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Alternative Techniques for Reducing the Use of Cutting Fluids

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Abstract - Modern machining processes face continuous cost pressures and high quality expectations. So the Industries must continually identify cost reduction opportunities in production, exploit economic opportunities and continuously improve production processes. A key technology that represents cost saving opportunities is related to improvement in the overall performance of cutting operations.

***Keywords** -- Authorization Metal Cutting process, selection of cutting fluid, Types of cutting fluid, Environmentally conscious machining techniques.*

I. INTRODUCTION TO METAL CUTTING PROCESS

The metal cutting is a thermo-mechanical process. During the process, the heat generation occurs as a result of plastic deformation and friction along the tool–chip and tool–work piece interface. The maximum temperature occurs at the tool-chip interface. The tool–wear and fracture considerably increase at higher temperatures. Temperature rise in machining has a controlling influence on the cutting parameters.

High cutting temperature is mostly detrimental in several respects. Therefore, it is necessary to control or reduce the cutting temperature as far as possible. Cutting temperature can be controlled in varying extent by the following general methods:

- Proper selection of material and geometry of the cutting tool(s)
- Optimum selection of cutting speed and feed combination without sacrificing MRR
- Proper selection and application of cutting fluid
- Application of special technique, if required and feasible.

I. Also, the demand for greener manufacturing is the primary drive for research on technologies that reduce cutting fluid use. The fact is that costs associated with fluid use often constitute between 7% and 17% of total production costs, as compared to 4% for tooling costs [1]. Fluid related expenses include the cost of installing a fluid supply system, fluid purchase and system maintenance, and discarded fluid (waste) treatment.

II. Fluid-related costs are large because high production manufacturing plants frequently utilize several cutting fluid reservoirs each containing thousands of gallons of cutting fluid, and often an entire reservoir is flushed to clean the system when quality issues arise.

III. Machining advanced engineering materials is usually associated with high machining costs and low productivity. This is due to the excessive generation of heat at the cutting zone and difficulties in heat dissipation due to relatively low heat conductivity of these materials. High material hardness and strength together with high temperatures at the cutting zone could result in excessive tool wear and thus short tool life and poor surface quality. In the subsequent section, the sources and causes of heat generation in machining are discussed.

II. SOURCES AND CAUSES OF HEAT GENERATION IN MACHINING

During machining heat is generated at the cutting point from three sources, as indicated in Fig. 1.

The sources and causes of development of heat are:

• Primary shear zone: The material is being cut by elasto-plastic deformation. The major part of the energy is converted into heat.
• Secondary shear zone: Chip slides on the rake face of the cutting tool resulting in high frictional force and heat.
• Tertiary deformation zone: Sliding of the tool flank face on the machined surface generates friction and heat and could cause flank wear.

The heat generated is shared by the chip, cutting tool and the blank. The apportionment of sharing that heat depends upon the configuration, size and thermal conductivity of the tool work material and the cutting condition.

It is noticed that, many cutting parameters depends on the temperature field during cutting e.g. tool life, mechanics of chip, formation, surface quality, cutting forces, cutting speed, process efficiency etc. Similarly, subsurface deformation,

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metallurgical structural alterations in the machined surface, and residual stresses in the finished part depend on the maximum temperature, the temperature gradient, and the rate of cooling of the part. Therefore determination of temperature distribution in cutting domain is one of the major subjects in the machining researches [3]

Prediction of temperature is complex issue mainly because metal cutting is highly localized, occurs at high temperatures, high pressures and strains. It is extremely difficult to develop a precise temperature prediction model in machining. Therefore, accurate and repeatable temperature prediction still remains a challenge due to the complexity of the contact phenomenon in the metal cutting process [4].

III. Coolants and lubricants

Today, One of the main issues that affect machinability is the heat generated during machining. Cutting fluids have been used in machining operations for decades in order to increase the machinability through lubricating the contact areas between rake face and chips, flank face and machined surface and reducing the friction induced heat and removing the generated heat from the cutting zone as a result of severe plastic deformation.

