2 Milling

Milling is a cutting process in which material is removed by a rotating multiple-tooth cutter. Milling includes a number of versatile machining operations, which are capable of producing a variety of configurations using a milling cutter - a multitooth tool that produces a number of chips in one revolution. Parts such as the ones shown in fig. 2.1. can be machined efficiently by use of various milling cutters and kinematics [7].

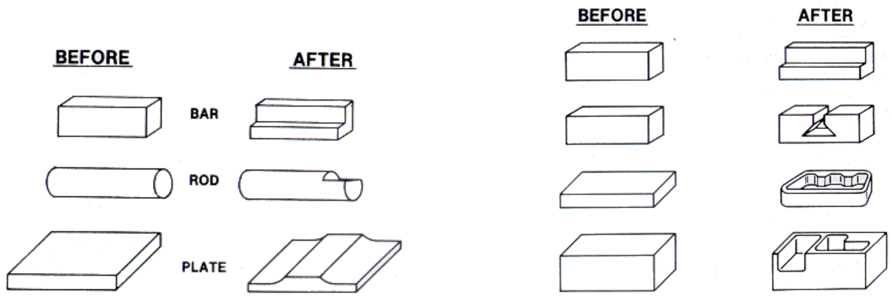

Fig. 2.1. Various shapes obtained by milling [15].

2.1. Kinematics

- primary motion – rotary motion of tool,
- feed motion – usually linear motion of workpiece.

2.2. Basic milling operations

2.2.1. Roller milling (slab milling, arbor milling)

In slab milling, the axis of cutter rotation is parallel to the machined workpiece surface (fig. 2.2). The cutter, generally made of high-speed steel, has a number of teeth along its circumference. Cutters used in roller milling may have straight or helical teeth producing orthogonal or oblique cutting action.

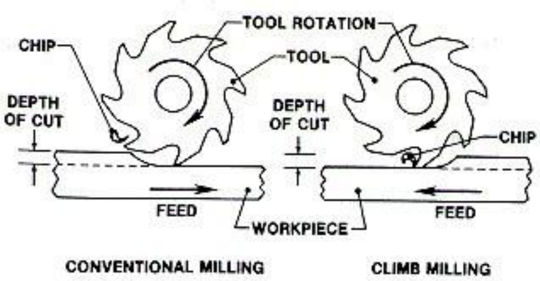

Fig. 2.2. Roller milling [15]

In this case the section of the cut is more complicated and changes from zero in the lowest point of cutting arc to the maximum value near the highest one (fig. 2.3).

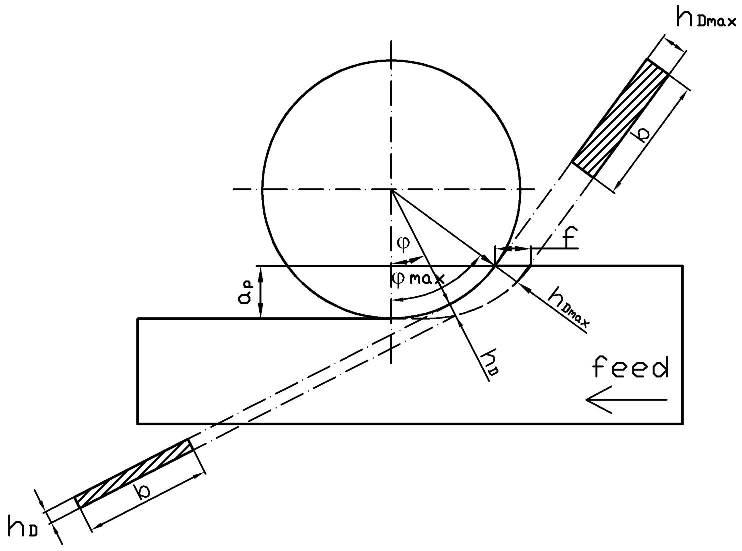

Fig. 2.3 Section of the cut for roller milling

2.2.1.1. Up-milling (conventional milling, out-cut milling)

In up-milling, the vectors of the cutting speed and feed speed in the lowest point of cutting line have reverse sense (fig. 2.4). Area of the cut increases from zero to maximum value at the end of the cut. Due to upward component of cutting force, the workpiece has tendency to be pulled upward. Thus proper clamping is important.

