



Development of a Software for Designing In-Hole Broaching Tools

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Abstract

In this study, the design parameters of the broaching tools in the round holes were taken into consideration, the design experiences of the manufacturers were brought together and the design stages were followed as a process and converted into an algorithm. Considering the necessary conditions for the correct design, it is aimed to rationalize this stage, which is based on experience, with mathematical formulas. The software is developed on the processing of involute forms, which is the widely used model in the in-hole broaching tools. At the end of the study, a case study has been done and the developed software is verified. A broaching tool is designed and produced using the parameters revealed by the software and the consistency levels of these parameters in terms of both dimensional and surface quality were examined by broaching trials. Results showed that software works properly.

Keywords: *Broaching Tool Design, Broaching, Tool Design Program.*

Icons and Abbreviations

D_b = Major diameter value (mm) (Chosen - used)

D_t = Minor diameter value (mm) (Chosen - used)

D_p = Pre-broaching diameter value (mm) (Chosen - used)

D_p^* = Pre-broaching diameter value (mm) (Recommended by program)

H_a = The amount of passes to be removed from the profile (on diameter - mm) (Chosen - used)

H_b = The amount of passes to be removed from the hole caliber (on diameter - mm) (Chosen - used)

L_b = Broaching length (mm)

H_o = Average pass (on diameter - mm) (Chosen - used)

H_o^* = Average pass (on diameter - mm) (Recommended by program)

t = Pitch value (mm) (Chosen - used)

t^* = Pitch value (mm) (Recommended by program)

t_{a1} = Rear caliber zone recommended 1. pitch (mm) (Chosen - used)

t_{a1}^* = Rear caliber zone recommended 1. pitch (mm) (Recommended by program)

t_{a2} = Rear caliber zone recommended 2. pitch (mm) (Chosen - used)

t_{a2}^* = Rear caliber zone recommended 2. pitch (mm) (Recommended by program)

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- N_a = Number of profile teeth (quantity)(Chosen - used)
- N_a^* = Number of profile teeth(quantity)(Recommended by program)
- N_{ay} = Number of profile spare teeth (quantity)(Chosen - used)
- N_{ay}^* = Number of profile spare teeth (quantity) (Recommended by program)
- N_b = Number of front caliber teeth (quantity) (Chosen - used)
- N_b^* = Number of front caliber teeth (quantity) (Recommended by program)
- N_{by} = Number of front caliber spare teeth (quantity)(Chosen - used)
- N_{by}^* = Number of front caliber spare teeth (quantity) (Recommended by program)
- N_c = Number of rear caliber teeth (quantity) (Chosen - used)
- N_c^* = Number of rear caliber teeth (quantity) (Recommended by program)
- N_{cy} = Number of rear caliber spare teeth (quantity) (Chosen - used)
- N_{cy}^* = Number of rear caliber spare teeth (quantity) (Recommended by program)
- N_t = Total number of teeth calculated (quantity) (Calculated based on selected values)
- L_k = Calculated cutting length (mm) (Calculated based on selected values)

1. Introduction

Broaching tools are the name given to the cutters that process simple or complex forms into the hole or on the surface of the part by moving in a single axis in a serial and precise manner by removing chips with gradually rising tooth, by means of appropriate apparatus and machine systems. The broaching tool is specially designed for the piece to be broached. In the design of the broaching tool, the dimensional details of the work piece, the type and hardness of the material, and the heat treatment conditions are taken into consideration. A typical pull type round broaching tool has the front pulling area, the area where the cutting teeth are and the rear holder area as shown in Figure 1.

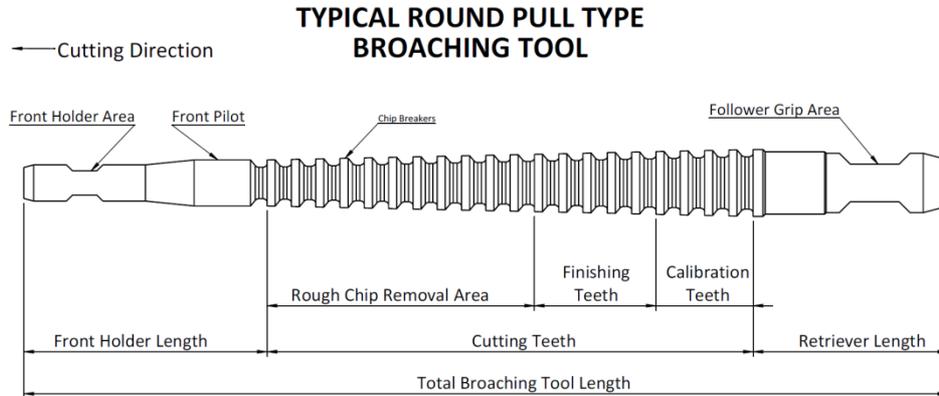


Figure 1. Representation of functional areas in round broaching tools [1]

