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RESEARCH ARTICLE

A REVIEW ON MACHINING PROCESS AND COOLING TECHNIQUES IN MACHINING: MILLING AND CUTTING OPERATION

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ABSTRACT

Machining is a major part of metal working that plays an important role in metal cutting and forming. In machining, the machine tools especially cutting tools play an important role in effective metal cutting. This is because of their roles in producing different shapes and forms. The importance of machining in modern automated manufacturing systems has, in fact, increased due to the significant increase in the production time and the need to offset the high capital investment. The need for improving the technological performance of machining operations, as assessed by the cutting temperature, cutting force, tool life and surface finish has long been recognized, to increase the economic performance of the machining operations.

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INTRODUCTION

Milling Process

Milling is one of the common high-production machining methods. It is accomplished with a cutting tool called a milling cutter. A milling cutter is a multiple edge tool, which is a revolving body with cutting elements called teeth, arranged on the circumferential surface, or on the end faces or both. The primary cutting motion in milling is rotation, which is imparted to the cutter. The feed motion is usually imparted in a straight line to either the cutter or the work piece. Milling is typically used to produce parts that are not axially symmetric and have many product features, such as holes, slots, pockets and even three dimensional surface contours. The milled surfaces are largely used to mate with other parts in die, aerospace, automotive, and machinery design as well as in manufacturing industries (Lee and Lin 2000).

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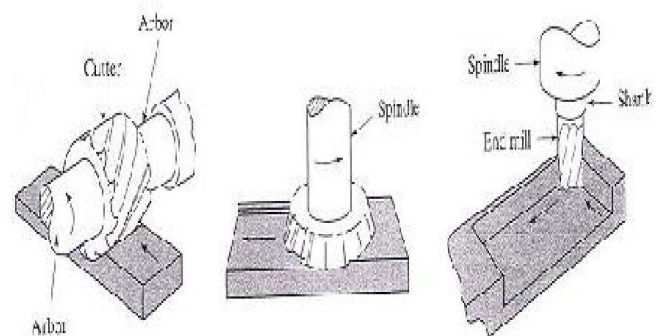


Figure 1. Milling processes

Metal Cutting

During metal cutting, the energy dissipated gets converted into heat. Consequently, high temperatures are generated in the region of the tool cutting edge, and this temperature has a controlling influence on the rate of wear of the cutting tool, and on the friction between the chip and the tool.

Longbottom (2005) described that during the machining process, a considerable amount of the machining energy is transformed into heat through plastic deformation of the workpiece surface, the friction of the chip on the tool face, and the friction between the tool and the workpiece. Figure 2 shows the heat generation zones in the metal cutting process. There are three main sources of heat generation during the process of metal cutting.

- Heat is produced in the primary shear zone as the workpiece is subjected to large irreversible plastic deformation.
- Heat is produced by friction and shear on the tool rake face, or secondary shear zone. The chip material is further deformed and some of them adhere to the tool face. In this region the last layer of the atoms of the chip material are stationary. The velocity of the adjacent layers gradually increases until the bulk chip velocity is attained. Thus, there exists both sticking and sliding friction. This combined shear and friction action produces heat.
- Heat is also produced at the tool – work interface, where the tool flank runs along the workpiece surface, and generates heat through friction.