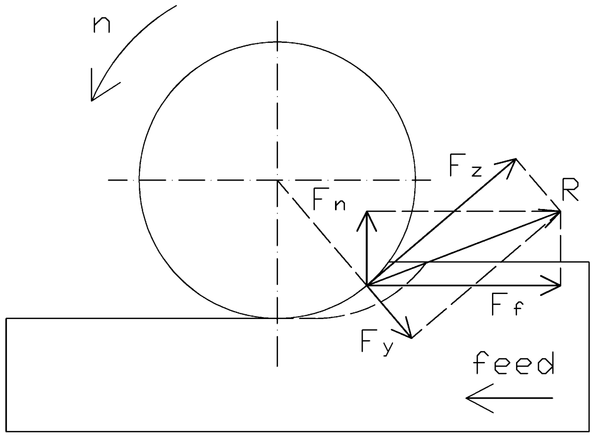

Fig. 2.4. Kinematics and components of cutting force while up-milling

2.2.1.2. Down-milling (climb milling, in-cut milling)

In down-milling, the cutting starts with the chip at its thickest location. The vectors of the cutting speed and feed speed have the same sense (fig. 2.5). The advantage is that the downward component of cutting force holds the workpiece in place, particularly for slender parts.
Generally the **down-milling** method is more expedient, but it has also a few important limitations.

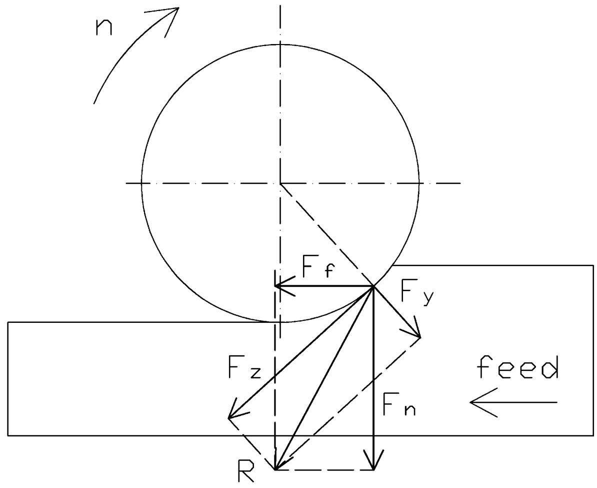

Fig. 2.5. Kinematics and components of cutting force while up-milling

2.2.1.3. Advantages of down-milling

1. Longer tool life, because there is no slip (friction) between the flank face and cut surface.
2. Better surface quality (lower roughness)
3. Better cooling of the blade
4. There is no hardening of the surface while machining.
5. Smaller tendency for the tool to chatter (vibration) – workpiece is held down by vertical component of cutting force
6. Smaller power for feed motion because of horizontal component of cutting force.
7. The downward component of cutting force holds the workpiece in place particularly for small, slender or thin-walled parts

2.2.1.4. Disadvantages of down-milling

1. Bigger pressure on the way - it is necessary to fit the machine tool with bigger or harder guideways.
2. Down-milling is not suitable for machining workpieces having surface scale , such as hot worked metals, forgings and castings.
3. Requirement of a rigid setup - backlash must be eliminated in the table feed mechanism because of the various direction of the lead screw loading.

2.2.2. End milling (face milling)

In end milling the cutter is mounted on a spindle having an axis of rotation perpendicular to the workpiece surface (fig. 2.6). The material is usually removed by both the end and the periphery of the tool. On occasion a single-point tool, such as a fly cutter, may be used. The end faces of some end mills have cutting teeth, and these can be used as a drill to start a cavity. End mills are also available with hemispherical ends for producing curved surfaces, as in making dies (*die sinking*) (fig. 2.7).
Face milling is a method of milling with a special tool – face mill (fig. 2.20.). This is a complex unit consisting on a tool holder and a number of cemented carbide tips. They are clamped to the adapter sockets of the tool holder.

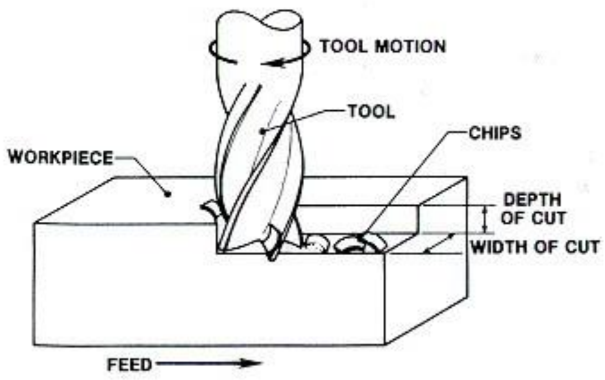

Fig. 2.6. End milling [15]

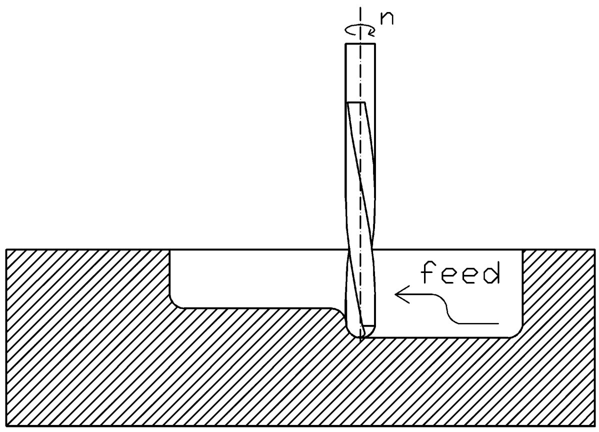

Fig. 2.7. Die sinking

2.2.3. Routing

In routing specially designed high speed cutters trim and shape a variety of machinable materials (fig. 2.8). Routing is typically limited to machining soft metals and rigid nonmetals. Cutter path is controlled by hand, with the aid of templates and routing fixtures, or by machine control.

