

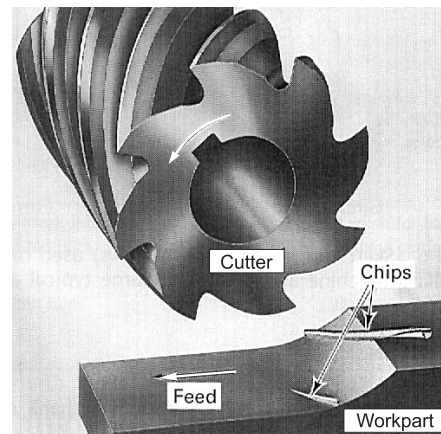
## 6.2 MILLING

### Introduction

Milling is a process of producing flat and complex shapes with the use of multi-tooth cutting tool, which is called a *milling cutter* and the cutting edges are called *teeth*. The axis of rotation of the cutting tool is perpendicular to the direction of feed, either parallel or perpendicular to the machined surface. The machine tool that traditionally performs this operation is a *milling machine*.

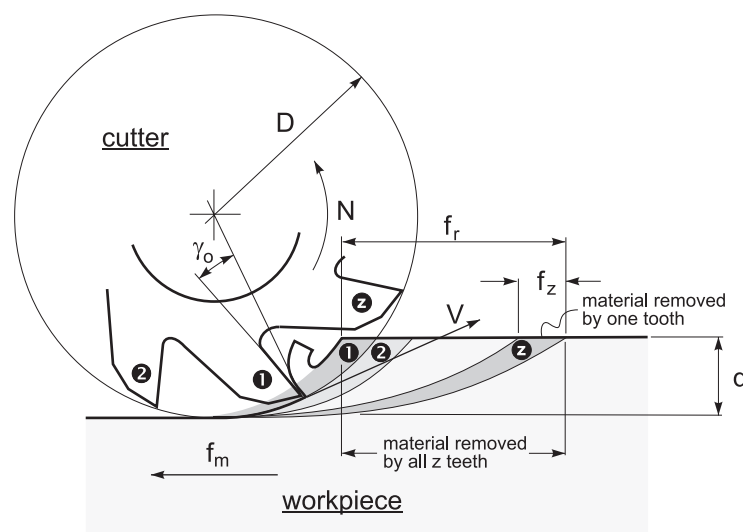
Milling is an interrupted cutting operation: the teeth of the milling cutter enter and exit the work during each revolution. This interrupted cutting action subjects the teeth to a cycle of impact force and thermal shock on every rotation. The tool material and cutter geometry must be designed to withstand these conditions. Cutting fluids are essential for most milling operations.

Milling operation. The cutter is lifted to show the chips, and the work, transient, and machined surfaces.



### Cutting conditions in milling

In milling, each tooth on a tool removes part of the stock in the form of a chip. The basic interface between tool and workpart is pictured below. This shows a only a few teeth of a peripheral milling cutter:



Basics of a peripheral (slab) milling operation.

Cutting velocity  $V$  is the peripheral speed of the cutter is defined by

$$V = \pi DN$$

where  $D$  is the cutter outer diameter, and  $N$  is the rotational speed of the cutter.

As in the case of turning, cutting speed  $V$  is first calculated or selected from appropriate reference sources (see *Section 5.10 Selection of Cutting Conditions*), and then the rotational speed of the cutter  $N$ , which is used to adjust milling machine controls is calculated. Cutting speeds are usually in the range of 0.1–4 m/s, lower for difficult-to-cut materials and for rough cuts, and higher for non-ferrous easy-to-cut materials like aluminum and for finishing cuts.

