IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)
e-ISSN: 2278-1684,p-ISSN: 2320-334X
PP. 75-82
www.iosrjournals.org

Design and manufacturing of square broach tool

Balaji D Tandle[1], K. Nagarjuna[2]
[1]*(Department of Mechanical engineering's. Martin's Engineering College, Hyderabad, Telangana,India)*
[2]*(Department of Mechanical engineering's. Martin's Engineering College, Hyderabad, Telangana,India)*

Abstract: *Broach tool is a multi-point cutting tool consisting a bar having surface containing a series of cutting teeth or edges which are gradually increase in size from the starting or entering and to the rear end. Broaches are used for machining either internal or external surface (i.e. sizing of holds and cutting of serrations, straight or helical planes, gun rifling and key ways). The quality of broach tool is maintained by grinding operation.*
Broaching is used when precision machining is required, especially for odd shapes. Commonly machined surfaces include circular and non-circular shapes. Even though broaches can be expensive, broaching is usually favored over other process when used for high quality production runs. It is capable of production rates as much as 25 times faster than any traditional metal removing methods.
Broaching is rapid and efficient because both roughing and finishing can be done in a single pass, close tolerances are added advantages of the process. In the present work Broach cutting tool is going to be designed to generate square teeth for square hole machining.

I. Introduction

Broaching is a machining process used intensively for making internal and external surfaces including intricate profiles in mass production. Basically broaching is a machining process that uses a toothed tool, called a broach, to remove material. Broach is a multipoint cutting tool in which the cutting edges are distributed along the axis or inclined to axis (helical) or sometimes inclined about the axis of rotation and finishes the operation in one or number of passes.

Broaches are shaped similar to a saw, except the height of the teeth increases over the length of the tool. Moreover, the broach contains three distinct sections: one for roughing, another for semi-finishing, and the final one for finishing. Broaching is an unusual machining process because it has the feed built into the tool. The profile of the machined surface is always the inverse of the profile of the broach. The rise per tooth (RPT), also known as the step or feed per tooth, determines the amount of material removed and the size of the chip.
The broaching machine will have straight line ram movement to pull or push the broach, while the component is held against the movement of tool. Generally broaching is done on pre machined component. One of the major advantages of using this operation in various industries is its ability to give better surface finish and good accuracy with mass production rate.

II. Broaching Can Be Classified Into Following Types:

Internal Broaching: Internal broaching is mainly used to enlarge holes. This process generally uses pull type broach but for lighter work piece, it sometime uses push type broach.
External Broaching: External broaching is mainly used to flattening of a surface, machining key ways, slots, grooves on outer part of an object such as shaft etc. This process is also used for gear manufacturing process.
Pull Types Broaching: A broach which is subjected to tensile force during machining, called pull broach and the type of broaching operation by pull broach is known as pull broaching. This operation prevents misalignment and buckling. The pull broach is usually made in single piece and used for internal broaching.
Push Type Broaching: Push type broach is usually subjected to compression force during machining. These are made shorter compare to pull type broach and mostly used for external broaching.
Ordinary Cut Broaching: Ordinary cut broaching uses ordinary broach in which teeth increases in height gradually from tooth to tooth along length of broach.
Progressive Cut Broaching: In progressive cut broaching teeth increase in width instead of height along length of the broach.
Solid, Section and Modular Broaching: Solid broaches are made in single piece which are mostly used for internal broaching. Sectional broaches are made in section by assembling various section of broach. Module broaches are made by various modules assembled in a single unit. It is used for external broaching.