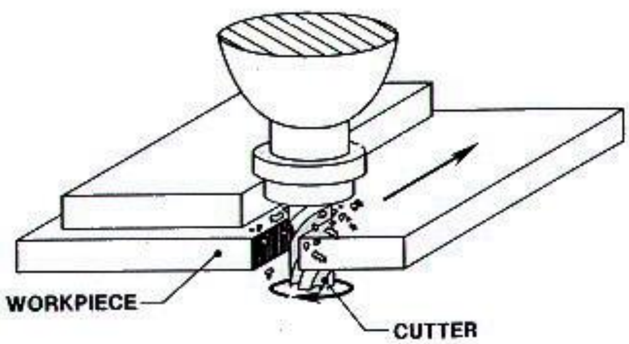

Fig. 2.8. Routing operation [15]

2.2.4. Other milling operations

- Form-end milling – using the form cutters the required shape of the part is obtained (fig. 2.9),

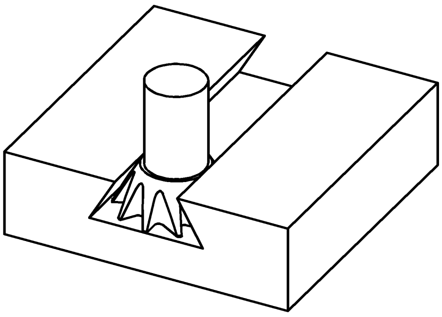

Fig. 2.9. Form-end milling

- Gang milling – the required shape is obtained by using a special gang-type cutter (tool combined by a set of typical ones) (fig. 2.10),

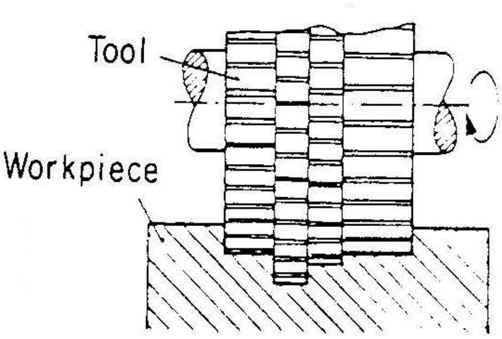

Fig. 2.10. Gang milling [14]

- Hobbing – generating method of gear cutting (fig. 2.11).

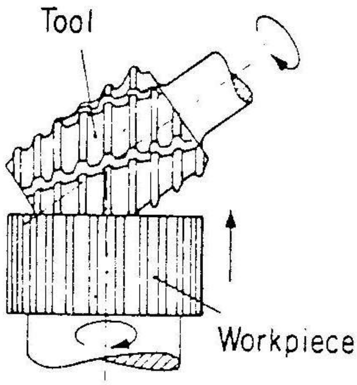

Fig. 2.11. Hobbing [14]

2.3. Machine tools [14]

Milling machine-tools (millers) belong to a large group of machine tools. However most of them have the same basic components [7]:

1. Work table, on which the workpiece is clamped, using the T-slots. The table moves longitudinally with respect to the saddle.
2. Saddle, which supports the table and can move transversely.
3. Knee, which supports the saddle and gives the table vertical movement for adjusting the depth of cut.
4. Overarm in horizontal machines, which is adjustable to accommodate different arbor lengths.
5. Head, which contains the spindle and cutter holders. In vertical machines the head may be fixed or vertically adjustable and can be swiveled in a vertical plane on the column for milling tapered surfaces.

2.3.1. Knee-type milling machines

In knee-type milling machines, the milling spindle is fixed. All co-ordinate movements are provided by a table and cross-slide, which are mounted on the knee and may be moved vertically (fig. 2.12). As the masses have to be moved in a vertical direction, this design is only applied for smaller machines.
The main spindle may be placed into vertical or horizontal bearings. With the use of an angular milling head, a horizontal machine may be converted into a vertical one (fig. 2.13).
In fig. 2.14., a vertical knee-type milling machine is shown. Its main use is for end-milling operations.
Horizontal milling machines are applied for the production of flat surfaces and slotted forms.

