$$\frac{30.4374}{10} = 3.0437 \text{ in.}$$

If the measurement is larger than this size, the pitch diameter is too large and the depth of cut will have to be increased. If it is less than the determined size, the gear is undersize. Gears having an odd number of teeth are calculated in a similar manner but using the proper tables for these gears.

HELICAL MILLING

The process of milling helical grooves, such as flutes in a drill, teeth in helical gears, or the worm thread on a shaft, is known as *helical milling*. It is performed on the universal milling machine by gearing the dividing head through the worm shaft to the leadscrew of the milling machine.

The term *spiral* is often used incorrectly in place of a *helix*.

A Helix is a theoretical line or path generated on a **cylindrical** surface by a cutting tool which is fed lengthwise at a uniform rate, while the cylinder is also rotated at a uniform rate (Fig. 11-55A). The flutes on a drill or the threads on a bolt are examples of helices.

A Spiral is the path generated by a point moving at a fixed rate of advance along the surface of a **rotating cone or plane** (Fig. 11-55B). Threads on a wood screw and pipe threads are examples of conical spirals, while watch springs and scroll threads on a universal lathe chuck are examples of plane or flat spirals.

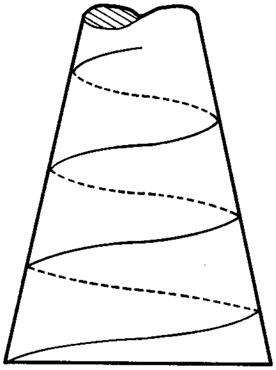


Fig. 11-55B A spiral is produced on a conical surface

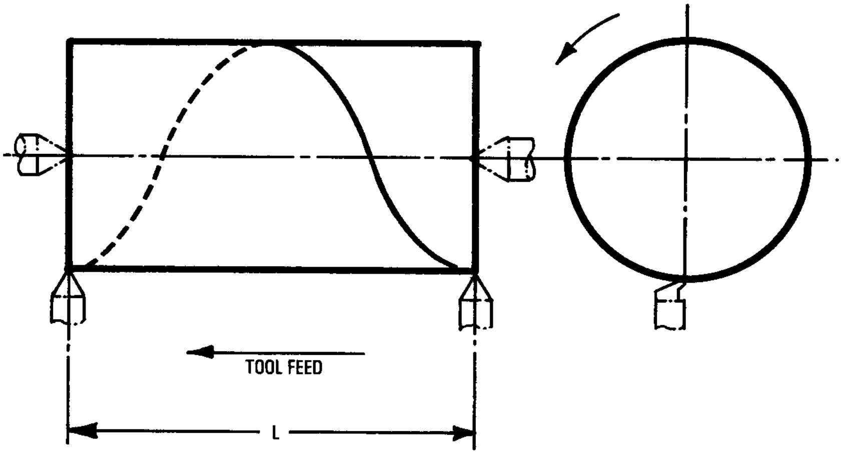


Fig. 11-55A A helix will be generated if the work is turned and the tool moved along uniformly

In order to cut either a metric or an inch helix, any two of the following must be known:

a) *The lead* of a helix is the longitudinal distance the helix advances axially in one complete revolution of the work.
b) *The angle of the helix* is formed by the intersection of the helix with the axis of the workpiece.
c) *The diameter (and circumference) of the workpiece.*

In comparing two different helices, it will be noticed that the greater the angle with the centre line, the shorter will be the lead. However, if the diameter is increased but the helix angle remains the same, the greater will be the lead. Thus it is evident that the lead of a helix varies with:

a) the diameter of the work
b) the angle of the helix

The relationship between the diameter (and circumference), the helix angle, and the lead is shown in Fig. 11-56. It will be noted that if the surface of the cylinder could be unwound to produce a flat surface, the helix would form the hypotenuse of a right-angled triangle, with the circumference forming the side opposite and the lead the side adjacent.