The design of the area where the cutting teeth are located is very critical and the design must be done by an expert. In the rough chip removal area, rapid chip removal takes place, depending on the type of material, broaching length and the form to be formed, the cutting loads to the tool and the chip gullet volumes (as shown in the Figure 2) should be calculated properly and designed in accordance with this calculation.

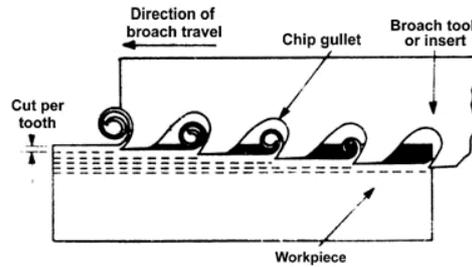


Figure 2. The working principle of the broaching tool [1]

By Sham Kumar Rajam in 1997, broaching tool types were analyzed and numerical modeling of the stresses occurring in different regions has been studied using method of finite element analysis with mesh method. In order to optimize these stresses, the formulas used in this study are compared with the relevant work. [2]

By Malyadri Akula et al. in 2013, a broaching tool was designed to be used in the production of an involute internal gear in a gearbox. It has been analyzed how the cutting forces and broaching forces will change when this tool is manufactured using different cutting edge angles. Through this study, the software determines the most suitable cutting edge angle according to the processing conditions over an average value instead of giving a size range. [3]

Also review of the experimental methods and the methods of mathematical modeling has been done, as confirmed by previous researchers. K. Ferhat Çelik, Banu Körbahti, Murad Kucur [4], Svetlana Lukina, Margarita Krutyakova, and Sergey Ivannikov[5], C. Monday[6], B. Nemyrovskiy et al[7], Riad Ahmad ,Hani Al-Rawashdeh, Ahmad O. Hasan [8], A. Hossein, H. A. Kishawy [9], O Zhed et al [10], Özelkan, E et al [11] and Jing Ni et al [12].

Broach types can be roughly divided into two: in-hole broaching tools and surface broaching tools. In this study, the most used in-hole broaching tools, involute broaching tools will be given point.

1.1 Designing Broaching Tools

Information such as the major and minor diameter of the part, whether the minor diameter will be calibrated, the pre-broaching diameter value, the part length, the broaching length, the material type and the standard to be used are needed both in classical and computer aided designs for involute broaching tools.

In the classical design, which is not computer aided; roughly the amount of chips to be removed is calculated first, in diameter. The pitch of the broaching tools teeth is determined based on the broaching length, and the total cutting length is determined considering the amount of passes that can be removed per tooth. After all this, detailed measurements of the pulling area are preferably determined using standards. Experience is needed in these designs made by calculating by hand, because rounding should be made according to certain directions over the values obtained as a result of the calculations. A designer who has made many designs examines the working performance of the broaching tool manufactured according to the design and examines the effects of the parametrically selected values on the life of the broaching tool and the surface quality of the processed part. Since all these processes take quite a long time, a great deal of experience is needed to make an efficient design with the classical method.

For computer aided design, equal distribution of cutting force is important, so in the article published by P. Vogtel, F. Klocke, D. Lung and S. Terzi, the formulation of the grading direction of the teeth of the broach tools and the cutting forces on each tooth in broaching complex forms has been studied. These parameters, which optimize the cutting forces, are also considered in this study. [13]

In this work, selection preferences for experience were turned into parameters and added to the applied formulas with certain coefficients. This is basically the difference of this study from its similar studies.

The front holder part is specially designed for each broaching tool in accordance with the holder head and holder locking mechanism for the broaching machine to catch the broach. There is a bearing area just behind the front holding part. This region takes on the task of centering the precision turned material to the broaching tool just before the broach teeth starts to cut. Before broaching, the part hole is required to fit this front shaft sweet-tight. When creating a form by removing chips, the broaching tool fits the axis of the part hole and if the part hole is wider than necessary, the axis of the form to be formed may create some offset from the desired axis. For this reason, precise turning of the hole before broach is an important process and suggestion for that value presents in the software.