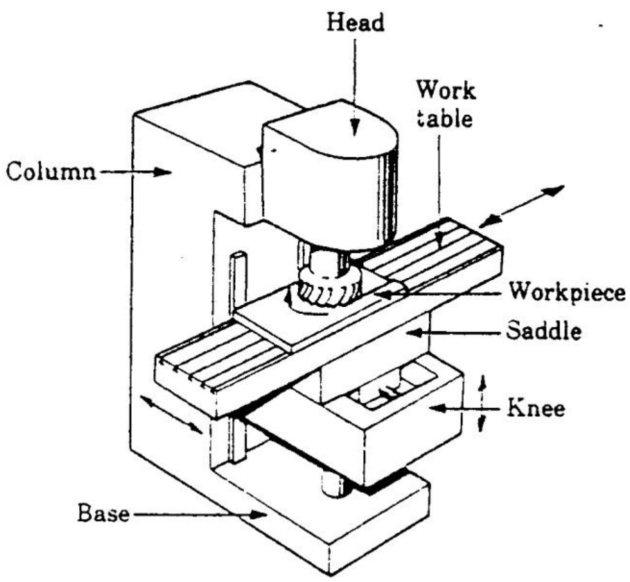

Fig. 2.12. Schematic illustration of a vertical-spindle column-and-knee-type milling machine [7].

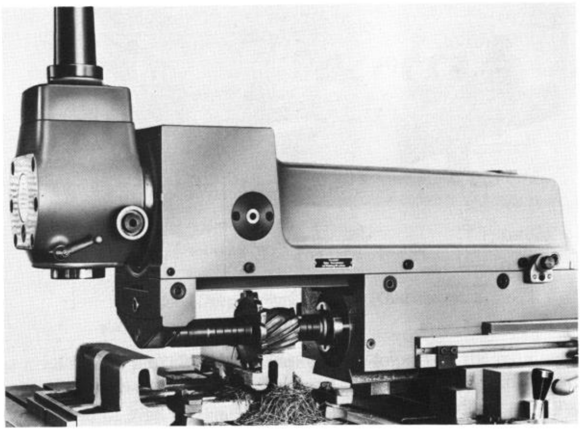

Fig. 2.13. Milling machine with horizontal and vertical milling spindles [14]

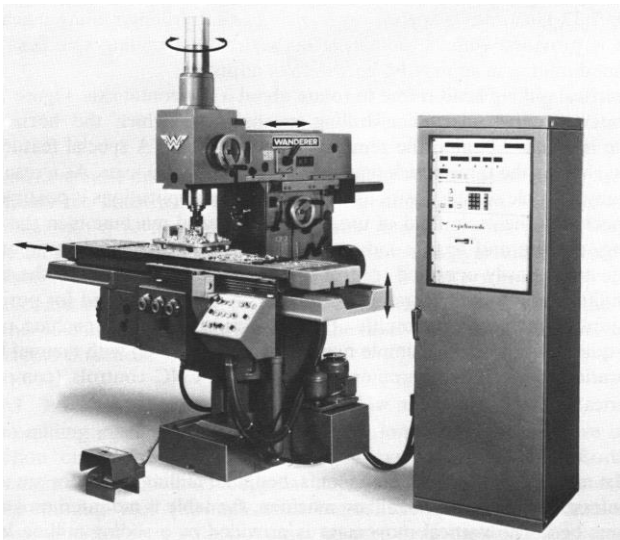

Fig. 2.14. Vertical knee-type milling machine (Wanderer) [14]

2.3.2. Universal milling machines

Figure 2.15. illustrates a universal milling/drilling machine, in which the horizontal spindle is situated behind the removable vertical head. A special feature of this machine is the table which may be rotated about two axes. As the result of many possible setting positions, a wide range of applications is possible on this machine.

Dividing head and slotting attachment may be also used as additional equipment.

The main field of use for this machine is the tool making. A digital read-out for position and input instructions simplify the operation of the machine. For small-quantity production, simple numerical controls (NC) with manual tape preparation, as well as computer-programmable CNC controls have been widely applied.

Fig. 2.15. Universal milling and drilling machine [14].

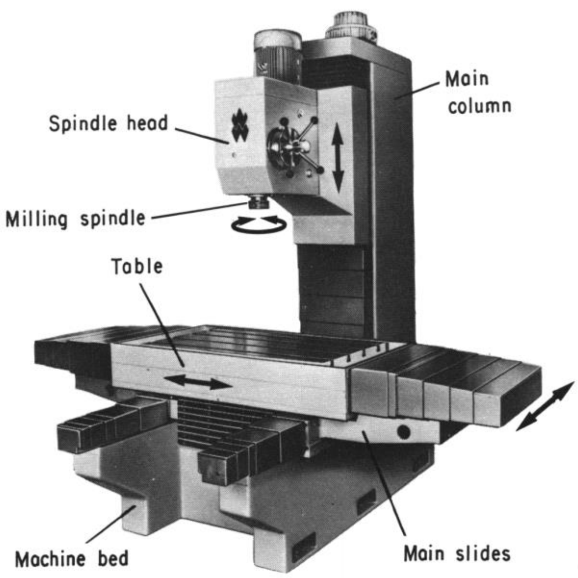

Fig. 2.16. Construction elements of a single-column bedplate milling machine (Wölfel) [14].