Three types of *feed* in milling can be identified:

- ① *feed per tooth*  $f_z$ : the basic parameter in milling equivalent to the feed in turning. Feed per tooth is selected with regard to the surface finish and dimensional accuracy required (see *Section 5.10 Selection of Cutting Conditions*). Feeds per tooth are in the range of 0.05–0.5 mm/tooth, lower feeds are for finishing cuts;
- ② *feed per revolution*  $f_r$ : it determines the amount of material cut per one full revolution of the milling cutter. Feed per revolution is calculated as

$$f_r = f_z z$$

$z$  being the number of the cutter's teeth;

- ③ *feed per minute*  $f_m$ : Feed per minute is calculated taking into account the rotational speed  $N$  and number of the cutter's teeth  $z$ ,

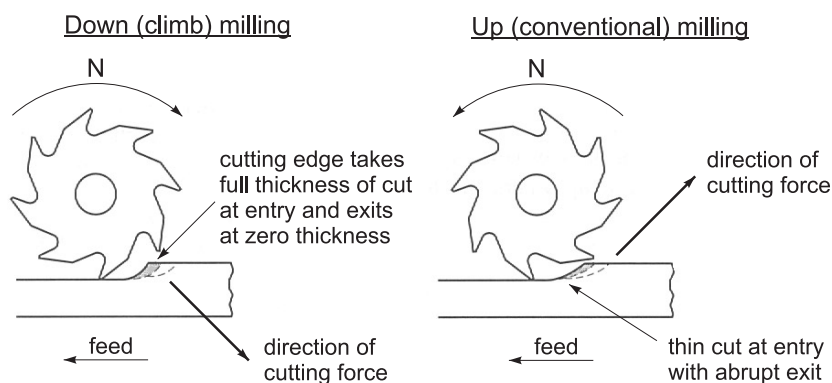
$$f_m = f_z z N = f_r N$$

Feed per minute is used to adjust the feed change gears.

## Types of milling

There are two basic types of milling, as shown in the figure:

- ① *down (climb) milling*, when the cutter rotation is in the same direction as the motion of the workpiece being fed, and
- ② *up (conventional) milling*, in which the workpiece is moving towards the cutter, opposing the cutter direction of rotation:



Two types of peripheral milling. Note the change in the cutting force direction.

In down milling, the cutting force is directed into the work table, which allows thinner workparts to be machined. Better surface finish is obtained but the stress load on the teeth is abrupt, which may damage the cutter.

In up milling, the cutting force tends to lift the workpiece. The work conditions for the cutter are more favourable. Because the cutter does not start to cut when it makes contact (cutting at zero cut is impossible), the surface has a natural waviness.

## Milling Operations

Owing to the variety of shapes possible and its high production rates, milling is one of the most versatile and widely used machining operations. The geometric form created by milling fall into three major groups:

- ❶ *Plane surfaces:* the surface is linear in all three dimensions. The simplest and most convenient type of surface;
- ❷ *Two-dimensional surfaces:* the shape of the surface changes in the direction of two of the axes and is linear along the third axis. Examples include cams;
- ❸ *Three-dimensional surfaces:* the shape of the surface changes in all three directions. Examples include die cavities, gas turbine blades, propellers, casting patterns, etc.

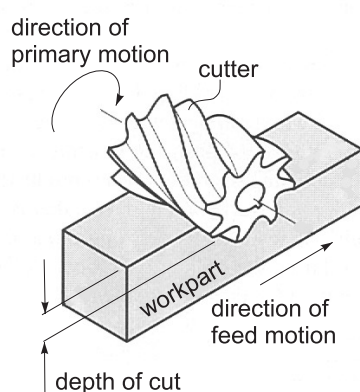
### MILLING OF FLAT SURFACES

#### Peripheral Milling

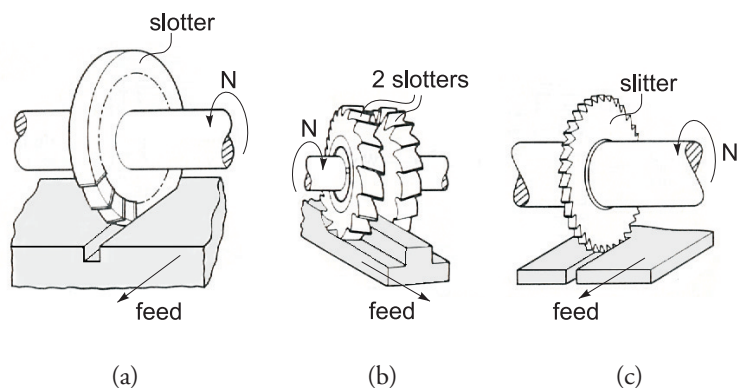
In *peripheral milling*, also called *plain milling*, the axis of the cutter is parallel to the surface being machined, and the operation is performed by cutting edges on the outside periphery of the cutter. The primary motion is the rotation of the cutter. The feed is imparted to the workpiece.