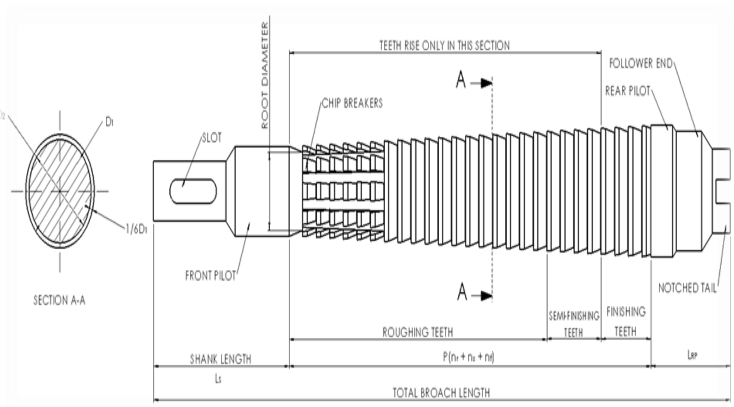
Advantages Of Broaching:
1) Roughing and finishing cuts are made in one pass only. Moreover it can also incorporate burnishing surfaces to produce smooth surface finish.
2) The accuracy and surface finish of the surface produced by broaching are high (in general up to 5th to 6th class).
3) Broaches have long life in terms of components produced.
4) The chip flow in broaching is unidirectional which reduces the clogging of chips and scoring of material surface.
5) Rate of production is very high with properly applied broaches, fixtures and machines, more pieces can be turned out per hour by broaching than by any other means.
6) Little skill is required to perform a broaching operation, in most cases the operator merely loads and unloads the work piece.
7) Cutting fluid may be readily applied where it is most effective because a broach tends to draw the fluid into the cut

Limitations In Broaching:
1) Due to difficulty in manufacturing, even heavy industries cannot make their tool.
2) Re-sharpening of broach is difficult and sometimes broach may be sent to the original manufacturer for this purpose.
3) Very large work pieces cannot be broached.
4) The surfaces to be broached cannot have an obstruction.
5) Broaching cannot be used for removal of large amount of stock.
6) Parts to be broached must be capable of being rigidly supported and must be able to withstand the forces that are set up during cutting.

Broach:

The broaching tool is based on a concept unique to the process-- rough, semi-finish and finish cutting teeth combined in one tool or string of tools. A broach tool frequently can finish machine a rough surface in a single stroke.

For exterior surface broaching, the broach tool may be pulled or pushed across a work piece surface, or the surface may move across the tool. Internal broaching requires a starting hole or opening in the work piece so the broaching tool can be inserted. The tool or the work piece is then pushed or pulled to force the tool through the starter hole. Almost any irregular cross-section can be broached as long as all surfaces of the section remain parallel to the direction of broach travel.



Broach Nomenclature:
Front pilot: When an internal pull broach is used, the pull end and front pilot are passed through the starting hole. Then the pull end is locked to the pull head of the broaching machine. The front pilot assures correct axial alignment of the tool with the starting hole, and serves as a check on the starting hole size.
Length: The length of a broach tool, or string of tools, is determined by the amount of stock to be removed, and limited by the machine stroke.
Rear pilot: The rear pilot maintains tool alignment as the final finish teeth pass through the work piece hole. On round tools the diameter of the rear pilot is slightly less than the diameter of the finish teeth.
Cutting teeth: Broach teeth are usually divided into three separate sections along the length of the tool:

The roughing teeth, semi-finishing teeth and finishing teeth .The first roughing tooth is proportionately the smallest tooth on the tool. The subsequent teeth progressively increase in size up to and including the first finishing tooth. The difference in height between each tooth (or) the tooth rise is usually greater along the roughing section and less along the semi-finishing section. All finishing teeth are the same size. The face is ground with a hook or face angle that is determined by the work piece material. For instance, soft steel work pieces usually require greater hook angles hard or brittle steel pieces require smaller hook angles.

Tooth land: The land supports the cutting edge against stresses. A slight clearance or back-off angle is ground onto the lands to reduce friction. On roughing and semi-finishing teeth, the entire land is relieved with a back-off angle. On finishing teeth, part of the land immediately behind the cutting edge is often left straight, so that repeated sharpening (by grinding the face of the tooth) will not alter the tooth size.