With the development of sectorial concepts such as increasing digitalization and technical calculations by computer-aided software, error-freeing and Industry 4.0, it has gained great speed. At the same time, broaching operations started to be produced in the form of PLC or CNC broaching machines, and by this means, elements such as broaching efficiency, cutting forces and vibration were started to be followed [14].

The design and production of broaching tools, which are used in machining processes, especially in the automotive and defense industry, are carried out by a small number of companies. Due to the fact that the calculation techniques and know-how are largely under the monopoly of European companies, other manufacturer companies use common formulas and algorithms in the design of broaching tools and try to develop these algorithms with their experience. However, these algorithms are still made by hand in each design and the performance of the broaching tools produced depending on the experience of the designer varies. The performance of each newly manufactured broaching tool was monitored jointly with the customers of the broach manufacturer, and these algorithms were used in design improvement processes, and these improvement studies continue today. And the improvement processes in this design have remained largely based on the designer's experience.

In this study, the design experiences of manufacturers in the production of in-hole round broaching tools were compiled, digitized and transformed into a computer-aided program with numerical based algorithms. In this way, software has been developed that outputs the ideal design dimensions of the round broaching tools with the selected parameters.

In the article published by Saiful ISLAM, an algorithm that gives the output of the geometric dimensions of the broaching tool, which is intended to be designed with the interrogation methods called "logical test", has been studied. This algorithm has provided ideas for the software in this study, based on Visual Basic. [15]

The study focused on in-hole broaching tools, because these are the types where broaching tools are used widely, and most of them are involute broaching tools.

The points to be considered in the design of the broaching tools are as follows [16];

1. Type of material to be processed; material type will determine the average pass per tooth, so it is critical to determine equal loads for each tooth.
2. Desired shape; it will determine where the cutting will start and where it will end. Because of that, design must be made for different cutting zones, and different cutting strategies.
3. Working conditions of the broaching tool; machine and lubrication is important, if the machine has vibration or rigidity problems, tooth load must be decreased, otherwise it will cause bad surface finish and dimensional problems.
4. Tensile or compressive strength of the broach; thin sections of the broaching tool will be critical sections, according to material type of the tool must compensate loads.
5. Cutting force on broaching tool; must match with broaching machine capacity.
6. The style is pulled or pushed; while pulled broaching tools are more rigid to buckling effect, pushed broaching tools must not be so long to avoid this effect.
7. The broaching stroke of the machine; this will limit the total usable broaching tool length.
8. The length of the surface to be broached; the longer the surface length means tool will need longer pitch to compensate more volume of cut chip.
9. Dimensions of the work piece; this will determine the diameters of the broaching tool.
10. Sizes of the broaching tools; big size means big weight, so this should be determined whether the machine has upper holder mechanism or has not.

11. Surface quality; if the desired surface quality has really low roughness values and then some polishing tooth can be added at the end of the broaching tool.
12. Amount of materials removed; if the amount of materials to be removed is too much, operation can be completed more than one broaching tool, to avoid exceeding the allowable length of the broaching tool.
13. Hardness of the material to be processed; average pass per tooth must be decreased for premature wear on the teeth.
14. Amount of parts to be produced; for longer tool life for mass production, coating for broaching tools might be considered.

2. Development of the Software

For designing a broaching tool, there are too many parameters to analyze every aspect of cutting conditions. When the designer has decided to make an assumption on the halfway of the designing process, other parameters can be affected. With a systematic approach to collecting data and decide the design parameters for broaching tool this can be avoided. With software which designed with approach to this problem step by step will result in good designs.

In this section, collection of the data and processing them will be instructed.

2.1 Inputting Data of the Part to Be Broached

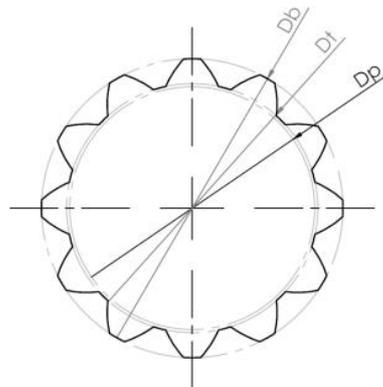


Figure 3. Major, minor and pre-broach diameters

In the first part of the program, the user is asked to enter major diameter (D_b) and minor diameter (D_t) (See Figure 3). However, "Will the minor diameter be calibrated?" asked in the form. If the desired minor diameter in the form of internal gear is not very sensitive, this question can be selected as "No".