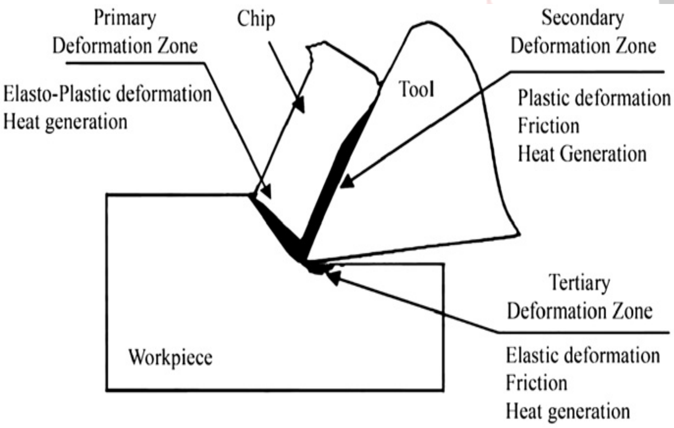

Figure 1: Sources of heat generation in machining [2]

Based on the first law of metal cutting developed by Makarow, the highest machinability is achievable at a critical cutting temperature known as optimal cutting temperature [5]. This temperature is independent of the cutting parameters and machining condition and is based on the material properties of the tool and work piece materials. It is noted that by increasing the cutting temperature close to optimal temperature, machinability increases.

Using cutting fluids is one of the most widely adopted techniques to maintain the cutting temperature below the optimal cutting. The cooling effect of cutting fluids increases tool life by maintaining temperature below the thermal softening temperature of the tool material and decreasing the thermally induced tool wear such as diffusion and adhesion.

In addition, the lubrication effect of the cutting fluids could reduce the mechanical wears such as abrasion on the rake face. In contrast, decreases in the work piece temperature in certain conditions could increase the material hardness therefore increasing cutting forces, power consumption and reducing tool life.

Other effects of cutting fluids are flushing chips away and preventing the machined surface and cutting tool from corroding. Maintaining the cutting edge for longer and reducing the heat and friction in machining operations can also lead to improved surface characteristics of the machined parts.

Proper selection of cutting fluids is particularly important as it could affect the tool life, cutting forces, power consumption, machining accuracy, surface integrity etc. For instance cutting fluids with a greater lubrication effect are usually employed in severe machining operations such as low speed machining and machining difficult-to-machine materials.One of the widely accepted characteristics of the cutting fluids is the miscibility in water. Thus, it has been used widely in order to categorize the cutting fluids into water-soluble (water-miscible) cutting fluids and non-water-soluble—also known as oil-based cutting fluids. In addition, gas- based CLs can also be defined as liquefied gases and gas-form Cls.

3.1. Water miscible cutting fluids:

As it was mentioned before, one of the effects of cutting fluids is to remove generated heat at the cutting zone by conduction. Thus, the desired cutting fluid used particularly for cooling should have high thermal conductivity and specific heat [6]. Specifically, water is the most favorable coolant fluid with this characteristics accompanied with low cost.

However water is corrosive to ferrous materials specifically used in expensive machine tools [5]. In addition, water has low lubrication effectiveness and tends to wash lubricants used on the sliding and rotating surfaces therefore increasing the machine wear. To overcome these problems and enhance the lubrication properties of water-based cutting fluids, different additives have been added to water [6].

Water miscible cutting fluids are categorized into soluble oil, synthetic and semi-synthetic fluids. Soluble oils consist of a mineral oil accompanied with emulsifiers which allow the oil to be dispersed in to the water [7].

Synthetic CLs are water-based and contain synthetic water-soluble lubricants, high pressure additives, corrosion inhibitors, biocides, surfactants and deformer. Synthetic fluids are generally considered as coolants with low lubrication

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characteristics and are particularly used for low force operations.

Abbre Semi- synthetic cutting fluids contain both mineral oils and chemical additives and have both characteristics of soluble oil and synthetic fluids. They are considered of better lubricants when compared to synthetic fluids and are cleaner and more effective in rust prevention than soluble oils.

3.2 Oil-based or neat oil cutting fluids:

Oil-based fluids are other alternative coolant fluids widely used in most machining operations. They are usually mineral oils which often contain some additives such as other kinds of lubricants and extreme pressure compounds in order to enhance their applications [7].