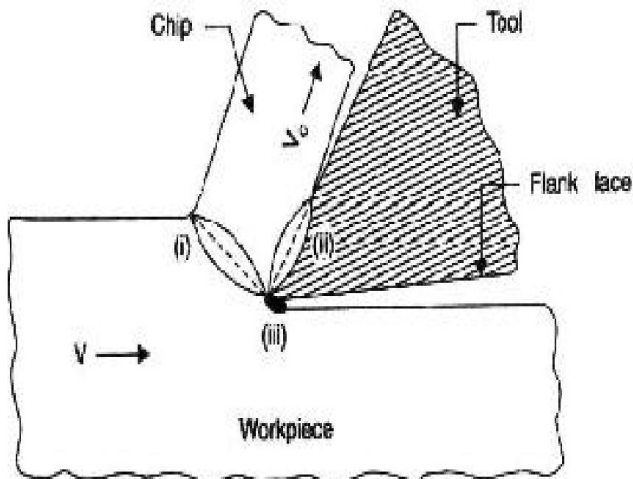


Figure 2. Heat generation zone in metal cutting

The heat generation becomes more intensified in machining of difficult-to-cut materials because the machining process requires much more energy than that in cutting a low strength material. As a result, the cutting temperatures in the tool and workpiece rise significantly during machining of difficult-to-cut materials. The higher the temperature at the cutting edge, the higher will be the softening of the tool and the higher the thermal stresses resulting in failure of the tool. High cutting temperatures strongly influence tool wear, tool life, workpiece surface integrity, chip formation mechanism and contribute to the thermal deformation of the cutting tool (Takeuchi *et al.*, 1982). The temperature generated in the region of the tool tip during metal cutting, controls the rate of tool wear, the practical cutting speed and the metal removal rate. The tool life is more dependent upon the chip – tool interface temperature, than on the total amount of heat flowing into the tool and workpiece. The cutting temperature is a decisive factor for other machinability indices such as the cutting force, surface finish and tool wear. It was reported that approximately 80%

of the generated heat is dissipated by the chip, about 18% by the tool and the rest by the work surface (HMT 2006).

Types of Milling Operations

The different types of milling operations include peripheral or slab milling, face milling and end milling and they can be utilized depending on the machining requirements as shown in Figure 1.

(a) Slab milling (b) Face milling (c) End milling

In peripheral milling or slab milling, the cutting tool has teeth located on the periphery of the cutter body. The axis of the cutter rotation is generally in a plane parallel to the work-piece surface to be machined. In face milling, the rotating cutting tool axis is perpendicular to the workpiece during the cutting. The milled surface is located on the periphery and face of the cutter. In end milling, the cutting tool rotates vertically with the workpiece. The cutting teeth are located on both the end face and the periphery of the cutter body (Trent and Wright 2000).

End Milling

End milling is a commonly used machining process in industry. The ability to control the process for better quality of the final product is of paramount importance. End Milling is an intermittent metal removal process, in which the material from the work piece is removed by a rotating tool comprising of multiple numbers of cutting edges mounted vertically in a spindle.

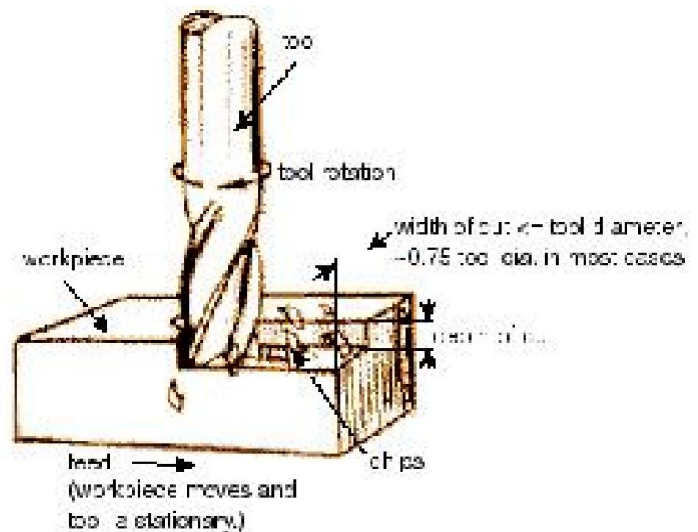


Figure 3. End milling process

During the cutting process, each cutting edge engages itself into and disengages itself from the work piece, thereby causing the process intermittent. Figure 3 shows the basic end milling process.