If there is an average accuracy, the "Front Caliber Broach" option is selected. (See Figure 4) The teeth of these broaches starts to cut the piece by cutting from the pre-broach hole diameter to the diameter of minor diameter and "calibrates" the minor diameter. The desired profile on the following teeth is grinded and processed into a broaching tool and the rising teeth form cuts the sides of the desired gear and finally the major diameter.

I. Data of the Part to be Broached

Major Diameter:

Minor Diameter:

Will the minor diameter be calibrated?

Selected pre-broach diameter: Suggested pre-broach diameter:

Part length:

Broaching length:

Material type:

Figure 4. The section where the data of the part to be processed are entered in the program interface

Another option is the "Rear Caliber Broach". In these broaching tools, the teeth that calibrate the minor diameter are placed one after the other with the teeth that calibrate the major diameter. Because of these teeth, which are arranged one after the other in the shape of a tooth that calibrates the minor diameter of the form, then the rear caliber teeth on the broach and then the tooth base again calibrates the tooth base, high precision "concentricity" can be achieved between the major diameter and minor diameter.

The following section displays the "Recommended pre-broach diameter" value and prompts the user to enter a recommended pre-broach diameter value (D_p). The software proposes a value with the following tests, if the pre-hole cannot be precision turned in the parts where the broach will be used, if there are probable dimensional variations, a smaller pre-broach hole diameter can be defined to accommodate these variations.

$$\begin{aligned} &\text{If } D_b > 60 \text{ mm;} \\ &D_p^* = D_b - 0,3 \end{aligned} \quad (1.1)$$

$$\begin{aligned} &\text{If } 60 > D_b \geq 30; \\ &D_p^* = D_b - 0,25 \end{aligned} \quad (1.2)$$

$$\begin{aligned} &\text{If } D_b < 60 \text{ mm;} \\ &D_p^* = D_b - 0,2 \end{aligned} \quad (1.3)$$

After that, the user is asked for the length of the piece and broaching length. The piece length is the distance from the surface of the broaching table to the surface of the broaching machine and this measurement is critical in determining the front holder length. In some cases, the inner diameter of the piece may have different diameters and the broaching length may be shorter than the length of the piece. For this reason, these two values will be requested separately.

After entering these values, the user is asked to select the "Material Type". A list defined in the program database is opened and a material type is selected from this list. This option will determine the recommended average pass per tooth, and this is determined from the Table 1. It is possible to add more material types to the program.

Table 1. Average passes values according to material type

Material Type	Average Normal Pass	Rear Caliber Average Pass
1040	0,08	0,06
1050	0,08	0,06
8620	0,08	0,06
CK45	0,08	0,06
Raw 4140	0,07	0,05
Treated 4140	0,06	0,04
Stainless	0,06	0,04
Aluminum	0,09	1
Bronze	0,09	1

After this selection, software progresses on "Number of Teeth and Pitch Selection" section.

2.2 Number of Teeth and Pitch Selection

In this part, while the values Recommended by the software are on the right side, the user is asked to fill in the boxes on the left as shown in the Figure-5. There are some reasons that prevent direct ideal designs in broaching tool design. Some of these may be reasons such as lowering the cost of the broaching tool, not having enough strokes on the machine where the broaching tool will be used, designing a shorter broaching tool to shorten the standard cycle time. Or the stroke may allow for a longer broaching tool, and the broach user company may be experiencing fluctuations in hardness measures in the heat treatment process from time to time in its parts, in this case, a longer than ideal broaching tool can be designed in order to reduce the loads per tooth. Since all these situations are taken into account, the software gives the recommended values and asks the user for the preferred value. The drawbacks of stretching from these ideal values are analyzed and notified to the user after the selections are completed.