Several types of peripheral milling are shown in the figure,

- ❖ *slab milling*, the basic form of peripheral milling in which the cutter width extends beyond the workpiece on both sides;
- ❖ *slotting*, also called *slot milling*, in which the width of the cutter, usually called *slotter*, is less than the workpiece width, creating a slot in the workpiece. The slotter has teeth on the periphery and over the both end faces. When only the one-side face teeth are engaged, the operations is known as the *side milling*, in which the cutter machines the side of the workpiece;
- ❖ *straddle milling*, which is the same as side milling, only cutting takes place on both sides of the work. In straddle milling, two slotters mounted on an arbor work together;
- ❖ when the slotter is very thin, the operation called *slitting* can be used to mill narrow slots (slits) or to cut a workpart in two. The slitting cutter (*slitter*) is narrower than the slotter and has teeth only on the periphery.



Peripheral slab milling operation.



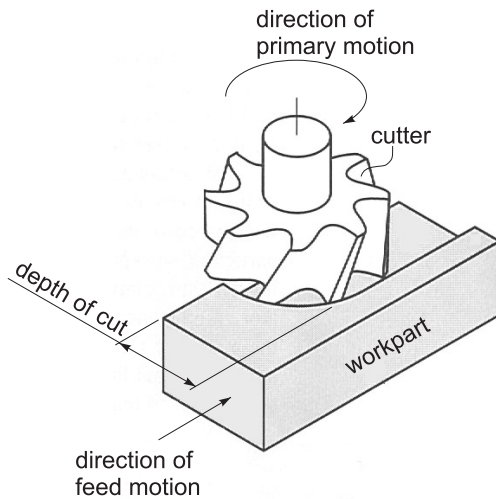
Peripheral milling operations with narrow cutters: (a) slotting, (b) straddle milling, and (c) slitting.

Some of the advantages of peripheral milling include,

- ❖ More stable holding of the cutter. There is less variation in the arbor torque;
- ❖ Lower power requirements;
- ❖ Better work surface finish.

## Face milling

In *face milling*, cutter is perpendicular to the machined surface. The cutter axis is vertical, but in the newer CNC machines it often is horizontal. In face milling, machining is performed by teeth on both the end and periphery of the face-milling cutter. Again up and down types of milling are available, depending on directions of the cutter rotation and feed.



Partial face milling operation. The face-milling cutter machines only one side of the workpiece.



Conventional face milling operation. The face-milling cutter machines the entire surface. The cutter diameter is greater than the workpart width.

Face milling is usually applied for rough machining of large surfaces. Surface finish is worse than in peripheral milling, and feed marks are inevitable. One advantage of the face milling is the high production rate because the cutter diameter is large and as a result the material removal rate is high. Face milling with large diameter cutters requires significant machine power.

## End milling

In *end milling*, the cutter, called *end mill*, has a diameter less than the workpiece width. The end mill has helical cutting edges carried over onto the cylindrical cutter surface. End mills with flat ends (so called *squire-end mills*) are used to produce pockets, closed or end key slots, etc.:



End milling operation used to cut a pocket in an aluminum workpart.