Tooth pitch: The distance between teeth, or pitch, is determined by the length of cut and influenced by type of work piece material. A relatively large pitch may be required for roughing teeth to accommodate a greater chip load. Tooth pitch may be smaller on semi-finishing teeth to reduce the overall length of the broach tool. Pitch is calculated so that, preferably, two or more teeth cut simultaneously. This prevents the tool from drifting or chattering.

Tooth gullet: The depth of the tooth gullet is related to the tooth rise, pitch and work piece material. The tooth root radius is usually designed so that chips curl tightly within themselves, occupying as little space as possible.

Shear angle: Broach designers may place broach teeth at a shear angle to improve surface finish and reduce tool chatter. When two adjacent surfaces are cut simultaneously, the shear angle is an important factor in moving chips away from the intersecting corner to prevent crowding of chips in the intersection of the cutting teeth.

Side relief: When broaching slots, the tool becomes enclosed by the slot during cutting and must carry the chips produced through the entire length of the work piece. Sides of the broach teeth will rub the sides of the slot and cause rapid tool wear unless clearance is provided. Grinding a single relief angle on both sides of each tooth does this. Thus, only a small portion of the tooth near the cutting edge, called the side land, is allowed to rub against the slot.

Classification Of Broaches:

Broaches are classified depending upon:

1) Type of work, i.e. internal or surface.
2) Method of operation, i.e. push or pull.
3) Construction, i.e. solid, segmental or inserted.
4) Function, i.e. keyway, spline, round hole, serration etc.
5) Type of tooth, i.e. helical tooth or straight tooth.

Types of construction of broaches

1) Solid broach made of single piece of stock material. It is rigid, but material cost is more.
2) Inserted type of broach- tooth inserts are clamped mechanically to the main body which is made of medium carbon steel.
3) Segmental broach- full length of the broach is divided into number of segmental parts and manufactured separately. Finally they are assembled together to form length of the broach. This is done to avoid the difficulty in heat treatment of broach.

Type 1 & 2 are easy to maintain but they are less rigid.

Material Selection:

M2 is a general purpose molybdenum high speed steel. This grade is characterized by balanced combination of abrasion resistance, toughness and good red hardness. Due to its comparatively low carbon content, M2 has an excellent combination of toughness properties and abrasion resistance when properly hardened and tempered. M2 is used in a wide used for all kinds of cutting tool, knife and punch and die applications.

Typical Chemistry: C = 0.83; Cr = 4.15; Mo = 5.00; V = 1.90; W = 6.35

Machinability: When properly annealed, M2 has a machinability rating of 65 percent when compared to a 1% Carbon Steel rated at 100.

Dimensional Stability: When air quenched from the proper hardening temperature, this grade can be expected to expand approximately .001 in. per in. Note: Distortion (bending, bowing and twisting) and part geometry can add to the variations in movement of a part that is being hardened.

Thermal Cycling: In order to avoid decarburization, this grade should be annealed and/or hardened in a controlled neutral atmosphere, vacuum, or neutral salt furnace environment.

Physical Properties:

Density	8.16 g/cm^3	0.294 lb./in^3
Melting point	4680°C	2600°F

The physical properties of M2 molybdenum high speed tool steel are given in the following table.