This type of cutting fluid is used to lubricate the tool–chip interface and thus reduce the friction and friction induced heat at the cutting zone. Reduction in friction can result in lower cutting forces crater wear on the tool rake face and other types of thermally induced tool wear in certain machining conditions. The application of oil-based fluids also lubricates the moving parts of the machine tool and reduces the corrosion/oxidation on the machined surface and machine tool [6].

3.3. Gas-based coolant-lubricants:

Gas-based CLs generally refer to the substances that at room temperature are in the gas form, however in machining applications they are used in the form of either gas or cooled-pressured fluids. Main gas-based CLs are air, nitrogen, argon, helium or carbon dioxide. The gas-based CLs might be used in conjunction with traditional cutting fluids in the form of mist or droplets to enhance their lubrication capability. The most broadly known usage of gases as coolants is in dry cutting where air is being used in order to cool the tool and work piece [6]. However, gases are poor thermal conductors and have low cooling capacity. Different approaches have been used in order to increase the cooling capability of gas-based CLs namely: compressing, cooling and liquefying. Compressed gas- based CLs are especially attractive where traditional cooling techniques fail to penetrate the chip–tool interface, such as heavy duty cutting conditions.

IV. ENVIRONMENTALLY CONSCIOUS MACHINING

As mentioned previously using cutting fluids in the cutting operations becomes a major problem due to the associated economical, environmental and health problems. The best approach to eliminate the effects of cutting fluids is to eliminate their usage completely which is known as dry cutting.

However dry cutting is not applicable in all machining operations mainly due to excessive tool wear or low surface quality. In order to improve machinability a minimum quantity lubricant (MQL) could be penetrated into the cutting zone. Although MQL reduces the CLs consumption it still uses them [15].

Another alternative is to use cryogenic coolant in order to dissipate the generated heat at the cutting zone and enhance the machinability through the changes in cutting tool/work piece material properties.

In this section different issues and achievements to eliminate or reduce the consumption of cutting fluids in machining are reviewed through four different methods, namely

1 Dry machining ;
2 MQL
3 Cryogenic machining.
4 Air cooling

The details are shown in the figure 2,

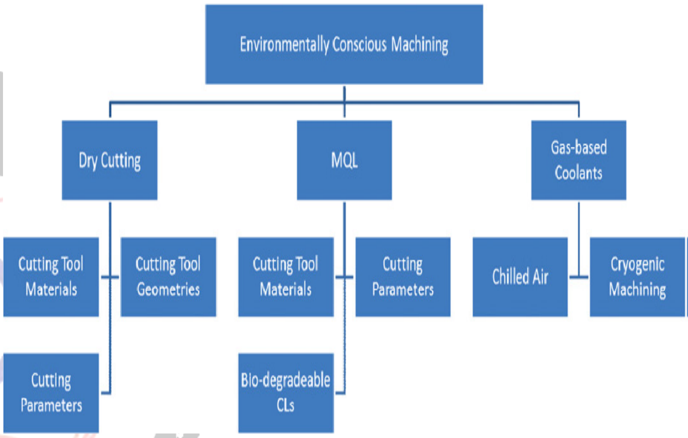

Fig. 2: Environmentally conscious machining techniques.

4.1. Dry cutting:

Dry machining is considered as the best approach to eliminate the use of cutting fluids in manufacturing and to reduce the machining costs and ecological hazards. Weinert et al. [16] identified the benefits of adopting dry machining which are shown in Fig. 3,

Fig. 3 Benefits of adopting dry machining [16]

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It is known that employing cutting fluids can improve tool life, prevent built-up edges (BUE) from forming on the cutting tool and reduce the cutting forces and surface roughness. On the contrary, in dry machining friction and cutting temperature could be more than that of wet machining. These could reduce the tool life, reduce the surface quality and cause thermally induced geometrical deviations in the machined part.

However, this is not the case for all materials and machining operations and dry cutting shows positive effects such as lower thermal shock and improved tool life in some cases [17].

Techniques employed by researchers to compensate the effects of the elimination of cutting fluids in machining could be categorized into:

(i) Indirect heat dissipation and (ii) improving cutting tools properties by introducing better tool materials, coatings or tool geometries.