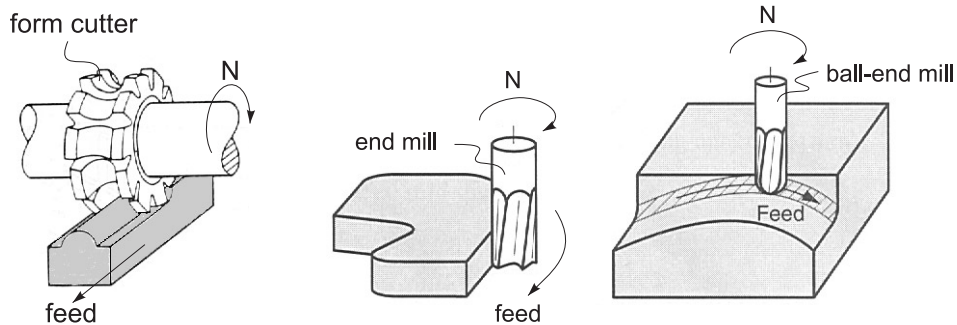


## MILLING OF COMPLEX SURFACES

Milling is one of the few machining operations, which are capable of machining complex *two- and three-dimensional surfaces*, typical for dies, molds, cams, etc. Complex surfaces can be machined either by means of the cutter path (*profile milling* and *surface contouring*), or the cutter shape (*form milling*).

### Form milling

In form milling, the cutting edges of the peripheral cutter (called *form cutter*) have a special profile that is imparted to the workpiece. Cutters with various profiles are available to cut different two-dimensional surfaces. One important application of form milling is in gear manufacturing (*Section 6.6*).



Form milling of two-dimensional surface.

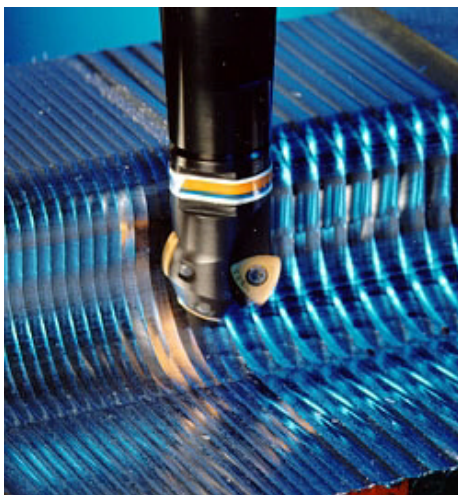
(Left) Profile milling of a cam, and (Right) Surface contouring of a complex three-dimensional surface.

### Profile milling

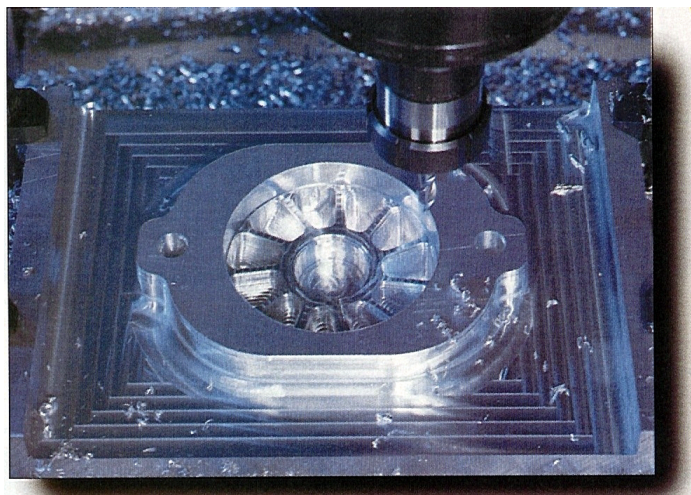
In profile milling, the conventional end mill is used to cut the outside or inside periphery of a flat part. The end mill works with its peripheral teeth and is fed along a curvilinear path equidistant from the surface profile.

### Surface contouring

The end mill, which is used in surface contouring has a hemispherical end and is called *ball-end mill*. The ball-end mill is fed back and forth across the workpiece along a curvilinear path at close intervals to produce complex three-dimensional surfaces. Similar to profile milling, surface contouring require relatively simple cutting tool but advanced, usually computer-controlled feed control system.



Close-up view of a hemispherical ball-end mill with indexed carbide inserts used for rough cutting of a three-dimensional surface.



Surface contouring of die cavity. The cutter used is a high-speed steel ball-end mill.

