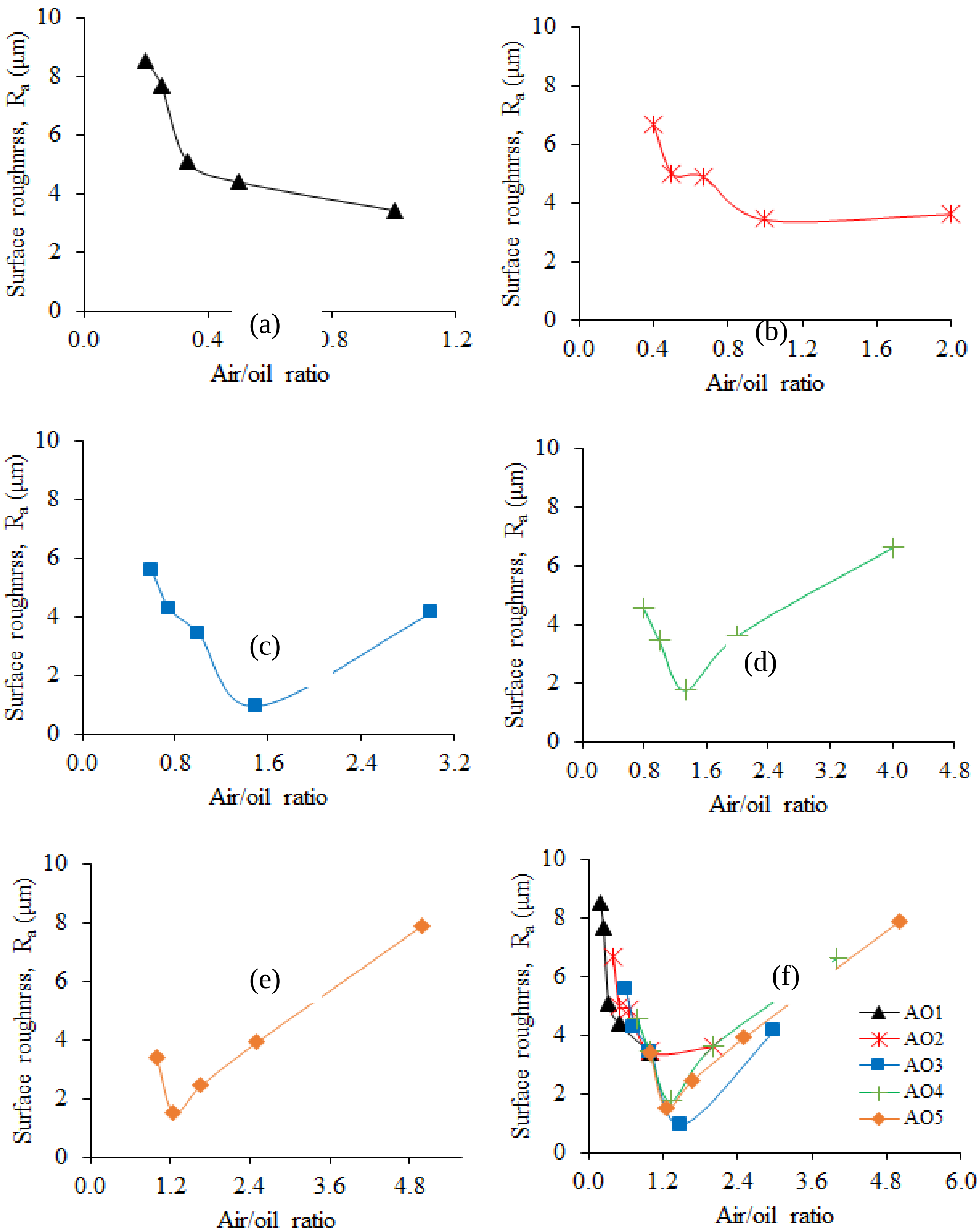

Figure 4.1: Surface roughness of the machined workpiece under different air/oil ratios of (a) A/O1, (b) A/O2, (c) A/O3, (d) A/O4, (e) A/O5 and (f) comparative study