Fabrication And Heat Treatment:
Machinability
Shaping of M2 tool steels can be carried out using grinding methods. However, they have poor grinding capability and hence they are regarded as "medium" machinability tool steel under annealed conditions. The machinability of these steels is only 50% of that of the easily machine able W group or water hardening tool steels.
Heat Treatment
M2 tool steels are pre-heated prior to hardening at 2610°C (4730°F) followed by rapid heating from 2610°C (4730°F) to 3960°C (7160°F). These steels are then cooled for 3 to 5 min and quenched in air, salt bath or oil.
The following information is provided for guidance only. The rate of heating, cooling and soaking times will vary due to the shape and size of each component and other external factors.
Annealing
Heat the M2 high-speed steel to 850 - 900°C. Hold at temperature for at least two hours or one hour per 25 mm of thickness. Furnace cools slowly. The maximum hardness should be 248 Brinell.
Stress relieving
Stress relieving M2 is recommended after machining or grinding and before hardening to minimize the chance of distortion. Heat the component to 600 - 700°C and soak well (for approximately two hours), then cool in air.
Hardening
Pre heat the M2 in two steps; 450 - 500°C then 850 - 900°C. Then continue heating to the final hardening temperature of 1200 - 1250°C. Do not leave the steel too long at the hardening temperature. Quench in warm oil or brine to about 500°C then air cool down to room temperature.
Tempering
Heat the M2 to the required tempering temperature, hold at temperature for at least two hours or one hour per 25 mm of thickness. Double tempering is recommended.

Tempering M2 high speed Steel				
Tempering °C	500	550	600	650
HRC	64	65	64	61

Forging
Pre- heat slowly to 850 - 900°C, then increase more quickly to the forging temperature of 1050 - 1150°C. Do not forge below 880 - 900°C. Cool very slowly after forging.
APPLICATIONS
M2 tool steels are suitable for making cutting tools.
The well balance properties of M2 means it is used in a wide range of cutting tools where demands for hot hardness are moderate, such as twist drills, reamers, broaching tools, milling tools, taps and metal saws.M2 is also suitable for cold work applications such as tools for punching, forming and pressing.
DESIGN OF BROACH

The following points must be considered before starting the broach design.
ABOUT THE COMPONENT:

1) Type of material and the condition of the component for estimating:
a) Life of the broach.
b) Specific cutting resistance.
c) Volume coefficient of chip.
2) Operations carried prior to and after broaching, so as to determine:
a) Guiding part.
b) Initial and final size of the broach.
c) Burnishing teeth.
3) Number of broaches to be manufactured so as to select the economical process.
4) Kind of broaching machine to select the holding portion, to determine maximum allowed length of broach and cutting load.

5) Surface finish required on the component so as to fix finishing and burnishing teeth.
6) The expected accuracy of the component to estimate the shrinkage and for selecting mode of cutting.

III. Definitions:

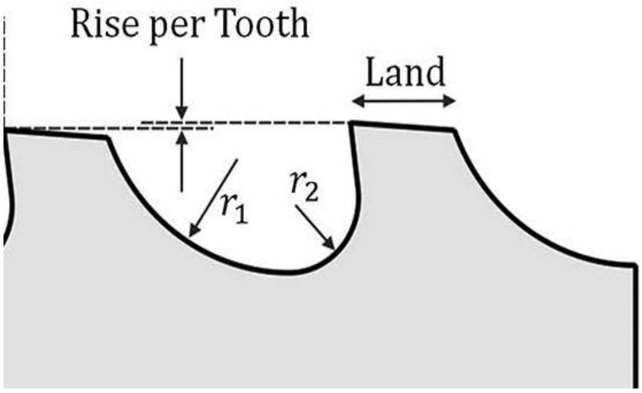
Clearance angle: It is made by grinding at the top of tooth at an angle to the line of cutting.
Rake angle: The angle between the cutting edge of tooth and a line perpendicular to the axis of cutting.
Chip space: The space between the teeth which accommodates the chip during the cut.
Cut per tooth: The amount by which tooth height increases over the preceding tooth.
Roughing teeth: The teeth which takes the first cut.
Finishing teeth: The teeth which take final cut to finish the surface.
Burnishing teeth: Round, non-cutting teeth which produce high degree of surface finish and high accuracy.
Chip breaker: Notches cut in broach teeth to break the chip into the small pieces for easier removal.
Pitch: The distance from the cutting edge of one tooth to a corresponding point on the next tooth.
Land: The thickness of the tooth at the top.
Front pilot: The part of a broach which fits the straight holes for centralizing the broach with the work.
Rear pilot: It provided after last tooth and presents the broach from locking.
Shear angle: The angle between the cutting edge of tooth and a plane perpendicular to the broach axis.