This has led to the introduction of advanced tool materials such as Cubic Boron Nitride (CBN), Polycrystalline Cubic Boron Nitride (PCBN), Polycrystalline Diamond (PCD), cermets, ceramics and different kinds of coatings.

Tool wear and the failure mechanisms of different tool materials were investigated by Dearnley and Grearson [18] during turning Ti–6Al–4V alloy. Their experimental studies revealed that the main tool failure mechanism was diffusion on the rake face resulting in excessive crater wear. This is attributed to high and localized temperature at the chip–tool contact on the rake face and high chemical reactivity of the work piece material. CBN tools performed better than other ceramic and carbide tools by showing a lower and smoother tool wear.

Ginting and Nouari [19] investigated the applicability of dry end milling of Titanium alloy Ti6242S with uncoated alloyed carbide tools. They used an uncoated tungsten carbide with cobalt binders. The investigations were limited to the study of chip formations, tool wear, cutting temperature and surface finish of the machined part. Observation of the worn tools after machining under the scanning electron microscope (SEM) revealed that localized flank wear was the dominant tool failure mode. Brittle fracture of the cutting edge accompanied with localized flank wear was reported to be the second most observed tool failure mode.

Krain et al. [20] studied the effects of machining parameters in end milling operation of Inconel 718 nickel based alloy in order to gain higher productivity through optimizing the material removal rate. Low thermal conductivity of Inconel 718 leads to high local temperature at the cutting zone which facilitates the wear mechanisms. The tool life of two different types of coatings is also compared. It is found that that PVD coated tungsten carbide tool performed better at less aggressive cutting conditions. At more aggressive cutting conditions CVD coated carbide tool outperformed the PVD coated tool.

Liu et al. [21] investigated the effect of adding aluminium to pearlitic cast iron on its machinability with CBN tools. They found that addition of Al could result in the formation of a harder protective layer of aluminium oxide on the tool surface. This layer protects the cutting tool from abrasive wear and makes it possible to increase the cutting speed up to 4500 m/min.

Experiments [22] in machining Ti64 with binderless CBN (BCBN) tools revealed that the highest material removal rate and tool life could be achieved through combining high cutting speed and low feed rate and depth of cut. High cutting speed increases the cutting temperature and reduces the work piece material strength where BCBN could maintain its hardness.

Another technique in enhancing the properties of conventional cutting tools is cryogenic treatment. The hardness and wear resistance of the metals which contain retained austenite could be improved by this technique [23].

As cryogenic treatment affects the whole material properties, unlike coating it preserves its properties after re-sharpening or regrinding.

Sreerama Reddy et al. [23] reported that cryogenic treatments increased the thermal conductivity and reduced the tool wear of multilayer coated carbide tool as compared to non-treated tools. Increased thermal conductivity resulted in lower temperature and better heat dissipation capability of the tool. This reduces the thermally induced tool wears such as adhesion and diffusion.

4.2. Minimum quantity lubricant (MQL):

MQL or near dry machining is another alternative to conventional flood coolant. It also provides an alternative for machining operations in which dry machining is not applicable especially where machining efficiency and/or high surface quality are of more interest [26]. Based on the recommendations by Klocke et al. [27] Table 1 provides a comparative application of MQL and dry machining for some materials in different machining operations.

MQL is referred to as the application of a small amount of cutting fluid (10–100 ml/h) mixed with compressed air to form an aerosol [28]. This mixture is then penetrated to the cutting zone in order to lubricate the chip–tool contact area and reduce the temperature.

Boundary lubrication on the contact surfaces results in a lower friction coefficient whilst heat transformation is mainly in the

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form vaporization at the cutting zone and conduction through the flow of the air. Evaporation of the CL at the cutting zone eliminates the requirements for maintenance, circulation and disposal of the cutting fluid and the associated costs.