In general, the surface finish R_a progressively decreases with an increase in A/O ratio as evident in A/O2 and A/O3 at relatively low Air and Oil value shown in Figure 4.1. When the air compressor was set at 1 bar (Figure 4.1a) and 2 bars (Figure 4.1b) the micro pump was set to vary the oil supply between 1 and 5 bars as designated as A/O1 and A/O2 respectively. This phenomenon ceases at a critical value of A/O of 1.5 (Figure 4.1 (c – e)), and increase in A/O results to increase in R_a. Figure 4.1(c – e) indicated that the R_a significantly decreases with increasing A/O ratio notably from 0.6 to 1.5 and beyond 1.5, the R_a exhibit a rise when the air pressure was set at 3 bars and above at varied oil supply (1 – 5 bars). The minimum value obtained for the R_a was 0.95 μm at 1.50 A/O ratio (when air compressor was set at 3 bars and oil micro pump at 2 bars). Previous related work carried out by Ali *et al.* (2017) indicated that smaller values of surface roughness are preferred for the optimum cutting conditions. This indicates that turning at A/O ratio at 1.50 significantly gives a high R_a of workpiece.

This finding is also buttressed by the report of Balan *et al.* (2013) who showed that increase in the air supply pressure and mass flow rate while the oil flow rate held constant could lead to a decrease in droplet size. They further explained that larger droplet with lower pressure can also lead to insufficient lubrication, owing to the fact that the droplets cannot be carried to the cutting zone because of its higher mass. Therefore, medium size droplet with an optimized pressure can easily penetrate the boundary layer and provide effective lubrication, thereby reducing the R_a. From the results, it is clearly seen that the A/O ratio at 1.50 gives the best surface finishing at 0.95 as a result of effective lubrication, while turning the mild steel (AISI 1018 mild steel).

4.2 Performance Evaluation

The performance evaluation was carried out using cutting velocity and machining time on surface finishing for turning mild steels which is shown in Figure 4.2 and 4.3.

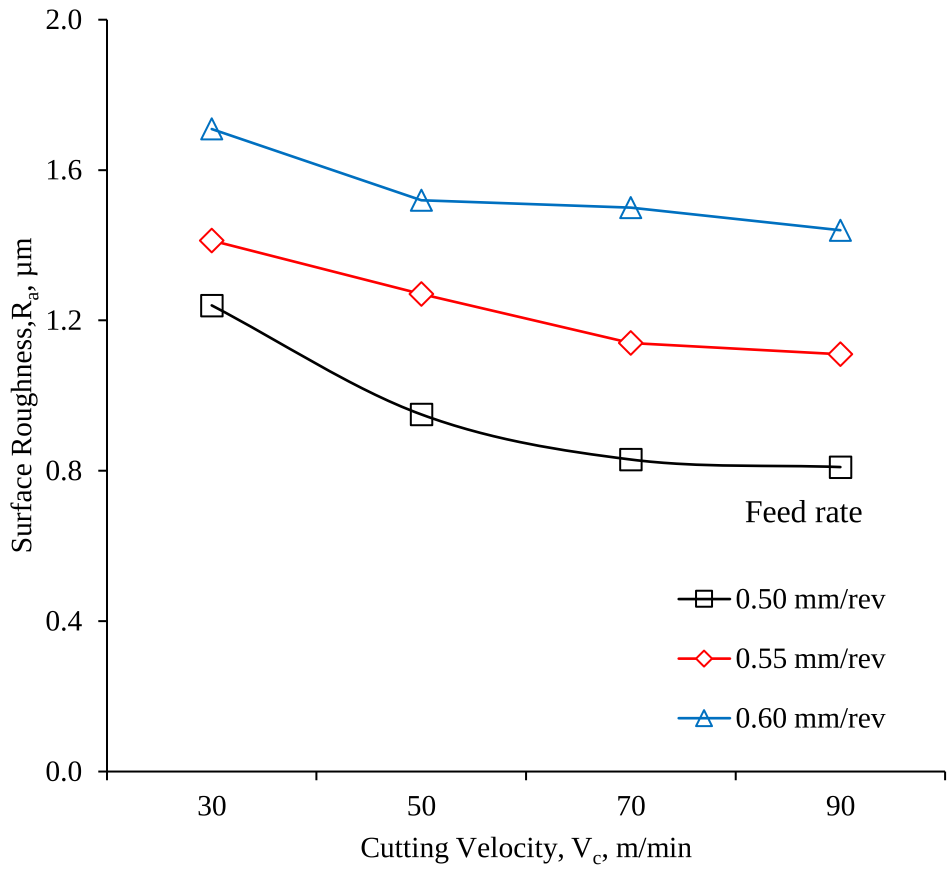

Figure 4.2: Surface roughness (Ra) of the machined workpiece under different cutting velocity and feed rate in turning mild steel