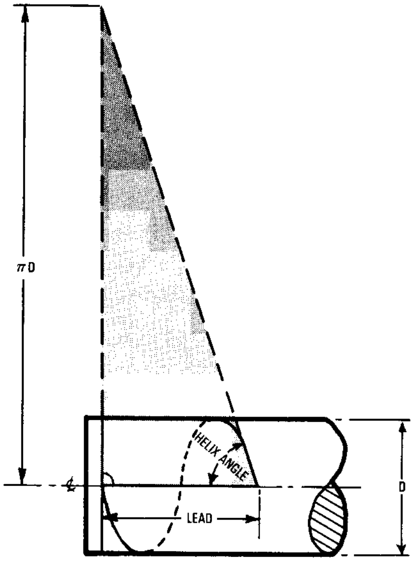


Fig. 11-56 Relationship of lead, circumference, and helix angle

CUTTING A HELIX

To cut a helix on a cylinder, the following steps are necessary:

1. Swing the table in the proper direction to the angle of the helix to ensure that a groove of the same contour as the cutter is produced.
2. The work must rotate one turn while the table travels lengthwise the distance equal to the lead. This is achieved by installing the proper change gears between the worm shaft on the dividing head, and on the milling machine leadscrew.

DETERMINING THE HELIX ANGLE

To ensure that a groove of the same contour as the cutter is produced, the table must be swung to the angle of the helix (Fig. 11-57A). The importance of this is shown in Fig. 11-57B.

Note that when the table is not swung (Fig. 11-57B), a helix having the proper lead but an improper contour will be generated. By referring to Fig. 11-56, it can easily be seen that the angle may be calculated as follows:

Tangent of the helix angle

$$= \frac{\text{circumference of the work}}{\text{lead of the helix}}$$

$$= \frac{3.1416 \times \text{diameter}}{\text{lead of the helix}}$$

EXAMPLE 1 (metric):

To what angle must a milling machine table be swivelled to cut a helix having a lead of 450 mm on a workpiece 40 mm in diameter?

Tangent of helix angle

$$= \frac{3.1416 \times \text{diameter (mm)}}{\text{lead of helix (mm)}}$$

$$= \frac{3.1416 \times 40}{450}$$

$$= 0.2796$$

$$= 15°31'$$

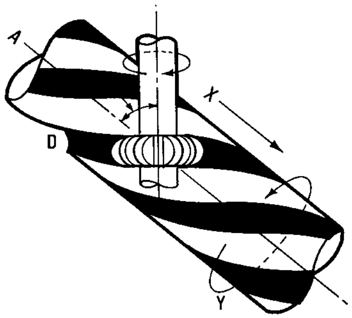


Fig. 11-57A When the table is swivelled to the correct helix angle, the exact profile of the cutter will be generated

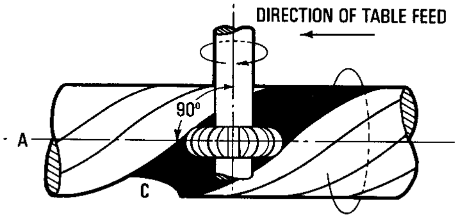


Fig. 11-57B An incorrect angle produces an incorrect profile

EXAMPLE 2 (inch):

To what angle must the milling machine table be swivelled to cut a helix having a lead of 10.882 in. on a piece of work 2 in. in diameter?

$$\text{Tangent of helix angle} = \frac{3.1416 \times D}{\text{lead of helix}}$$

$$= \frac{3.1416 \times 2}{10.882}$$

$$= \frac{6.2832}{10.882}$$

$$= .57739$$

$$\therefore \text{Helix angle} = 30°$$

After the helix angle has been calculated, it is necessary to determine the *direction* in which to swivel the table to produce the proper hand of helix (that is, right- or left-hand).

DETERMINING THE DIRECTION TO SWING THE TABLE

In order to determine the hand of a helix, hold the cylinder on which the helix is cut in a horizontal plane with its axis running in a right-left direction.

If the helix slopes *down* and to the right, it is a right-hand helix (Fig. 11-58). A left-hand helix slopes *down* and to the left. When a *left-hand helix* is to be cut, the table of the milling machine must be swivelled in a clockwise direction (operator standing in front of the machine). A right-hand helix may be produced similarly by moving the right end of the table in towards the column or by moving it in a counterclockwise direction.