2.3.3. Bedplate milling machines

For the machining of heavy components, bedplate milling machines are used. In contrast to the knee-type milling machine, the table is mounted on a solid machine bed. The vertical movement is provided by a sliding milling head. The work spindle may be in horizontal or vertical bearings.

Figure 2.16. illustrates the constructional elements of a single-column, bedplate-milling machine with a vertical spindle. The table and cross-slide lie on the wide guides of the bed. This results in very high static and dynamic rigidity.

2.3.4. Plano-milling machines

Plano-milling machines are fitted with very long tables which move in one direction only. The bed is twice as long as the table. All co-ordinate movements are applied vertically to the feed motion of the table, in relation to the cutting tool. As may be seen from the various construction forms of these machines illustrated in fig. 2.17., the single-column machines are particularly suitable for the machining of very wide workpiece. The more stable double-column or gantry form of construction provides a better stress absorbtion, and may be used for the simultaneous machining of several milling and drilling operations.

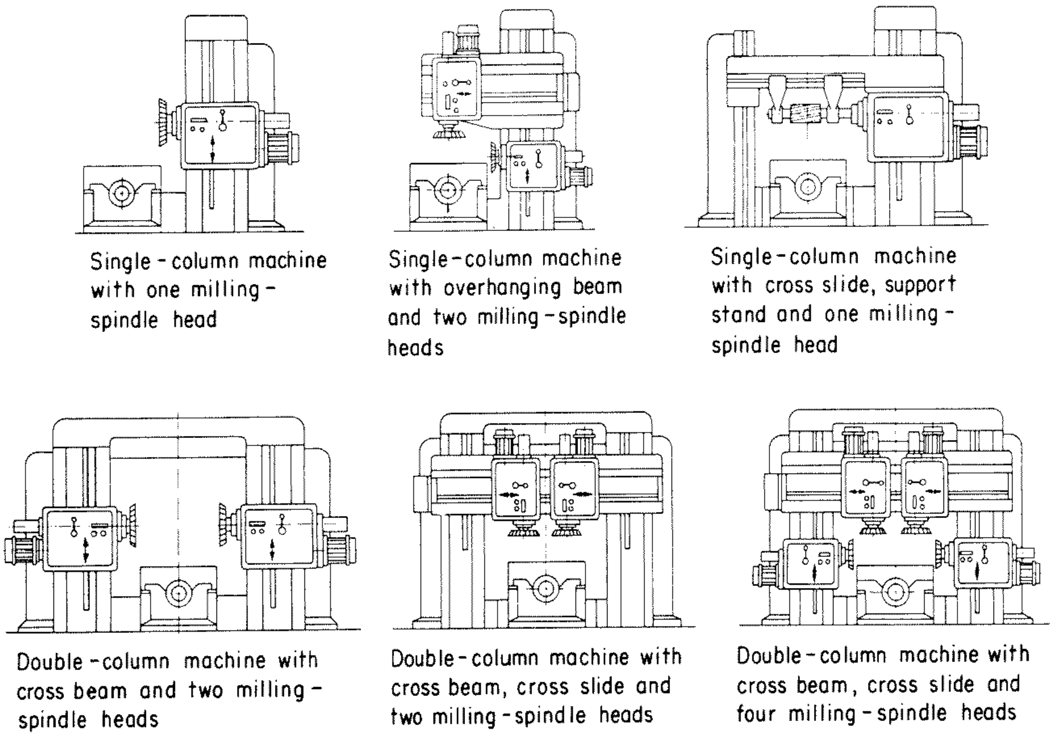

Fig. 2.17. Basic construction forms of plano-milling machines (Heller) [14].

2.3.5. Apron drilling and milling machines

For the machining of very large workpiece, as a body of the machine tool, apron-type drilling and milling machines may be used. Figure 2.18. illustrates the main construction elements of such machines. All feed and approach motions are made by a cutting tool (from the column and milling slides). The workpiece is stationary upon the apron-clamping table. The machine has an angular milling head, adjustable in two planes (enabling machining to take place in five axes). In order to enable the workpiece to be machined on all sides, it may be mounted on a circular table.