Figure 4.2 show that the surface roughness, R_a increases with the increase in feed rate and decreases with the increase in cutting velocity V_c. Increase in feed rate from 0.50 mm/rev to 0.55 mm/rev, then to 0.60 mm/rev raises R_a. Reduction in R_a with the increase in V_c may be attributed to smoother chip – tool interface with lesser chance of built-up edge formation in addition to possible truncation of the feed marks and slight flattening of the tool-tip. Increase in V_c may also cause slight smoothing of the abraded auxiliary cutting edge by adhesion and diffusion type wear and thus reduces surface roughness (Dureja, *et al.*, 2015). So, cutting velocity, V_c influences on surface roughness under MQL machining. It has been also observed that the roughness of the machined surfaces is high at high feed rates and vice versa. This result corroborates the work of Suresh *et al.* (2012) who investigated the influence of cutting speed, feed rate, depth of cut and machining time on machinability characteristics such as machining force, surface roughness and tool wear using response surface methodology (RSM) based second order mathematical models during turning of AISI 4340 high strength low alloy steel using coated carbide inserts. The result revealed that, the combination of low feed rate, low depth of cut and low machining time with high cutting speed is beneficial for minimizing the machining force and surface roughness.

Furthermore, previous works by other investigators such as Bhattacharya *et al.* (2009) who investigated the effects of cutting parameters on finish and power consumption during high speed machining of AISI 1045 steel employing Taguchi techniques. The results showed a significant effect of cutting speed on the surface roughness and power consumption, while the other parameters did not substantially affect the responses. In another study, Benga & Arabo (2003) underlined that feed rate is most significant factor affecting surface finish than cutting speed for both cubic boron nitride (CBN) and ceramic inserts. Ozel *et al.* (2005) experimentally investigated the effects of feed rate and cutting speed on surface roughness and resultant forces in the finish hard turning of AISI H_{13} steel, the study shows that the effects of feed rate and cutting speed on surface roughness are statistically significant. Cekir *et al.* (2009) examines the effects of cutting parameters (cutting speed, feed rate and depth of cut) onto the surface roughness through the mathematical model developed by using the data gathered from a series of turning experiments performed. From the results it was shown that feed rate had the most influence on the surface roughness which was followed by the cutting speed.