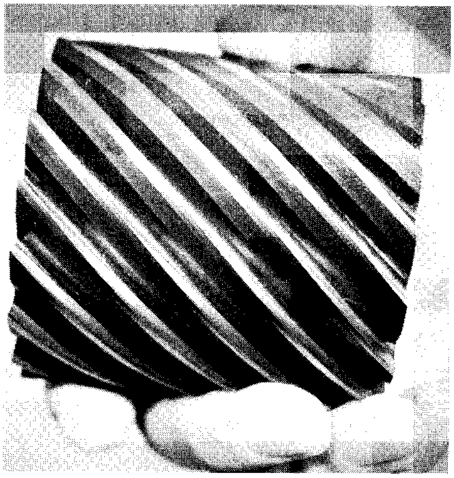
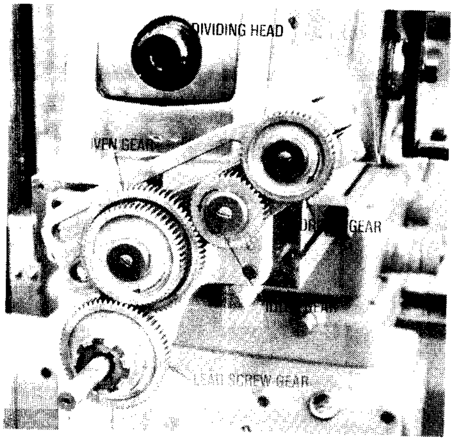


Fig. 11-58 The grooves of a right-hand helical cutter slope down and to the right

CALCULATING THE CHANGE GEARS TO PRODUCE THE REQUIRED LEAD

To cut a helix, it is necessary to have the work move lengthwise and rotate at the same time. The amount the work (and table) travels lengthwise as the work revolves one complete revolution is the *lead.* The rotation of the work is caused by gearing the worm shaft of the dividing head to the leadscrew of the machine (Fig. 11-59).

The pitch of the leadscrew on a metric milling machine is stated in millimetres. Most milling machine leadscrews have a 5 mm pitch and the dividing head has a ratio of 40 to 1. As the leadscrew revolves one turn, it would revolve the dividing



Courtesy Kostel Enterprises Ltd.

Fig. 11-59 Worm shaft and the leadscrew are connected for helical milling

head spindle 1/40 of a revolution. In order for the dividing head spindle (and work) to revolve one full turn, the leadscrew must make 40 complete revolutions. Therefore the lead of the machine would be 40 times the pitch of the leadscrew.

For metric calculations, the change gears required are calculated as follows:

$$\frac{\text{Lead of helix to be cut (mm)}}{\text{Lead of machine (mm)}}$$

$$= \frac{\text{product of driven gears}}{\text{product of driver gears}}$$

The normal change gears in a set are 24, 24, 28, 32, 36, 40, 44, 48, 56, 64, 72, 86, 100.

EXAMPLE:
Calculate the change gears required to cut a helix having a lead of 500 mm on a workpiece using a standard set of gears. The milling machine leadscrew has a pitch of 5 mm.

$$\frac{\text{Driven gears}}{\text{Driver gears}} = \frac{\text{lead of helix}}{\text{pitch of leadscrew} \times 40}$$

$$= \frac{500}{5 \times 40}$$

$$= \frac{500}{200}$$

$$= \frac{5}{2} \times \frac{20}{20}$$

$$= \frac{100}{40}$$

Driven gear $= 100$
Driver gear $= 40$

To cut a helix on an inch milling machine, it is necessary first to understand how to calculate the required change gears for any desired lead. Assume that the dividing head worm shaft is geared to the table leadscrew with equal gears (for example, both having 24-tooth gears). The dividing head ratio is 40:1, while a standard milling machine leadscrew has 4 threads/in. The leadscrew, as it revolves one turn, would revolve the dividing head spindle 1/40 of a revolution. In order for the dividing head spindle to revolve one turn, it would be necessary for the leadscrew to revolve 40 times. Thus the table would travel 40 × 1/4 in. or 10 in. while the work revolves one turn. Therefore, the lead of a milling machine is said to be 10 in. when the leadscrew (4 threads/in.) is connected to the dividing head (40:1 ratio) with equal gears.