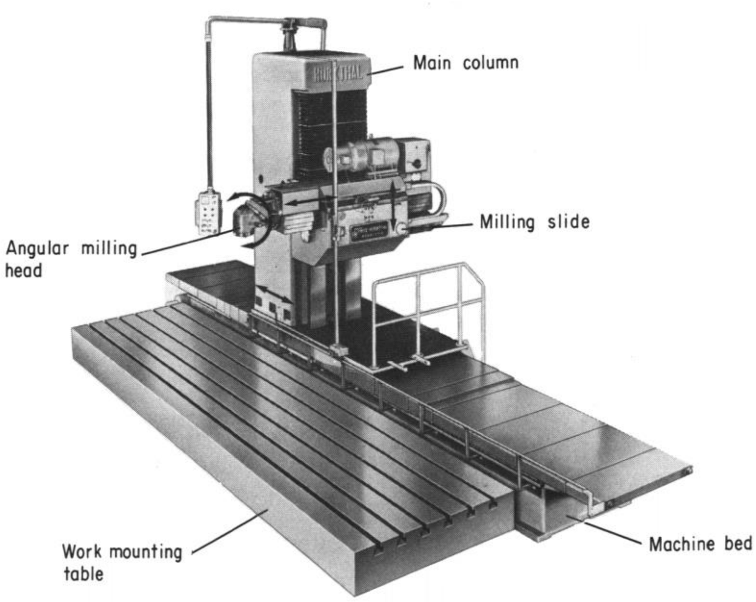

Fig. 2.18. Main constructional units and movements of an apron drilling and milling machine (Hürxthal) [14]

2.3.6. Machining centres

Machining centres make possible a complete range of machining operations (drilling, milling, reaming, screw cutting etc.) to be carried out in one setting of the workpiece. Cutting tools are normally exchanged automatically. Usually machines are built in knee-type, bed-plate or boring-mill construction forms.

The cutting tool may be guided in three (or more) co-ordinated axes, while the workpiece is clamped during machining on interchangeable tables, rotary tables or on platens. Machining centres usually have the following features available [14]:

- numerical control(NC),
- tool magazines with automatic tool changers,
- rotary tables enabling all sides of the workpiece to be machined,
- within flexible production systems, automatic loading and unloading devices.

These machining centres are mainly intended for small- to medium-sized-batch production, since owing to the high degree of automation, they may be reset for different production requirements in a relatively short time.

2.4. Tools - milling cutters (mills)

Due to many various shapes, dimensions, and construction solutions, milling cutters belong to the largest group of the tools. Generally all mills are divided into two groups: arbor milling cutters (based at tool bore) and shank cutters (based at straight or taper shank). In figs. 2.19 and 2.20 holding systems of milling cutters are presented. Typical milling cutters are shown in fig. 2.21..

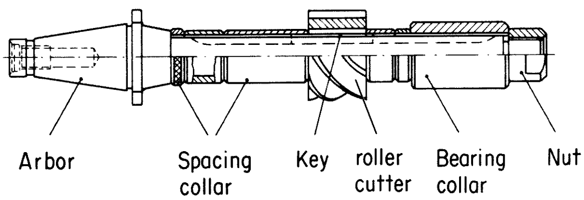

Fig. 2.19. Holding system for roller milling cutter [14]

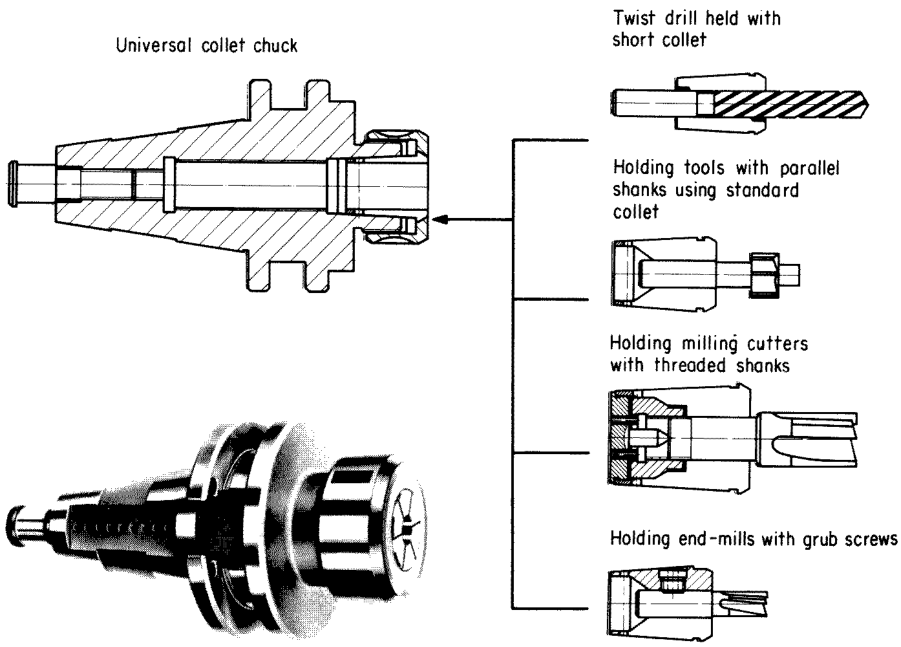

Fig. 2.20. Methods used for holding milling cutters (Ortlieb) [14]