Mode Of Cutting:

The tooth rise is provided in the broach:
a) Depth wise
b) Side wise
c) Combination of both
If chip is removed in layers perpendicular to the axis of broach it is easy to manufacture. In other cases manufacturing becomes difficult especially for combined mode of cutting.
The choice of mode of cutting depends on the functional surface to be broached and on the strength of the component in the direction of broaching.

Selection Of Chip Thickness:

After studying the component thoroughly, the first thing is to select the chip thickness that is the rise per tooth. The successful working and tool life depends upon the selected chip thickness.



If chip thickness is more:
a) Gullet depth, consequently pitch should be more.
b) The rubbing action between face and chip will be more and chip particles may get welded to the face.
c) Specific cutting resistance will be less.
d) Less number of teeth will be in contact with the work and vibrations may come due to fluctuation of load.
f) The surface finish of the component will be poor.

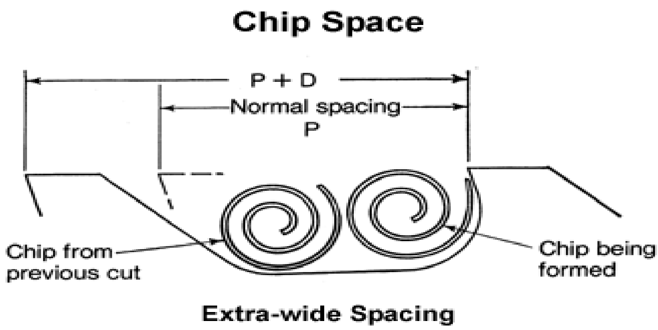
If chip thickness is less:
a) The specific cutting resistance will be more.
b) The length of broach may become too long.
c) The surface finish will be better.
d) If the chip thickness is smaller than the cutting edge radius, teeth may not cut but it will rub which reduces the life of the tool considerably.

Considering the advantages and disadvantages of more and less chip thickness the chip thickness is selected in the way to the optimum thickness for particular tooth geometry and tool life.
The suggested chip thicknesses for different materials are given in below table 1:

Chip thickness/ rise per tooth in millimeters.

Material to be broached	Characteristic of material		Shape to be broached		
	Hardness BHN	Strength in kg/sq.mm	Spline	Round	Key way surface
Carbon steels	Below 200	Below 70	0.04-0.06	0.02-0.03	0.04-0.07
	200-230	70-80	0.04-0.08	0.02-0.05	0.07-0.09
	Above 230	Above 80	0.03-0.05	0.02-0.03	0.04-0.06
Alloy steels	Above 200	Below 70	0.03-0.05	0.02-0.03	0.03-0.05
	200-230	70-80	0.04-0.06	0.02-0.04	0.06-0.10
	Above 230	Above 80	0.03-0.05	0.02-0.03	0.04-0.08
Cast iron	200	--	0.06-0.10	0.04-0.08	0.08-0.12
	200	--	0.04-0.08	0.03-0.06	0.07-0.10
Bronze and brass	--	--	0.05-0.12	0.05-0.1	0.06-0.12
Aluminum	--	--	0.02-0.1	0.02-0.05	0.05-0.08

SELECTION OF GULLET:
The space between the teeth is called gullet.



Gullet is provided to accommodate the chips formed during the broaching by each of teeth which cannot escape until the enclosing adjacent teeth have cleared the component. Chip space is limited by the pitch of the tooth and in small diameter broaches.
The ratio of the volume occupied by deformed chip to its own volume is called the volume factor 'K_v'. This factor depends upon:
a) Type of chip, because continuous chip occupies more volume then segmental chips.
b) Thicker the chips curling of chips become less.
c) Surface finish of the gullet, hook should be as smooth as possible otherwise excessive heat generation due to friction will cause to occupy more space.
d) Type of production.