II. Number of Teeth and Pitch Selection

Pass to be removed from profile:

Pass to be removed from hole caliber:

Pass to be removed in total:

Suggested average pass:

Chosen Pitch: ▼

Suggested pitch:

Chosen front caliber teeth quantity:

Suggested front caliber teeth quantity:

Chosen front caliber spare teeth quantity:

Suggested front caliber spare teeth quantity:

Chosen profile teeth quantity:

Suggested profile teeth quantity:

Chosen spare profile teeth quantity:

Suggested profile spare teeth quantity:

Calculated total teeth quantity:

Suggested total teeth quantity:

Calculated cutting length:

Suggested cutting length:

Figure 5. The section where the number of teeth and pitches are selected in the program interface

Therefore, in this section, the amount of passes to be removed from different regions, the recommended average passes per tooth, the recommended pitch, the recommended number of teeth and the recommended number of spare teeth are presented to the user.

If the minor diameter is not calibrated or the broach is front caliber;

$$H_a = D_b - D_t \quad (2)$$

If the minor diameter is to be calibrated and this is a rear caliber broach;

$$H_a = D_b - D_p \quad (3)$$

$$H_b = D_t - D_p \quad (4)$$

If the minor diameter is not calibrated;

Total amount of passes to be removed = (2)

If a front caliber or rear caliber broach is designed;

Total amount of passes to be removed = (3) + (4)

In determining the recommended pitch, three tests should be done first.

(L_b = Broaching length (mm), H_o = Average pass (mm, in diameter))

Test A -> If major diameter > 50 mm then A = 1, otherwise A = 0

Test B -> If $\frac{L_b}{3,5 \times \sqrt{H_o \times L_b \times 4,5}} > 5$ then B = 1, otherwise B = 0

Test C -> If $\frac{L_b}{3,5 \times \sqrt{H_o \times L_b \times 4,5}} > 8$ then C = 1, otherwise C = 0

According to this test results;

1. Test,

If A = 0 and B = 1;

$$\text{Recommended pitch} = \text{ROUND DOWN} \left(L_b / 6,5 \right) \quad (5.1)$$

2. Test,

If A = 0 and B = 0;

$$\text{Recommended pitch} = \text{ROUND UP} \left(3,5 \times \sqrt{H_o \times L_b \times 4,5} \right) \quad (5.2)$$

3. Test,

If A = 1 and C = 1;

$$\text{Recommended pitch} = \text{ROUND DOWN} \left(L_b / 7,5 \right) \quad (5.3)$$

4. Test,

If A = 1 and C = 0;

$$\text{Recommended pitch} = \text{ROUND UP} \left(3,5 \times \sqrt{H_o \times L_b \times 4,5} \right) \quad (5.4)$$

Tests are done. These four tests are run from top to bottom in the order stated above, and the formula of the first provided condition is applied.

The recommended pitch is specified in the program interface and the user is asked to select a pitch value. Choosing a different pitch than the recommended value may result in chattering on the broach or breaking the broach due to excessive load on the tool. The disadvantages of these force changes will be stated to the user in the analysis section.

After this section, in I. Work piece Data section, "Will the minor diameter be calibrated?" If the answer is given to the question is no, the program will continue with the section "Recommended profile teeth number". If the "Front Caliber Broach" option is selected in the caliber question, the value "Recommended number of front caliber teeth" will be given in this section.

$$H_b = D_t - D_p \quad (6)$$

$$N_b^* (\text{Recommended number of front caliber teeth}) = \text{ROUND} \left(H_b / 0,062 \right) \quad (7)$$

The rounding function here means that the digits after the comma are deleted and the result is rounded to a multiple of 1.

The recommended number of front calibrated spare teeth value is 4 as standard. There is no increase in the amount of passes in these teeth and is equal to the diameter of the previous teeth. Due to the rake angle value specified in Figure 3 on the broach teeth, the tooth diameters on the basis of microns decrease after each sharpening operation. The task of these spare teeth is to keep the broach teeth cut without being affected by this diameter reduction. For this reason, these teeth are called calibration spare teeth and they ensure that the desired measurements are taken on the part until the broach completes its life. The recommended number is 4 based on experience and it is concluded that the

teeth width that decreases as the broach is sharpened, 4 teeth are sufficient until the broach becomes unable to function. If this number is chosen less than 4, it may cause the desired area to be calibrated to be smaller than the desired as the broach is sharpened. Again, if this number is selected more than 4, it can be observed that when the broach ends its life, calibration spare teeth will increase and this is an unnecessary cost.