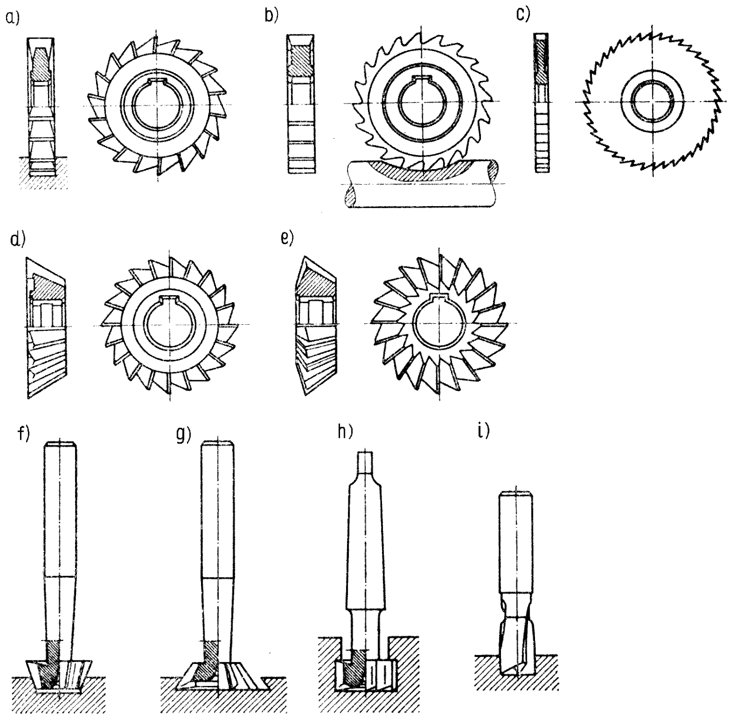

Fig. 2.21. Typical milling cutters: a, b, c, d, e – arbor milling cutters, f,g, h, i – shank cutters: a) side and face cutter, b) cutter for disk-type splineway, c) metal slitting saw, d) single-angle cutter, e) double-angle cutter, f, g) straight shank trapezoid slotting cutter, h) taper shank T-slot cutter, i) straight shank slotting cutter [4].

Separate group of mills is created by the face mill cutters, being complex tools consisting of the body and cemented carbide tips clamped to the body sockets (fig. 2.22).

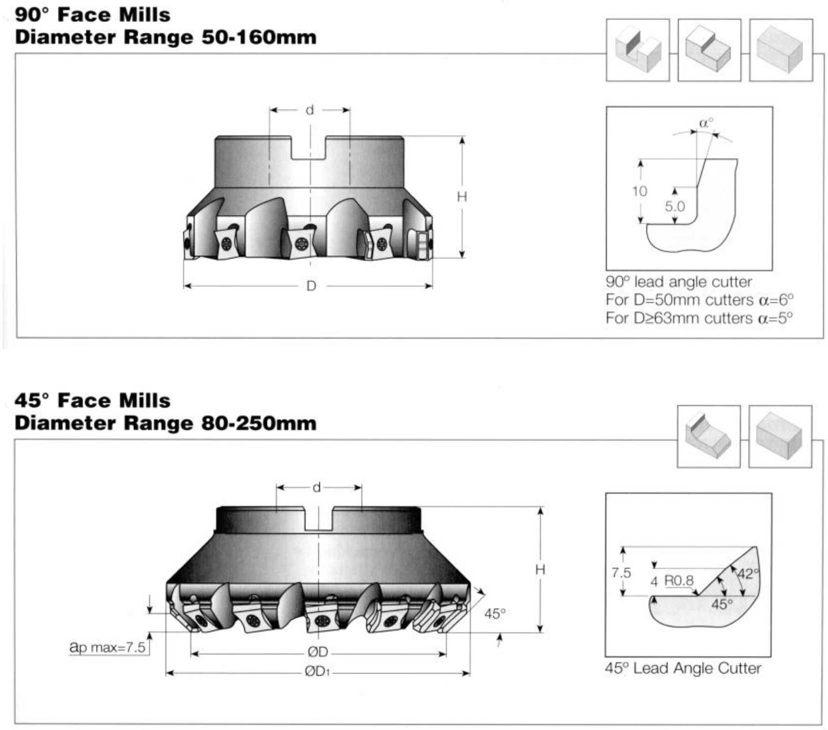

Fig. 2.22. Examples of face mills (ISCAR) [6].