In calculating the change gears required to cut any lead, the following formula may be used:

$$\frac{\text{Lead of helix to be cut}}{\text{Lead of machine (10 in.)}}$$

$$= \frac{\text{product of driven gears}}{\text{product of driver gears}}$$

The ratio of gears required to produce any lead on a milling machine having a leadscrew with 4 threads/in. is always equal to a fraction having the lead of the helix for the numerator and 10 for the denominator.

NOTE: The preceding formula may be inverted if preferred.

$$\frac{\text{Lead of the machine}}{\text{Lead of the helix}}$$

$$= \frac{\text{product of driver gears}}{\text{product of driven gears}}$$

EXAMPLE 1:
Calculate the change gears required to produce a helix having a lead of 25 in. on a piece of work. The available change gears have the following number of teeth: 24, 24, 28, 32, 40, 44, 48, 56, 64, 72, 86, 100.

SOLUTION:
Gear ratio

$$= \frac{\text{lead of helix (driven gears)}}{\text{lead of machine (driver gears)}}$$

$$= \frac{25}{10}$$

Since 10- and 25-tooth gears are not supplied with standard dividing heads, it is necessary to multiply the 25/10 ratio by a number that will suit the change gears available.

$$\text{Gear ratio} = \frac{25}{10} \times \frac{4}{4}$$

$$= \frac{100 \text{ (driven gear)}}{40 \text{ (driver gear)}}$$

As both 100-tooth and 40-tooth gears are available, simple gearing may be used.

EXAMPLE 2:
Calculate the change gears required to produce a helix having a lead of 27 in. The available change gears are as in Example 1.

SOLUTION:
Gear ratio

$$= \frac{\text{lead of helix (driven gears)}}{\text{lead of machine (driver gears)}}$$

$$= \frac{27}{10}$$

Since there are no gears in the set which are multiples of both 27 and 10, it is impossible to use simple gearing. Compound gearing must therefore be used, and it becomes necessary to factor the fraction $\frac{27}{10}$ as follows:

$$\text{Gear ratio} = \frac{27}{10}$$

$$= \frac{3}{2} \times \frac{9\ (\text{driven})}{5\ (\text{driver})}$$

It is now necessary to multiply both the numerator and denominator of each fraction by the same number in order to bring the ratio into the range of the gears available.

NOTE: This does not change the value of the fraction.

$$\frac{3 \times 16}{2 \times 16} = \frac{48}{32}$$

$$\frac{9 \times 8}{5 \times 8} = \frac{72}{40}$$

$$\text{The gear ratio} = \frac{48 \times 72\ (\text{driven gears})}{32 \times 40\ (\text{driver gears})}$$

∴ The driven gears are 48 and 72 and the driver gears are 32 and 40.

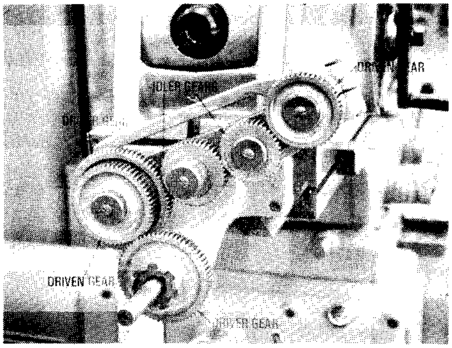
The gears would be placed in the train as follows (Fig. 11-59):

Gear on worm	72	(driven)
1st gear on stud	32	(driver)
2nd gear on stud	48	(driven)
Gear on leadscrew	40	(driver)

The preceding order is not absolutely necessary; the two driven gears may be interchanged and/or the two driver gears may be interchanged, *provided a driver is not interchanged with a driven gear.*

DIRECTION OF SPINDLE ROTATION

Fig. 11-59 illustrates the setup required to cut a right-hand helix. Note that the gear on the leadscrew and the worm gear revolve in the same direction. To cut a left-hand helix, the spindle must revolve in the opposite direction, and therefore an idler must be inserted as in Fig. 11-60. The idler in this case acts neither as a driven nor a driver gear and is not considered in the calculation of the gear train. It acts merely as a means of changing the direction of rotation of the dividing head spindle. It should also be noted that the direction of spindle rotation for simple gearing will be opposite to that for compound gearing.