	Material				
	Aluminium		Steel		Cast iron
Process	Cast alloys	Wrought alloy	High alloyed bearing steel	Free cutting, quenched and tempered steel	GG20-GG70
Drilling	MQL	MQL	MQL	MQL/DRY	MQL/DRY
Reaming	MQL	MQL	MQL	MQL	MQL
Tapping	MQL	MQL	MQL	MQL	MQL
Thread forming	MQL	MQL	MQL	MQL	MQL
Deep hole drilling	MQL	MQL		MQL	MQL
Milling	MQL/DRY	MQL	DRY	DRY	DRY
Turning	MQL/DRY	MQL/DRY	DRY	DRY	DRY
Gear milling			DRY	DRY	DRY
Sawing	MQL	MQL	MQL	MQL	MQL
Broaching			MQL	DRY	DRY

Table 1 Application areas of dry and MQL [27]

The technique described by Lopez de Lacalle et al. [29] not only enhanced the tool life but also reduced the consumption of cutting fluids by 95%. Experiments showed that, 0.04– 0.06 ml/h of lubricant, if sprayed in a suitable area could reduce the tool wear by up to 40% as compared to conventional cooling.

Yuan et al. [30] studied the effect of air temperature in MQL milling of titanium alloy. They used 20ml/h of synthetic ester oil in the flow of air at different temperatures of 0, -15, -30 and -45 C compared to MQL at the room temperature, dry and flood cooling. Formation of BUE was observed under dry, wet, MQL at room temperature and MQL at 0 C. They noticed that the work piece material became harder at very low air temperatures of -30 C and -45 C which resulted in higher cutting forces as compared to that of dry machining. The longest tool life and lowest surface roughness were achieved under a MQL environment with an air temperature of -15 C. Application of MQL at -15 C increased the tool life by the factor of three by eliminating the formation of BUE on the cutting tool while not affecting the work piece material hardness. Kamata and Obikawa [31] pointed that in machining Inconels 718 the cooling effect is more significant than lubrication. It has been found that changing the lubricant carrier gas from air to argon reduces the tool life to that of dry cutting or even lower. This is attributed to the lower heat conductivity, specific heat and lubricating capability of argon in comparison with air.As mentioned before, the MQL method is considered as a lubricating method rather than cooling. This poor cooling capability limits the effectiveness of MQL in machining difficult-to- machine materials such as titanium and nickel based alloys where excessive heat generation is the main problem.

4.3. Cryogenic machining

Cryogenic machining is a term referred to machining operations conducted at very low temperatures typically lower than 120 K [32]. In cryogenic machining a super cold medium, usually liquefied gases, is directed in to the cutting zone in order to reduce the cutting zone temperature and cool down the tool and/or work- piece.

The cryogenic medium absorbs the heat from the cutting zone and evaporates in to the atmosphere. As most cryogenic coolants used in machining operations such as liquid nitrogen and liquid helium are made from air, they are not considered as pollutants for the atmosphere. Nitrogen in particular is a inert gas which forms 78% of the atmosphere and is lighter than air. As a result it is dispersed in to the atmosphere and does not harm the workers on the shop floor.

On the contrary carbon dioxide is considered as an air pollutant; however Liquid carbon dioxide could be produced from the exhaust gases of power plants thus not forcing additional contamination to the atmosphere. It is noteworthy that carbon dioxide is heavier than air and could cause CO2 accumulation and oxygen deficiency problems on the shop floor [33].

The cooling effect of the cryogens are particularly interesting in machining difficult-to-machine materials that suffer from excessive tool wear mainly due to high cutting temperatures such as titanium and nickel based alloys. Venugopal et al. [34] reported that applying LN_2 as a coolant in turning Ti-6Al-4V alloy resulted in 77% and 66% reduction in crator and flank wear, respectively, as compared to dry machining. The details are shown below

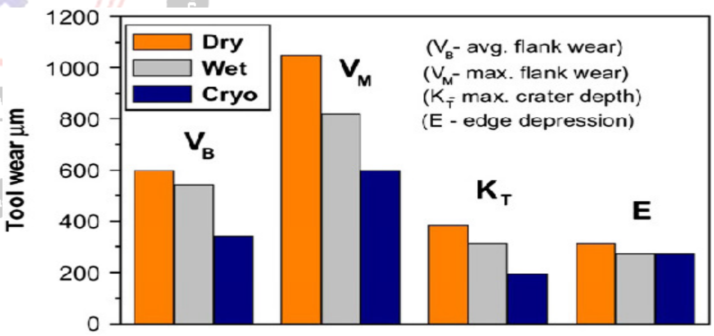

Fig 4: Comparison of tool wear in turning with carbide tools

It has been proved [36] that some cryogenic coolants such as LN2 do not only act as a coolant but has good lubrication characteristics. LN2 could be penetrated between the tool-chip interface and produce a gas/liquid cushion which reduces the friction at second shear zone.