Cutting Tools

The cutting tools vary based on the specific purpose of cutting preference. The various types of end mill are given below:

- Solid End Mill
- Ball End Mill
- Tapered End Mill
- Roughing End Mill
- Shell End Mill

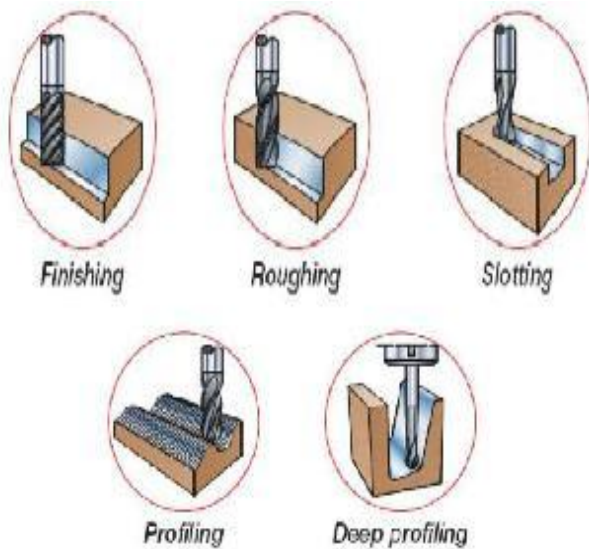


Figure 4. Various types of end milling operations

Solid end mills are the most generic type of milling cutter and they are suitable for light and medium cutting. The face of the solid end mill is perpendicular to the axis of the cutter. The solid end mill has either two or four flutes, though it is possible to have more. The number of flutes on a milling cutter strongly influences the cutter's usage. The ball end mill has a hemispherical end. The radius of the hemispherical end and the end mill body are equal. Half round channels can be easily machined by ball end mills. Ball end mills are also used for die making to make complex internal curves. Usually, ball end mills are solid and two fluted.

The tapered end mill is similar to a standard end mill, except that the tool itself is tapered (thicker at the top than at the bottom). It is also used for die making when a specific angle edge cut is the custom. Roughing end mills are used for roughing, or removing greater amount of metals quickly. It is similar to a standard end mill that has threaded cutting edges. Normally these types of mills have four flutes. Shell end mills look like solid end mills, with only the shell and the centre removed. End mill cutter have traditionally been made from high speed steel, but are now mostly made of tungsten carbide, a rigid and wear-resistant material, usually pressed from carbide powder into rods, which are then ground into blanks of industry-standard sizes. A variety of end mill tools are being made and used nowadays. In this research work, the traditional solid end mills are replaced by better cost-effective inserted cutting tools. These end mill cutting inserts are initially more expensive. However, inserted cutting tools do reduce tool – change times, and permit much simpler replacement of worn or broken cutting edges, instead of having to replace the entire tool. The indexable inserts were clamped with the turn of a key into the tool holder. This indexable insert type tool holder not only provides good support and retention, but also improving

dimensional accuracy and high degree of flatness, which determine the appropriate cutting geometry and chip breaking. The cutting tool body has to provide the accurate positioning and secure good support of the cutting inserts under tough working conditions.

Effect of Temperature Raise in Metal Cutting

In machining operations, the energy dissipated in cutting operations is converted into heat which will consequently increase the temperature in the cutting zone. The raise in temperature during cutting is important because (Kalpakjian and Schmid 2003):

- It affects the strength, hardness and wear resistance of the cutting tool.
- It causes dimensional changes in the part being machined, thus causing difficulty in controlling the accuracy.
- It causes thermal damage to the workpiece and affects its properties and service life.
- It causes distortion in the machine, due to the machine tool being subjected to elevated and uneven temperature, thus affecting the dimensional control of the workpiece.

The heat generations in intermittent machining operations like milling differ significantly from the heat generations in continuous cutting operations, such as turning. In milling operations the tool is subjected to cyclic heating and cooling, when the tool enters and exits the workpiece material. This leads to a phenomenon known as thermal fatigue (Wang *et al.*, 1996). Generally, thermal fatigue plays a significant role in shortening the tool life for tungsten carbide tools during the milling operation, where the cutter teeth gets heated intermittently at the corners, through contact with the workpiece. This causes cracks to develop in the tool and ultimately leads to thermal fracturing of the tool (Wang *et al.*, 1996). The temperatures attained in metal cutting are important, only so far as they affect the thermally activated mass transport phenomenon at the work – tool interface contacts. These may involve interfacial diffusion and alloy formation or self diffusion, resulting in creep and/or softening of the tool material. The mutual diffusion of materials at the chip-tool contact is a significant cause for the formation of crater wear. Crater wear is essentially an exponential function of the average chip – tool interface temperature, provided the temperature is sufficient to cause interfacial diffusion (Kuppuswamy 1996). Kitagawa and Maekawa (1990) and Mazurkiewicz *et al* (1989) have reported that the temperature of the cutting tool in machining plays an important role in thermal distortion, and the dimensional accuracy of the machined part, as well as tool life. Brown and Hinds (1985) have reported that the high temperature at the cutting zone results in dimensional deviations, fast oxidation and corrosion, thermal residual stresses and micro cracks on the workpiece.