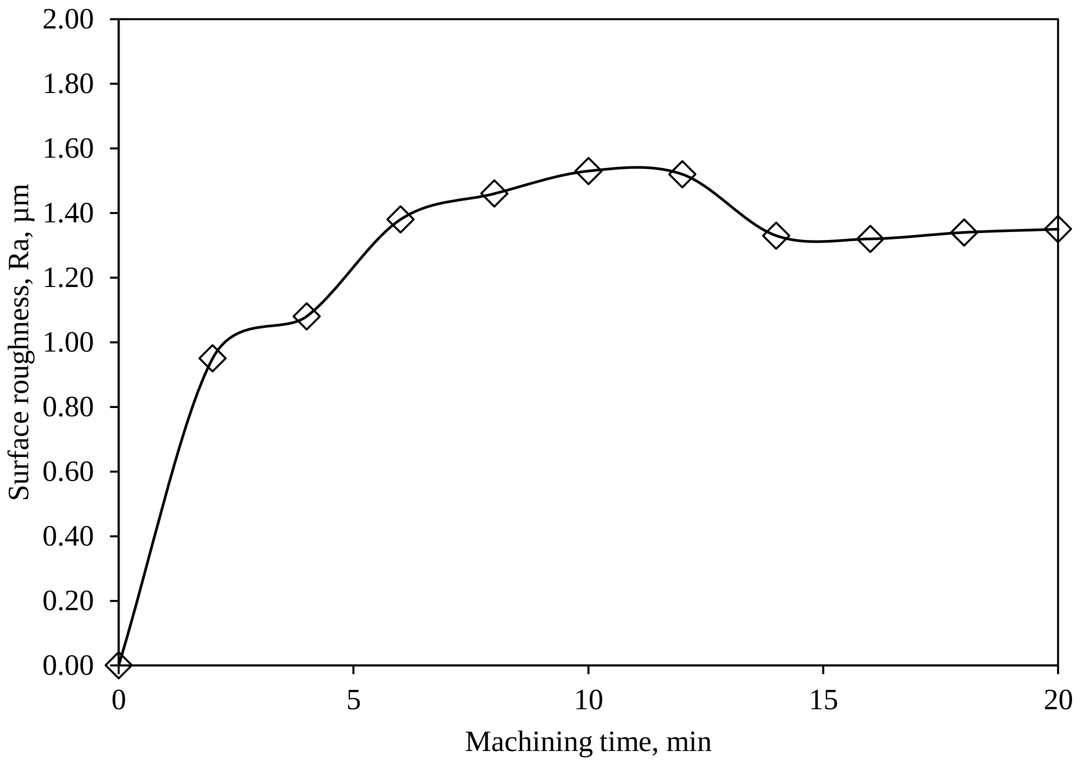

Figure 4.3: Surface roughness (Ra) with machining time

From the Figure 4.3 it is clear that surface roughness gradually increases with the machining time which may be due to gradual increases in auxiliary flank wear. It can also be seen that roughness values exhibit a falling and rising trend with the machining time. High roughness values are observed especially at the early stage between 6 minutes to 12 minutes where the inserts are relatively new. Afterwards, the roughness values become smaller and rather stable which may be ascribed to the wearing of the inserts by friction resulted to the increase of radiuses of tool edges at the latter stage. Dhar *et al.* (2006) found that the pattern of growth of surface roughness also bears similarity with that of growth of flank wear. Moreover, adhesion and built-up edge formation are more likely to affect surface finish because it may directly be stuck to the cutting edge as well as the finished surface (Yan *et al.*, 2012).

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This study designed and fabricated locally the Minimum Quantity Lubrication (MQL) device for turning operation.

The result of performance evaluation demonstrated for the surface roughness is as follows:

i. Surface roughness (R_a) of the machined workpiece progressively decreases with increasing in A/O ratio at relatively high ratio values.

ii. The minimum value obtained for the R_a was 0.95 μm at 1.5 A/O ratio which gives the best surface finishing.

iii. Turning at A/O ratio below or above 1.5 significantly gives a high R_a of workpiece.

iv. Surface roughness increases with the increase in feed rate and decreases with the increase in cutting velocity V_c. Increase in feed rate raises surface roughness mainly.

v. Surface roughness gradually increases with the machining time

5.2 Recommendations

Based on the findings, the following recommendations were made:

i. The results of the surface roughness satisfied basic requirements for the surface finishing which make the MQL device suitable for use in turning operation of the mild steel.

ii. A/O ratio of 1.5 (air compressor fixed at 3 bar and micropump at 2 bar) is recommended as an optimum value for MQL turning operation for mild steel.

iii. Other machining conditions such as depth of cut and nozzle distance and orientation should be investigated.

iv. The cutting fluid volume dispensed at a time.

5.3 Contribution of the Study to Knowledge

The development of minimum quantity lubrication (MQL) device with locally source materials has shown that, the technology of using MQL as a means of applying cutting fluid during turning process is possible. Experiment conducted using the developed MQL device serve comparatively good result with others means of cutting fluid application in turning process