## Milling machines

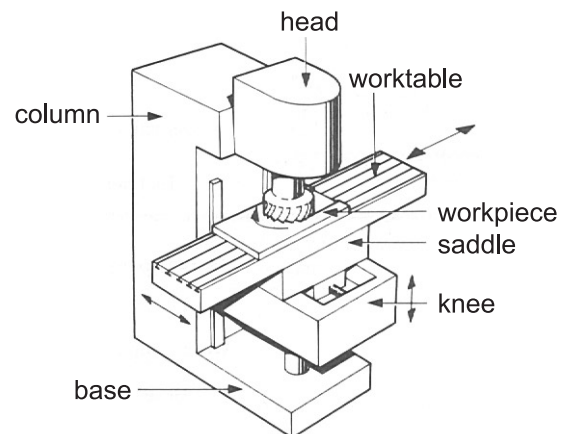
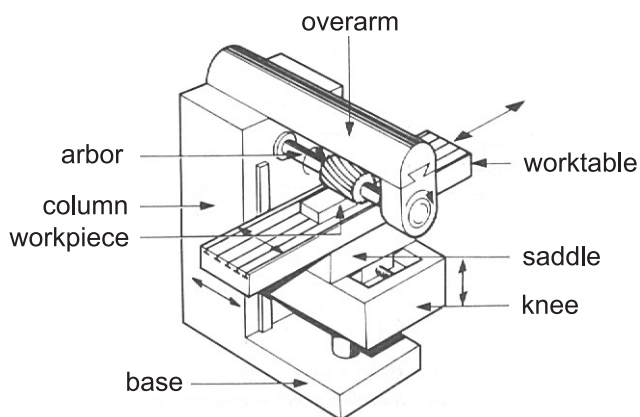
The conventional milling machines provide a primary rotating motion for the cutter held in the spindle, and a linear feed motion for the workpiece, which is fastened onto the worktable. Milling machines for machining of complex shapes usually provide both a rotating primary motion and a curvilinear feed motion for the cutter in the spindle with a stationary workpiece. Various machine designs are available for various milling operations. In this section we discuss only the most popular ones, classified into the following types:

- ❖ Column-and-knee milling machines;
- ❖ Bed type milling machines;
- ❖ Machining centers.

### Column-and-knee milling machines

The *column-and-knee milling machines* are the basic machine tool for milling. The name comes from the fact that this machine has two principal components, a *column* that supports the spindle, and a *knee* that supports the work table. There are two different types of column-and-knee milling machines according to position of the spindle axis:

- ① horizontal, and
- ② vertical.



Two basic types of column-and-knee milling machines, (*Left*) horizontal, and (*Right*) vertical.



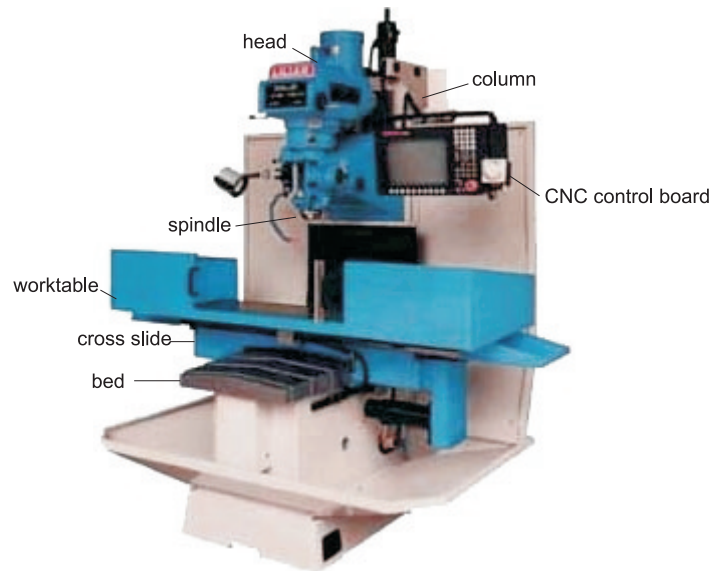
The column-and-knee milling machine is one of the most versatile machine tool suitable for most of the milling operations. There are many modifications of the basic type, some of them allow for worktable and/or head swivelling at an angular orientation to machine angular shapes on workparts. Many of modern column-and-knee milling machines are CNC type used to machine complex shapes.