2.5. Dividing head (indexing head)

For uniform circular divisions, the universal dividing head showed in fig. is widely used. It is one of the most useful additional equipment for the milling machine tool. There are three methods of indexing [14]:

- *direct indexing* is carried out by means of the indexing disc,
- *indirect indexing* through the worm and worm wheel drive and with the aid of various hole plates,
- *differential indexing* with the use of an additional change train (fig. 2.23).

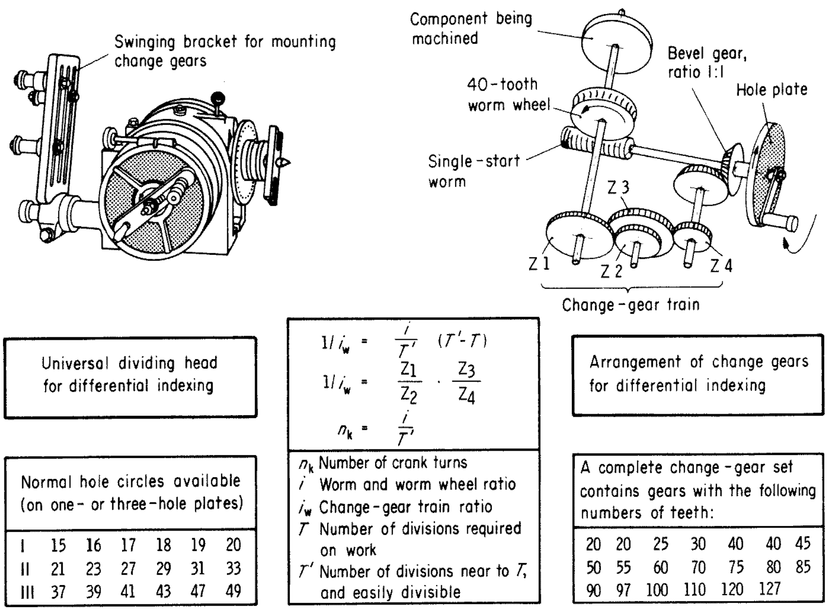

Fig. 2.23. Dividing head, nomenclature and differential indexing principle [14].

Example 1
A workpiece in the form of bar has to be machined to the pentagon shape in miller equipped with universal dividing head. Calculate a number of revolution of the crank handle of dividing head needed to cut each side of the pentagon.

$$n_c = \frac{40}{z}$$

n_c – number of crank handle revolutions,
z – number of parts to divide,
40 – transmission ratio of the worm gear of universal dividing head (i = 40/1)

$$n_c = \frac{40}{5} = 8$$

Answer: For cutting the next side of pentagon one should turn 8 revolutions of dividing head handle.

Example 2
A universal milling machine tool with universal dividing head is used for cutting a spur gear. Number of teeth z = 26. Calculate a number of crank handle revolutions for cutting the following teeth spaces.

$$n_c = \frac{40}{z}$$

$$n_c = \frac{40}{26} = 1\frac{14}{26} = 1\frac{7}{13} = 1\frac{21}{39}$$

Answer: For cutting a spur gear z = 26 teeth it is necessary to use a hole plate III. Next tooth space is obtain after 1 full revolution and 21/39 parts of a second one (21 holes on a 39 hole circle) (fig.   ).

2.6. Basic formulas

- Machine time (t_m)

$$t_m = \frac{L}{v_f} = \frac{l_i + l_c + l_o}{f\,n} \qquad [\text{min}]$$

L – action path [mm],
l_i – tool input,
l_c – cutting length (length of the workpiece),
l_o – tool output,
v_f – feed speed [mm/min],
f – feed per revolution [mm/rev],
n – rotational speed of the mill [rev/min]

- Cutting time (t_c)

$$t_c = \frac{l_c}{v_f} \qquad [\text{min}]$$

- Cutting speed (v_c)

$$v_c = \frac{\pi\, d\, n}{1000} \qquad \left[\frac{\text{m}}{\text{min}}\right]$$

d – diameter of the mill [mm],
n – rotational speed of the mill [rev/min]

- Feed per tooth (f_z)

$$f_z = \frac{v_f}{n\, z} \qquad \left[\frac{\text{mm}}{\text{tooth}}\right]$$

z – number of teeth

- Material removal rate (*MRR)* – volume of material removed per unit time

$$MRR = \frac{l_c\, b_D\, a_p}{t_c} = b_D\, a_p\, v_f \qquad \left[\frac{\text{mm}^3}{\text{min}}\right]$$

l_c – cutting length (length of the workpiece) [mm],
b_D – width of cut [mm],
a_p – depth of cut [mm],
t_c – cutting time [min],
v_f – feed speed [mm/min]