Courtesy Kostel Enterprises Ltd.

Fig. 11-60 A second idler reverses the direction of rotation

CUTTING SHORT LEAD HELICES

When it is necessary to cut leads smaller than those shown in most handbooks, it is advisable to disengage the dividing head worm and wormwheel and connect the change gears directly from the table leadscrew to the dividing head spindle, rather than to the worm shaft. This method permits machining leads to 1/40 of the leads shown in the handbook tables. Thus, if the machine is geared to cut a lead of 4.000 in. by connecting the worm shaft and the leadscrew, the same gearing would produce a lead of 1/40 × 4.000 in., or .100 in. when geared directly to the dividing head spindle.

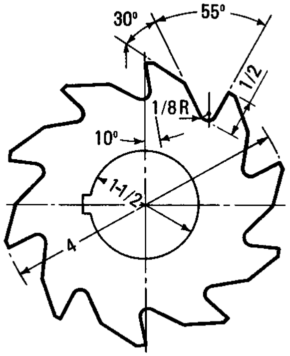
PROBLEM:

A plain helical milling cutter is required to the following specifications:

Diameter: 4 in.
Number of teeth: 9
Helix: right hand
Helix angle: 25°
Rake angle: 10° positive radial rake
Angle of flute: 55°
Depth of flute: 1/2 in.
Length: 4 in.
Material: tool steel

Procedure

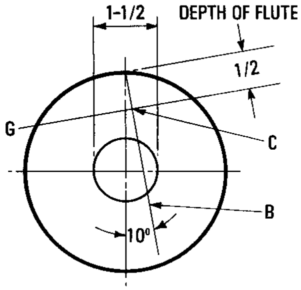
1. Turn blank to sizes indicated (Fig. 11-61).



Courtesy Cincinnati Milacron Inc.

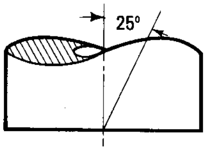
Fig. 11-61 Dimensions of a helical milling cutter (in inches)

2. Apply layout die to the end of the blank, and lay out as in Fig. 11-62A.
3. Lay out a line on periphery to indicate direction of the *right-hand* helix (Fig. 11-62B).



Courtesy Cincinnati Milacron Inc.

Fig. 11-62A Locating the first tooth on the cutter



Courtesy Cincinnati Milacron Inc.

Fig. 11-62B Laying out the direction of the flute

4. Press the cutter blank firmly on the mandrel. If a threaded mandrel is used, be sure to tighten the nut securely.
5. Mount the dividing head and footstock.
6. Calculate the indexing for 9 divisions.

$$
\begin{aligned}
\text{Indexing} &= \frac{40}{9}\\
&= 4\text{-}4/9\\
&= 4 \text{ turns, } 8 \text{ holes on an } 18\text{-hole circle}
\end{aligned}
$$

7. Set the sector arms to 8 holes on the 18-hole circle.
NOTE: Do not count the hole in which the pin is engaged.
8. Disengage the index plate locking device.
9. Calculate the lead of the helix.

$$
\begin{aligned}
\text{Lead} &= \frac{3.1416 \times D}{\text{tan helix angle}}\\
&= 3.1416 \times D \text{ cot helix angle}\\
&\quad \left(\text{since } \frac{1}{\text{tan}} = \text{cot}\right)\\
&= 3.1416 \times 4 \times 2.1445\\
&= 26.949 \text{ in.}
\end{aligned}
$$