Cryogenic cutting environment could also increase the strength and hardness of the work piece material hence increasing the cutting forces [36]. Higher cutting forces could reduce the tool life, increase vibration and chatter and thus surface roughness.

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4.4. Air cooling

Employing chilled and compressed air for cooling in machining operations is a relatively new technique which has attracted many researchers. As in this technique the cooling media is air, it could be defined as the cleanest and most environmentally friendly method of cooling in cutting operations. Using chilled air as coolant in machining resulted in longer tool life. The effect of chilled air on the surface finish is highly dependent on the machining parameters. In general it could be claimed that air cooling produces lower surface roughness than dry cutting. However, the produced surface roughness is higher than MQL. Liu and Kevinchou [37] studied the effects of chilled air produced by a vortex tube in turning A390 aluminium with an uncoated WC tool. Studies showed that at the cutting speed of 5 m/s and feed rate of 0.055 mm/rev chilled air reduced the flank wear by 20%. In addition the cooling system was found to be effective in reducing the tool-chip contact temperature up to 7%.

Rahman et al. [38] reported that in end milling AISI P-20 steel with uncoated tool machining at -30 C produced lower surface roughness than flood cooling only at higher feed rates. Whilst at the feed rate of 0.01 mm/tooth chilled air cooling produced the highest surface finish, increase in the feed rate reduced the surface finish where at the feed rate of 0.02 mm/tooth chilled air resulted in the lowest surface roughness irrespective of the cutting speed.

Sun et al. [39] used cryogenically cooled air and compressed air in turning Ti64. They also found that while chilled air cooling increased the cutting forces, the average cutting forces reduced in comparison with dry machining due to reduction in the tool wear. They reported that in dry machining cutting forces along the x, y and z axes increased by 54%, 41%, 23%, respectively, while it was 30%, 16% and 6% for compressed air and 17%, 7%, 4% for cryogenically cooled air. However, studies revealed that this is not the case in milling operations.

Yuan et al, [30] stated that using chilled MQL the tool life increased by a factor of three in machining Ti64 using uncoated cutting tool. In addition, they noted that the best results in terms of tool life and surface roughness were achieved using MQL at the temperature of -15 C compared to dry, wet, MQL at 0, -30 and -45 C.

V. Conclusion

The Using cutting fluids is a traditional approach for reducing the temperature and friction at the cutting zone [1]. They are considered as hazardous substances for the workers' health and environment. Extending governmental and environmental regulations have limited the usage and increased the costs associated with cutting fluids. The best approach to reduce the usage of cutting fluids is dry cutting. However, it fails to produce desired tool life and surface finish in some cases due to the excessive generation of heat at the cutting zone. In order to realize the dry machining, improved cutting tool materials and further studies on the cutting parameters is inevitable. MQL is an effective way to lubricate the cutting zone, reduce the heat generation, extend the cutting speed limits and reduce the usage of the cutting fluids; it is not an effective cooling method. This is the case especially in machining engineering alloys where the temperature at the cutting zone could reach the melting point of the work piece. Using air as coolant has been studied for several years. However it is known that air has poor thermal conductivity and cooling capability. Thus some researchers used chilled air to cool the cutting zone although the effect of the chilled air on the machinability is not consistent and is highly dependent on the cutting parameters and tool-material pairing. Using cryogenic LN2 is acknowledged as an effective technique to improve the tool life. However the literature has revealed that the effects of cryogenic cooling are not consistent for all tool-work piece material pairs and cryogenic cooling techniques. The main reason behind this is that cryogenic temperatures change the properties of the tool and work piece materials but to a different extent. None of the above mentioned techniques could be mentioned as a general method to be used for all tool-piece material pair. Indeed at the current stage each of the techniques has benefits and disadvantages.

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