Variables Affecting Cutting Temperature

Workpiece and Tool Material

The mechanical properties of the workpiece material, particularly the tensile strength and hardness, have a considerable influence on the cutting temperature. Generally, as more energy is required for chip formation, more heat is

generated, resulting in a corresponding increase in the cutting temperature. In addition, the thermal properties of the workpiece material also influence the rise in temperature. The higher the thermal conductivity, the lower is the rise in temperature. The performance of a cutting tool is dependent on the form stability of the cutting edge, which in turn is mostly dependent on the hardness and thermal conductivity of the tool – work materials (Sreejith and Ngoi 2000)

Cutting Conditions

In a given combination of the work and tool material, the cutting temperature depends upon the cutting speed, feed and depth of cut, and to a limited extent, the cutting fluids. Among these factors, cutting speed has a predominant effect. The mean temperature is proportional to the cutting speed and feed as follows: Mean Temperature $\propto V^a f^b$, where a and b are constants depending on the tool and workpiece materials, V is the cutting speed and f is the feed of the tool (Kalpakjian and Schmid 2000, Shaw 2005 and Thomas Childs *et al.*, 1999).

Cutting Fluid

One of the important functions of the cutting fluid is to conduct the heat away from the tool and workpiece interface and avoid heat accumulation and temperature build-up in the vicinity of the active cutting edge. The fluid would be carried away by the outward flowing chip more rapidly than it could be forced between the tool and the chip. The effectiveness of the cutting fluid in lowering the tool temperature decreases with an increase in cutting speeds, and at higher speeds the fluids become completely ineffective in reducing the temperature. A flood of cutting fluid directed over the back of the chip loses its effectiveness at higher cutting speeds (Kovacevic *et al.*, 1995).

Tool Geometry

The geometry of cutting tool has a significant effect on machining performance. Among various parameters of tool geometry, radial rake angle is one of the most important parameters, which determines the tool and chip contact area and hence affects the power consumption. A negative rake tool requires more energy input, since the tool contact area is correspondingly increased. In addition, owing to a more massive tool point, the heat flow into the shank is more effective and the temperature level is maintained. With an increase in the approach angle, the cutting temperature increases, since, for the same feed and depth of cut, the chip thickness increases. The nose radius of the tool has an influence on the total heat generation and its distribution. A large nose radius raises the cutting temperature, but at the same time it promotes the heat flow, as the contact area is also increased for a given combination of work and tool material (HMT 2006).

Conventional Coolants

Historically, cutting fluids have been used extensively for the last 200 years. Cutting fluids are widely utilized to improve the process of machining operations such as turning, drilling, boring, grinding, and milling. The most common metal working fluids used today are either oil-based fluids including straight oils and soluble oils or chemical fluids including

synthetics and semi-synthetics. The primary function of the cutting fluid is temperature control through cooling and lubrication. Cooling and lubrication are critical in decreasing tool wear, extending the tool life and achieving the desired dimensional accuracy and surface finish. A secondary function of the cutting fluid is to flush away chips and metal fines from the tool/workpiece interface, to prevent a finished surface from becoming marred, and also to reduce the occurrence of a built-up edge. However, a conventional coolant fails to penetrate into the chip – tool interface, and hence the coolant cannot remove the heat effectively, due to the bulk chip-tool contact under high cutting velocity and feed, where the temperature is the maximum (Shaw *et al.*, 1951, Merchant 1958, Cassin and Boothroyd 1965 and Kitagawa *et al.*, 1997). Furthermore, the presence of extreme pressure additives in the cutting fluids is also one of the reason that prevent the cutting fluid to penetrate into the tool – chip interface.