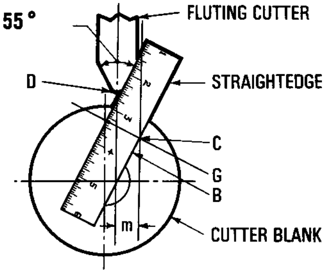
10. Consult any handbook for the change gears to cut the lead closest to 26.949 in. Obviously this is 27.
11. If a handbook is not available, change gears can be calculated for the closest lead which is 27 in.
12. Change gears required for 27 in. lead.

$$
\frac{\text{Required lead}}{\text{Lead of machine}} = \frac{27}{10} = \frac{9}{5} \times \frac{3}{2}
$$

$$
\frac{9 \times 8}{5 \times 8} = \frac{72}{40} \qquad \frac{3 \times 16}{2 \times 16} = \frac{48}{32}
$$

$$
\text{Change gears} = \frac{72 \times 48 \text{ (driven gears)}}{40 \times 32 \text{ (driver gears)}}
$$

13. Mount the change gears, allowing a slight clearance between mating teeth.
14. Mount the work between the centres with the large end of the mandrel against the dividing head.
15. Swivel the table 25° in a counterclockwise direction.
16. Adjust the crossfeed handwheel until the table is about 1 in. (25 mm■) from the face of the column. This is to ensure that the table clears the column when machining the cutter.
17. Swing the table back to "0."
18. Mount a 55° double-angle cutter so that it revolves towards the dividing head, and centre it approximately over the flute layout.
19. Rotate the blank until the flute layout is aligned with the cutter edge. This may be checked with a rule or straightedge (Fig. 11-63).



Courtesy Cincinnati Milacron Inc.

Fig. 11-63 Aligning the cutter blank with the cutter

20. Move the blank over, using the crossfeed for the distance of M (Fig. 11-63) or until the point C (Fig. 11-62A) is in line with the centre line of the cutter.
21. With the work clear of the cutter, set the depth to .500 in.
22. Rotate the table 25° and lock securely (right end in towards the column).
23. Carefully cut the first tooth space, checking the accuracy of the location and the depth.
24. Index for and cut the remaining flutes.
25. Remove the fluting cutter and mount a plain helical milling cutter.
26. Rotate the work (using the index crank) until a line at 30° to the side of the flute is parallel to the table (Fig. 11-62A). This may be checked by means of a surface gauge. The blank, however, may be rotated by indexing an amount equal to

$$
\begin{aligned}
&90 - \left(30 + \frac{55}{2}\right)\\
&= 90 - 57.5\\
&= 32.5^\circ \ (32^\circ 30')
\end{aligned}
$$

Indexing for 32°30′:

$$
\begin{aligned}
32^\circ \times 60' &= 1920'\\
30' &= \underline{30'}\\
32^\circ 30' &= 1950'\\
&= \frac{1950}{540}\\
&= 3\frac{330}{540}\\
&= 3\frac{11}{18}\\
&= 3 \text{ turns} + 11 \text{ holes on the } 18\text{-hole circle}
\end{aligned}
$$

27. Adjust the workpiece under the cutter.
28. With the cutter rotating, raise the table until the width of the land on the workpiece is about 1/32 in. (0.8 mm■) wide.
29. Cut the secondary clearance (30° angle) on all teeth of the workpiece.

HELICAL MILLING CALCULATIONS (Metric)

For any helical milling calculations it is necessary to determine:

1. The angle at which the table must be swivelled to produce the proper helix angle.
2. The change gears required to revolve the work one turn as the work travels the distance of the lead.

For metric helices, these calculations are as follows:

1. Helix angle or angle to which to swivel the table.

$$\text{Tangent } \angle = \frac{\text{circumference of workpiece}}{\text{lead of the helix}}$$

2. Change gears required.

$$\frac{\text{Driven gears}}{\text{Driver gears}} = \frac{\text{lead of the helix}}{\text{pitch of the leadscrew} \times 40}$$

The normal change gears in a set are: 24, 24, 28, 32, 36, 40, 44, 48, 56, 64, 72, 86, 100.