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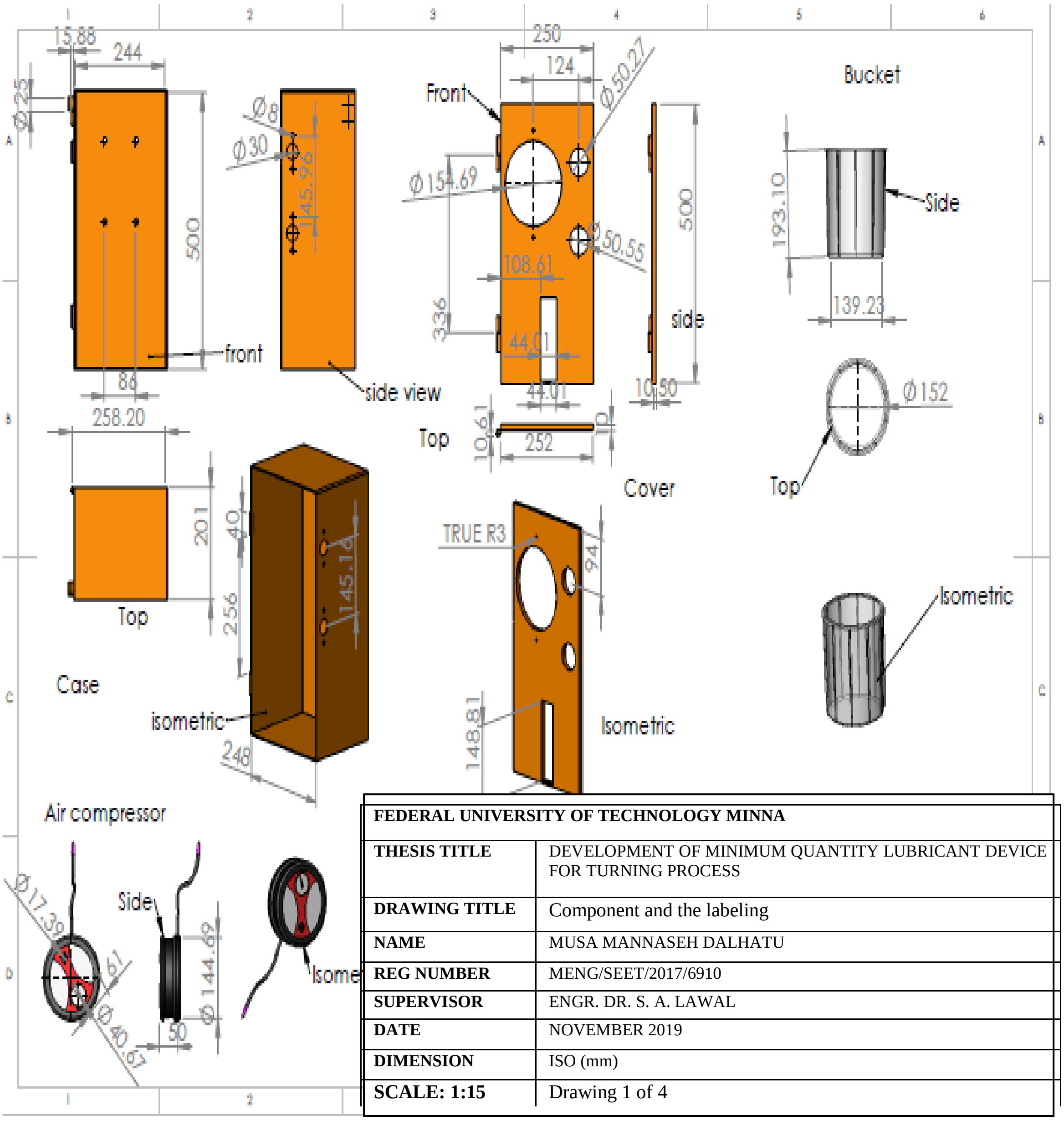
APPENDIX A

ANALYSIS SURFACE FINISHING RESULTS

Air pressure (bar)	Oil guage (bar)	A/O ratio	1st Reading (µm)	2nd Reading (µm)	3rd Reading (µm)	Average (µm)
1.0	1.0	1.00	3.23	3.66	3.40	3.43
1.0	2.0	0.50	4.40	4.42	4.41	4.41
1.0	3.0	0.33	5.08	5.09	5.10	5.09
1.0	4.0	0.25	7.70	7.72	7.71	7.71
1.0	5.0	0.20	8.53	8.56	8.50	8.53
2.0	1.0	2.00	3.50	3.73	3.66	3.63
2.0	2.0	1.00	3.44	3.43	3.45	3.44
2.0	3.0	0.67	4.80	4.92	5.01	4.81
2.0	4.0	0.50	5.01	5.02	5.00	5.01
2.0	5.0	0.40	6.60	6.68	6.74	6.67
3.0	1.0	3.00	4.13	4.16	4.10	4.13
3.0	2.0	1.50	0.90	1.00	0.95	0.95
3.0	3.0	1.00	3.40	3.44	3.42	3.42
3.0	4.0	0.75	4.24	4.21	4.27	4.24
3.0	5.0	0.60	5.50	5.59	5.54	5.56
4.0	1.0	4.00	6.66	6.65	6.61	6.64
4.0	2.0	2.00	3.64	3.60	3.62	3.62
4.0	3.0	1.33	1.77	1.78	1.76	1.77
4.0	4.0	1.00	3.43	3.47	3.44	3.45
4.0	5.0	0.80	4.44	4.58	4.56	4.56
5.0	1.0	5.00	7.93	7.92	7.91	7.92
5.0	2.0	2.50	3.90	3.93	3.93	3.92
5.0	3.0	1.67	2.45	2.97	2.46	2.46
5.0	4.0	1.25	1.53	1.52	1.54	1.54
5.0	5.0	1.00	3.40	3.42	3.41	3.41