DIMENSIONS OF THE GULLET:
While broaching, material forming continuous chips gets curled in a circular path, in the gullet space. Let the cross section of chip is 'A'. By neglecting the differences in width between chip and width of cut gullet space cross sectional area should be 'K_vA'. Height of the gullet is the diameter of the inscribed circle 'H'.
Therefore
$H^2 = K_v \times A$
But $A = L \times a$
Where L = length of the component.
a= rise per tooth/chip thickness.
$H = 1.13\sqrt{KvLa}$
If H value is high, the strength of the broach teeth is less and also chip may bet welded to the face of the gullet.
Width of land:
The width of the land should be sufficient to take the load even after the allowable sharpening limit of the surface. This depends upon the unit load on the cutting edge.
Required minimum thickness of the land to withstand the cutting load on the tooth can be found out from the formula.

$t^2 = 6K_s aH/f_s$

Where t = minimum thickness of land to withstand the cutting load.

K_s = specific cutting resistance of the material.

f_s = allowable bending stress of the tool material.

Sharpening allowances is generally 0.2-0.4 mm per sharpening.

Burnishing teeth:

Burnishing teeth are provided not to cut the work surfaces but to a) To smoothen b) Make the hole accurate
4 to 6 number of burnishing tooth are provided in the broach if required, at the end of finishing teeth, sometimes separate burnishing tool is used in the process after the broaching operation.

Chip breaker:

In broaches chip breakers are provided to divide the width of cut. For all internal broaches which cuts on its complete periphery chip breakers should be provided, because the periphery at the cutting edge greater than at the bottom of the tooth space which makes chip to be crowded and unable to curl properly into the space.

Chip breakers are not necessary to provide on the finishing teeth because of less depth of cut. When tough materials are broached the width of the chip will be more than the width of cut which may cause the scoring of the machined surfaces and this can be reduced by providing chip breakers. If the width of cut is more than 7mm, chip breakers must be provided.

The standard no of chip breakers for key way broaches are shown in table 2.

Width b in mm	No of chip breakers n
6-8	1
8-10	1
10-20	2
20-30	3
30-45	4
45-60	6
60-75	8
75-100	10
100-125	12

Pitch:

It is the distance between the two cutting edges. It depends upon

1) The chip thickness
2) Length of cut
3) Type of work material
4) Number of components

The general formula for pitch = 0.35 length of job

Or = 2.75H

Generally the pitch is constant when a tooth leaves the work, resistance will be less than the broach begins to accelerate, so next tooth starts to cut at high speed and produces a shocks.

If pitch is constant, the shocks occur at regular intervals and set up vibration. This can be reduced by using different pitches.

Points to be checked in designing broach:

The point to be checked in view of the tool is the strength of the broach core cross section which should withstand the cutting load for the specific component at the minimum cross section.

It is found out from the equation

$P_{max} = P_z n$ and $Pz = a.b.K_s.k$

Where Pz = cutting load acting on each tooth.

n = number of teeth in action in operation

a = thickness of the chip

b = width of the chip

K_s is the specific cutting resistance depends on the material and chip thickness.

IV. Conclusion

A conclusion section must be included and should indicate clearly the advantages, limitations, and possible applications of the paper. Although a conclusion may review the main points of the paper, do not replicate the abstract as the conclusion. A conclusion might elaborate on the importance of the work or suggest applications and extensions.

Acknowledgements

I would like to place on record my deep sense of gratitude to Prof. Balaji D Tandle, Dept. of Mechanical Engineering, SMEC, Secunderabad for his generous guidance, help and useful suggestions.
I would like to place on record my deep sense of gratitude to Prof. P P C Prasad, Dept. of Mechanical Engineering, SMEC, Secunderabad for his generous guidance, help and useful suggestions.
I express my sincere gratitude to Prof. D V Srikanth, Head, Dept. of Mechanical Engineering, SMEC, Secunderabad, for his stimulating guidance, continuous encouragement and supervision throughout the course of present work.

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