EXAMPLE:

A lead of 480 mm is to be cut on a workpiece 40 mm in diameter. The leadscrew of the milling machine has a pitch of 5 mm. The dividing head has a ratio of 40:1 (40 turns of the crank are required to revolve the work one turn). Calculate the angle at which to set the table and the change gears necessary to produce the required lead:

a) *Helix angle*

Tan helix angle

$$= \frac{\text{circumference of work}}{\text{lead of helix}}$$

$$= \frac{40 \times 3.1416}{480}$$

$$= 0.26180$$

helix angle = 14.67°

b) *Change gears*

$$\frac{\text{Driven gears}}{\text{Driver gears}}$$

$$= \frac{\text{lead of the helix}}{\text{pitch of the leadscrew} \times 40}$$

$$= \frac{480}{5 \times 40}$$

$$= \frac{480}{200}$$

$$= \frac{12}{5} \quad \frac{(6 \times 2)}{(5 \times 1)}$$

$$\frac{6}{5} \times \frac{8}{8} = \frac{48}{40} \qquad \frac{2}{1} \times \frac{28}{28} = \frac{56}{28}$$

$$\text{Gears} = \frac{48}{40} \times \frac{56}{28}$$

Driven gears = 48 and 56

Driver gears = 40 and 28

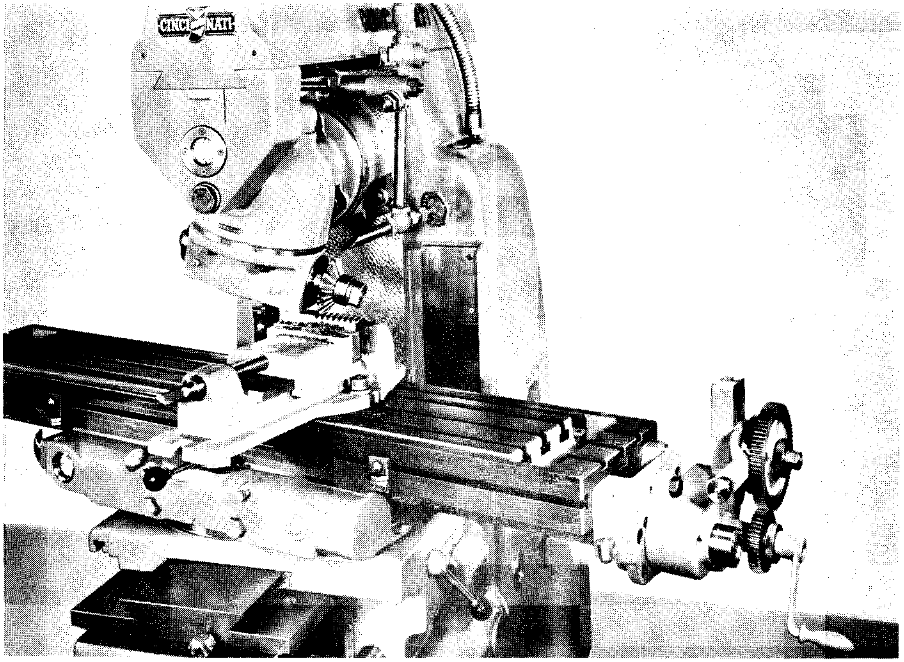
RACK MILLING

A *rack*, in conjunction with a gear (pinion), is used to convert rotary motion into longitudinal motion. Racks are found on lathes, drill presses, and many other machines in a shop. A rack may be considered as a spur gear which has been straightened out so that the teeth are all in one plane. The circumference of the pitch circle of this gear would now become a straight line which would just touch the pitch circle of a gear meshing with the rack. Thus the pitch line of a rack is the distance of one addendum below the top of the tooth or $\frac{1}{DP}$ below the top of the tooth.

The pitch of a rack is measured in linear (circular) pitch, which is obtained by dividing 3.1416 by the diametral pitch:

$$\frac{3.1416}{DP}$$

The method used to cut a rack will depend generally on the length of the rack. If the rack is reasonably short (10 in. or less), it may be held in the milling machine vise in a position parallel to the cutter arbor. On short racks, the teeth may be



Courtesy Cincinnati Milacron Inc.

Fig. 11-64 **Cutting the teeth on a helical rack using the rack milling and indexing attachments**