APPENDIX B

HOUSING AND LAYOUT OF THE COMPONENTS

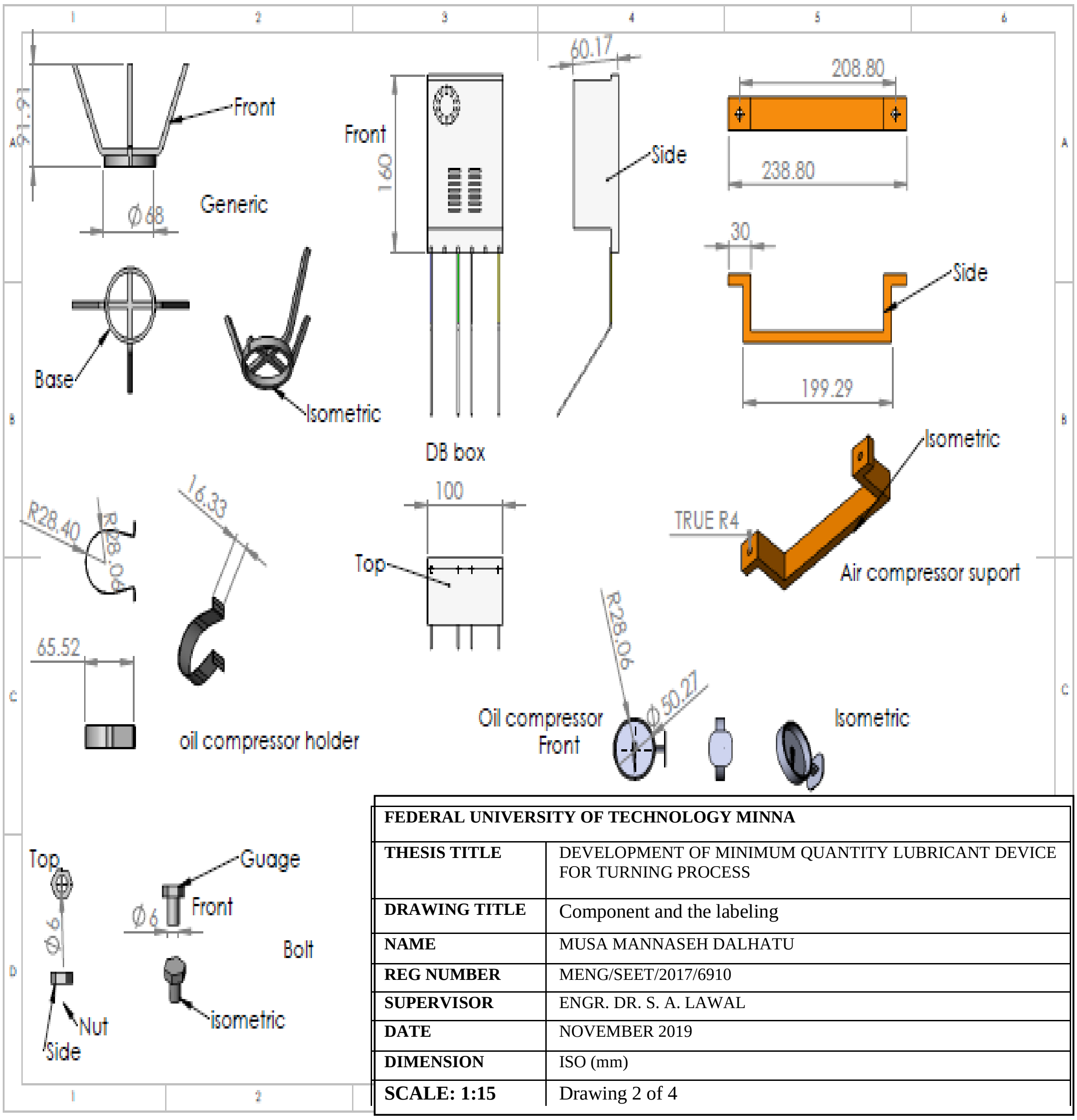


FEDERAL UNIVERSITY OF TECHNOLOGY MINNA	
THESIS TITLE	DEVELOPMENT OF MINIMUM QUANTITY LUBRICANT DEVICE FOR TURNING PROCESS
DRAWING TITLE	Component and the labeling
NAME	MUSA MANNASEH DALHATU
REG NUMBER	MENG/SEET/2017/6910
SUPERVISOR	ENGR. DR. S. A. LAWAL
DATE	NOVEMBER 2019
DIMENSION	ISO (mm)
SCALE: 1:15	Drawing 1 of 4

Figure A: Component and the labeling

APPENDIX C

HOUSING AND LAYOUT OF THE COMPONENTS



FEDERAL UNIVERSITY OF TECHNOLOGY MINNA	
THESIS TITLE	DEVELOPMENT OF MINIMUM QUANTITY LUBRICANT DEVICE FOR TURNING PROCESS
DRAWING TITLE	Component and the labeling
NAME	MUSA MANNASEH DALHATU
REG NUMBER	MENG/SEET/2017/6910
SUPERVISOR	ENGR. DR. S. A. LAWAL
DATE	NOVEMBER 2019
DIMENSION	ISO (mm)
SCALE: 1:15	Drawing 2 of 4