Conventional cutting fluids pose serious health and environment hazards. People exposed to cutting fluids may have health problem when these fluids contacts the skin, inhale mists or vapour, or even swallow mists particles. Due to their toxicity, they may cause health problems, like dermatitis, problems in the respiratory and digestive systems and even cancer. Recent studies have reported increased rates of respiratory effects, including pneumonia, asthma, chronic bronchitis and impaired pulmonary function (Ameille *et al.*, 1995 and Greaves 1997). According to some extensive assessments of current and past coolant exposures in relation to cancer mortality, an elevated risk of pancreatic cancer was also reported for all workers exposed to synthetics (Bardin *et al.*, 1997, Ely *et al.*, 1970). Improper disposal of these cutting fluids may even cause serious environmental problems, such as water pollution and soil contamination. Strict regulations and their enforcement against using cutting fluids has therefore, been tightened. Thus, the waste disposal and post handling of the cutting fluids and other related costs have increased substantially with tougher environmental laws. Companies and organizations are being forced to implement strategies to reduce the usage of cutting fluids in their machining operations. Further, extra floor space and additional systems are required for pumping, storage, filtration and recycling of the conventional coolants (Howes *et al.*, 1991, Byrne and Scholta 1993, Klocke and Eisenblatter, 1997, Sreejith and Ngoi 2000, Sutherland *et al.*, 2000 and Dhar *et al.*, 2002).

Sokovic and Mijanovic (2001) have reported that on the shop floor, the operators may be affected by the bad effects of cutting fluids, such as skin and breathing problems. Chen *et al* (2000) and Barry and Byrne (2002) have stated that the cooling lubricant causes an increase both in the worker's health and social problems, related to their use (working environment), and correct disposal (ecological aspect). This, in turn, means an increase in the costs for the manufacturing companies. Therefore, there is a need to look for new coolant application techniques. Cryogenic cooling is an effective cooling technique that does not pollute the environment, and hence it is becoming very popular. Besides pollution control, the industries also reasonably derive economic viability through technological benefits, in terms of product quality, tool life and saving in power consumption by using the cryogenic cooling technique.

Cryogenic Cooling

Cryogenics are defined as working at very low temperatures, below -150°C (123K). Various gases such as nitrogen, helium, oxygen, hydrogen, and neon can be utilized. In cryogenics, the normal boiling point of such gases lies below -180°C (93K). Cryogenic cooling has wider applications in industries, such as manufacturing, automotive, aerospace, electronics, food processing, and health, for cooling purposes. Liquid nitrogen is the most commonly used element in cryogenics. At atmospheric pressure, molecular nitrogen condenses (liquefies) at -196°C and freezes at -210°C ; it is the most abundant gas, and composes about four-fifths (78.03%) by volume of the atmosphere. The LN₂ in a cryogenic machining system quickly evaporates and goes back into the atmosphere, leaving no residue to contaminate the part, chips, machine tool, or operator, thus eliminating disposal costs. It is a colorless, odorless, tasteless, non-toxic and non-flammable gas. These characteristics of liquid nitrogen have made it a preferred coolant (Yakup and Muammer 2008).

Cryogenic cooling is a process which reduces the cutting temperature in the metal cutting process, by applying cryogenic fluids as the coolants. When liquid nitrogen is used as a coolant, it is environmentally safe (Kalyan Kumar and Choudhury 2008) and requires no disposal facilities. To economize the cryogenic machining process, liquid nitrogen consumption must be minimized by applying it judiciously to the cutting area. Cryogenic cooling provides improved tool life, lesser cutting force, better surface finish, better chip breaking and chip handling, better dimensional accuracy, higher productivity and lower production cost.

Conclusion

This review paper focuses on milling and cutting operations. Further types of milling operations, cutting tools and variables affecting cutting temperature are studied in detail. Cooling techniques play a vital role by reducing the temperature in cutting vicinity of the material. It is necessary so as to achieve higher tool life and reduced cutting forces during machining. Cryogenic cooling proves better results over conventional cooling techniques.

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