CNC vertical column-and-knee milling machine.

## Bed type machines

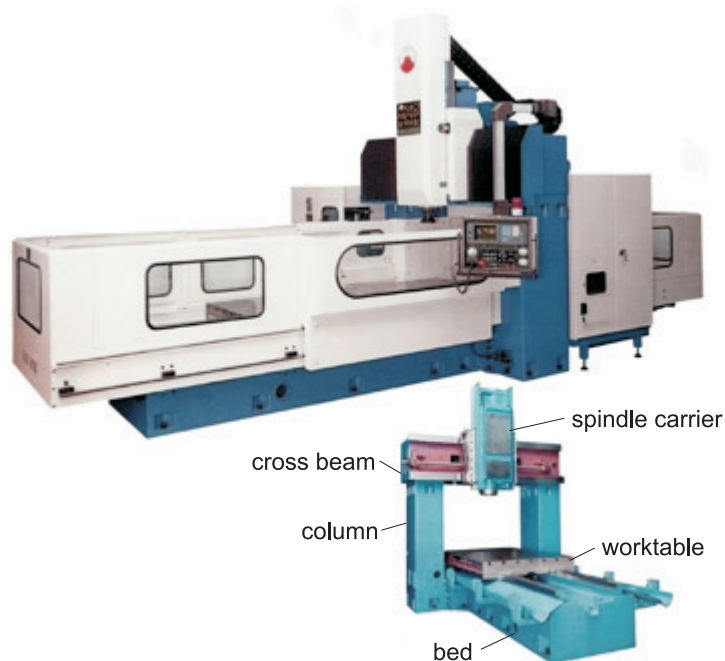
In bed type milling machines, the worktable is mounted directly on the bed that replaces the knee. This ensures greater rigidity, thus permitting heavier cutting conditions and higher productivity. These machines are designed for mass production.

Single-spindle bed machines are called *simplex mills* and are available in either horizontal or vertical models. *Duplex mills* have two spindle heads, and *triplex mills* add a third spindle mounted vertically over the bed to further increase machining capability.



CNC vertical bed type simplex milling machine.

One modification of bed type milling machines are the *planer-type mills*. They are the largest category of milling machine. Planer mills are designed to machine very large parts. The spindle carrier or carriers if more than one, is supported by a bridge structure (portal) that spans across the table.



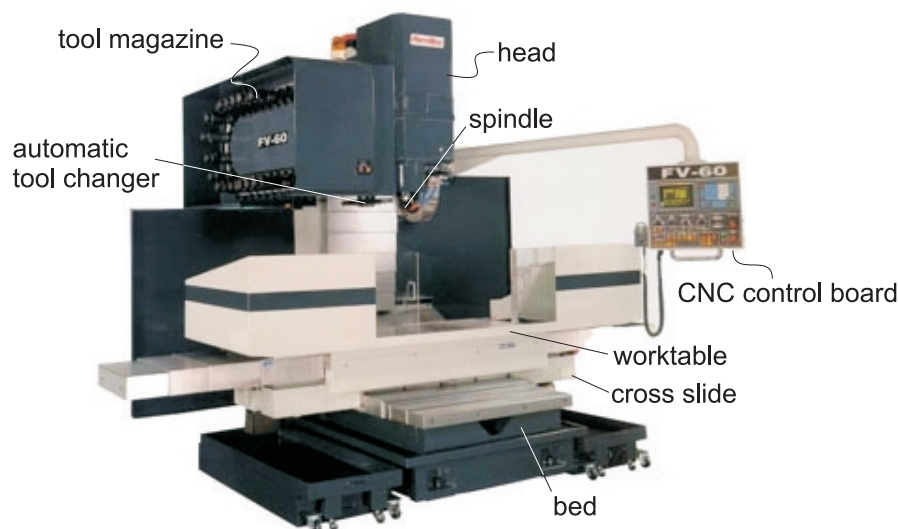
Portal planer mill for heavy machining of large workparts.