Figure B: Component and the labeling

APPENDIX D

HOUSING AND LAYOUT OF THE COMPONENTS

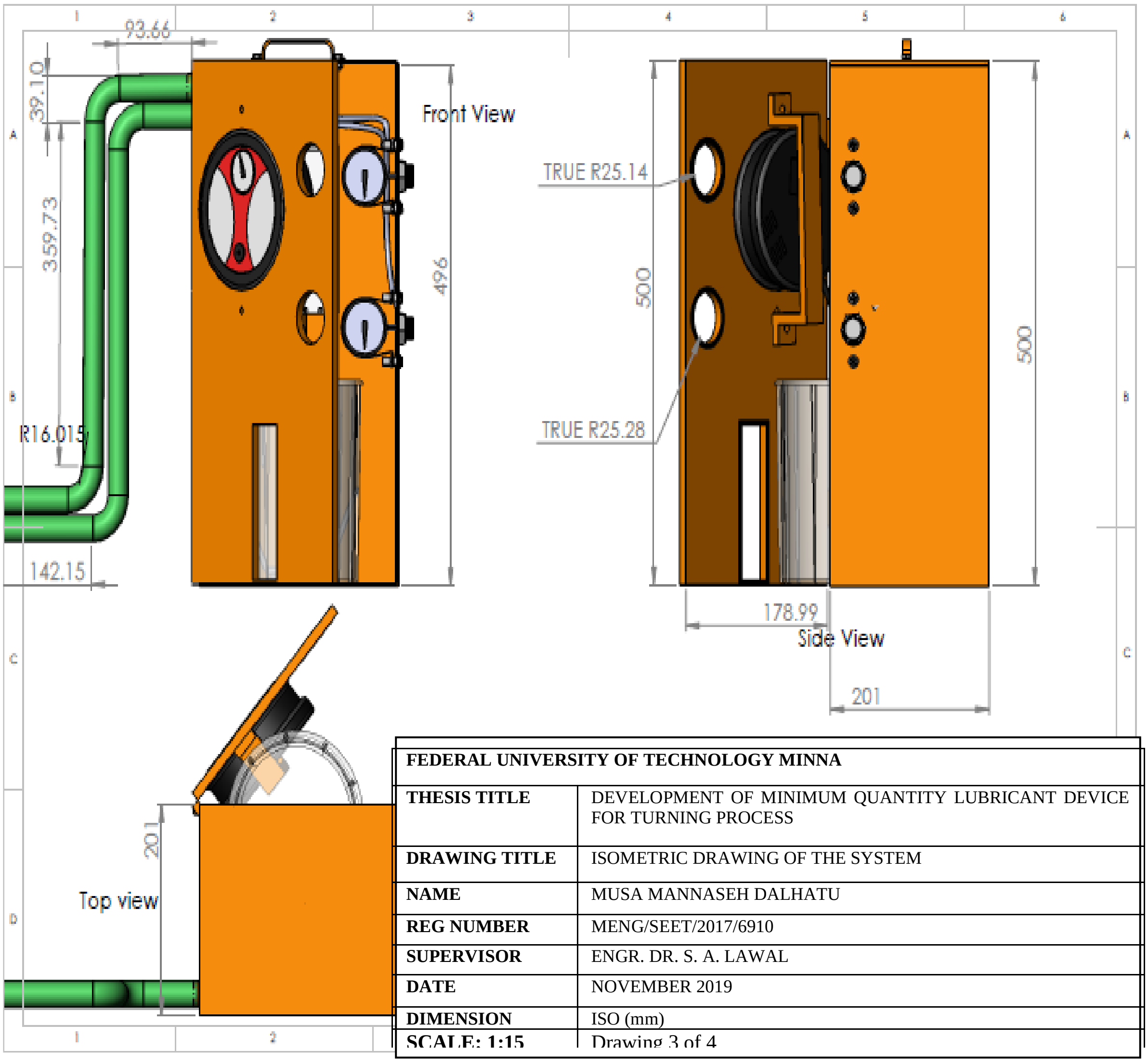
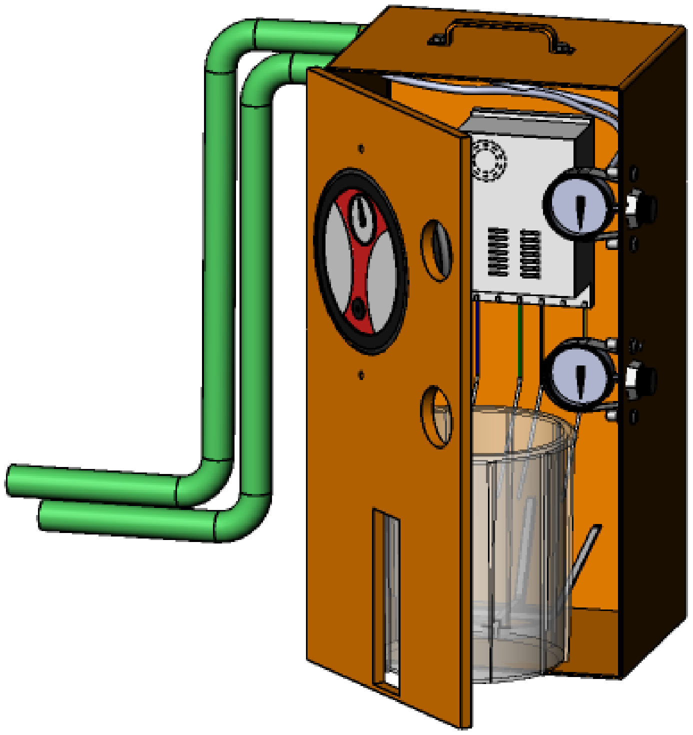


Figure C: Lubricating oil reservoir holder

APPENDIX E

HOUSING AND LAYOUT OF THE COMPONENTS



FEDERAL UNIVERSITY OF TECHNOLOGY MINNA	
THESIS TITLE	DEVELOPMENT OF MINIMUM QUANTITY LUBRICANT DEVICE FOR TURNING PROCESS
DRAWING TITLE	ISOMETRIC DRAWING OF THE SYSTEM
NAME	MUSA MANNASEH DALHATU
REG NUMBER	MENG/SEET/2017/6910
SUPERVISOR	ENGR. DR. S. A. LAWAL
DATE	NOVEMBER 2019
DIMENSION	ISO (mm)
SCALE: 1:15	Drawing 4 of 4

Figure D: Isometric drawing of the system