## Machining centers

A machining center is a highly automated machine tool capable of performing multiple machining operations under CNC control. The features that make a machining center unique include the following:

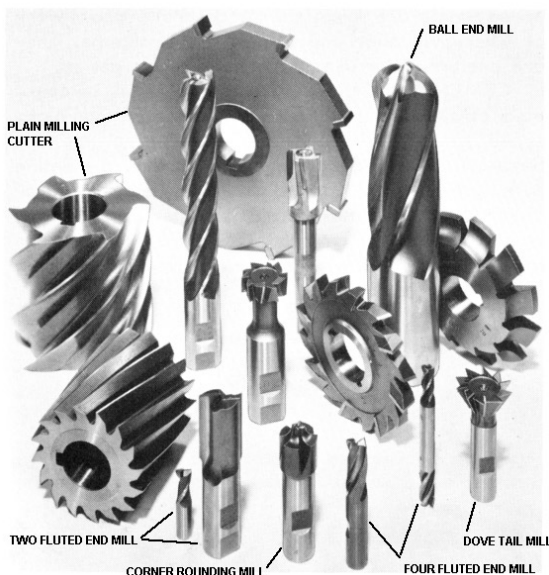
- ❖ Tool storage unit called *tool magazine* that can hold up to 120 different cutting tools.
- ❖ *Automatic tool changer*, which is used to exchange cutting tools between the tool magazine and machining center spindle when required. The tool changer is controlled by the CNC program.
- ❖ *Automatic workpart positioning*. Many of machining centers are equipped with a rotary worktable, which precisely position the part at some angle relative to the spindle. It permits the cutter to perform machining on four sides of the part.



Universal machining center.

## Milling cutters

Classification of milling cutters according to their design include the following:



- ❖ *HSS cutters*. Many cutters like end mills, slitting cutters, slab cutters, angular cutters, form cutters, etc., are made from high-speed steel (HSS).

Assortment of high-speed steel milling cutters. High-speed steel is the cutting tool material that is used to produce cutting tools of complex designs for low to medium cutting speeds.



- ❖ *Brazed cutters:* Very limited number of cutters (mainly face mills) are made with brazed carbide inserts. This design is largely replaced by mechanically attached cutters.
- ❖ *Mechanically attached cutters:* The vast majority of cutters are in this category. Carbide inserts are either clamped or pin locked to the body of the milling cutter.

Classification of milling cutters may also be associated with the various milling operations. The figures below illustrate two of the most important types of milling cutters, end mills and ball-end mills.



Two of the most widely used types of milling cutters with mechanically attached carbide inserts, (Left) end mills, and (Right) ball-end mills.

### *Process capabilities and process planning in milling operations*

The surface quality and dimensional accuracy achieved in different types of milling depend on the type of milling operation. For rough cuts, the best surface finish is  $R_a$  100~50  $\mu\text{m}$ , while for finishing cuts much better surface finish of  $R_a$  6.3~3.2  $\mu\text{m}$  could be achieved. These values are approximate and for machining of steel. When cutting gray cast iron or non-ferrous materials, the surface finish is a grade higher.

The process plan for milling of a single prismatic part includes the following basic steps:

- ① Cut off the stock slightly larger than required;
- ② Cut the basic outside dimensions to size using a milling machine;
- ③ Lay out the basic features of the parts (in manual setups, this involves coating the surface with a blue stain, this is then cut and marked);
- ④ Rough cut steps, radii, angles, grooves, etc.;
- ⑤ Lay out the holes to be drilled, and then drill them starting with a center drill and gradually increasing the drill diameter;
- ⑥ Finish cut part features;
- ⑦ Make internal threads and ream holes if required;
- ⑧ Deburr the finished part.

For mass production, the process plan is significantly changed.