If the "Rear caliber broach" option is selected in the caliber question, in this section, the "back caliber region recommended 1st pitch" and "Rear caliber recommended 2nd pitch" value will be given.

Rear caliber broaches were mentioned in I. Work piece Data. A chip chamber problem occurs in these teeth, which are arranged one after the other to ensure concentricity. Generally, there is a 3-4 mm diameter difference between the major and minor diameter. In rear caliber broaches, if the teeth that are required to remove chips major and minor diameters in order, arranged in the same form, the chip holding capability of the minor diameter tooth's chip chamber will decrease. Because the next tooth will remain high and the 40 degree back angle will be located in the chip chamber of the small tooth and reduce the volume of this area. In order to prevent this, in rear caliber broaches, pitches in caliber area from behind;

$$t_{a1}^* \text{ (Rear caliber section recommended 1st pitch (mm))} = t - 1 \quad (8)$$

$$t_{a2}^* \text{ (Rear caliber section recommended 2nd pitch (mm))} = t + 1 \quad (9)$$

It is recommended to be manufactured in these results. The teeth arranged in this way will not affect each other's chip chamber and a healthy chip accumulation will be provided.

In addition, when the "Rear Calibrated Broach" option is selected in the calibration question, the "Recommended number of rear caliber teeth" value will also be displayed on the screen. In the calculation of this value, if the recommended pass value (H_{oa}) is called, the average pass value corresponding to the material selected from Table 1 is taken and the following formula is applied;

$$H_{oa} = D_t - D_p \quad (10)$$

$$N_c^* \text{ (Recommended number of rear caliber teeth)} = \text{ROUND UP} \left(\frac{H_b}{H_{oa}} \right) \quad (11)$$

The user is asked to select the number of rear caliber teeth against the recommended number of rear caliber teeth. Again, in case of deviating from the value recommended in the final analysis section, how the loads will change will be presented to the user.

The determination of the number of rear-calibrated spare teeth is almost parallel to the determination of the number of front-calibrated spare teeth. The recommended rear caliber spare tooth number value is 5 as standard and this value has been determined as an average as a result of experience. If it is anticipated that the hole diameter before the broach is being calibrated for different reasons, there will be more tool load or teeth will become blunt faster, this number of teeth can be increased by 1 or 2 more.

After this selection, the user is offered a normal profile tooth number. This suggestion is made with the following formula:

If we say the normal average pass (H_o) determined according to Table 1 according to the selected material;

$$N_a^* \text{ (Recommended number of profile teeth)} = \text{ROUND UP} \left(\frac{H_a}{H_o} - 0,012 \right) \quad (12)$$

The value determined as a result of the formula is presented to the user, and in the same way, if it deviates from the ideal; its reflections on the broach are presented to the user in the analysis section.

The number of normal profile spare teeth is recommended as "4" as standard, but this number can be increased by 1 or 2 more, considering the extreme scenarios.

After the normal profile spare teeth number is selected software progresses with "Calculated total number of teeth" value is displayed on the screen over the selected tooth numbers. Just below this, the value of "Calculated cutting length" is also displayed. This size of broach will vary depending on the caliber condition. Because rear caliber broaches use variable pitch and this is reflected in the total value. The calculated cutting tooth length is important because the broaching stroke of the machine to be used in broaching should be at least this value. Before moving on to these neck calculation formulas, let's talk about the formulas of the total number of teeth value calculated:

If the broach is not a front or rear caliber model;

$$N_t \text{ (Calculated total number of teeth)} = N_a + N_{ay} \quad (13.1)$$

If the broach is a front caliber model;

$$N_t = N_b + N_{by} + N_a + N_{ay} \quad (13.2)$$

If the broach is a rear caliber model;

$$N_t = N_c + N_{cy} + N_a \quad (13.3)$$

When the total number of teeth calculated according to the broach caliber status is determined, the calculated cutting tooth length values are calculated as follows;

If the broach is not a front or rear caliber model;

$$L_k \text{ (Calculated cutting length (mm))} = t \times (N_t - 1) \quad (14.1)$$

If the broach is a front caliber model;

$$L_k = t \times (N_t - 1) \quad (14.2)$$

If the broach is a rear caliber model;

The 1st pitch value of the rear caliber zone= t_{a1} ,

The 2nd pitch value of the rear caliber zone= t_{a2} ,

$$L_k = (N_c + N_{cy}) \times t_{a1} + (N_c + N_{cy}) \times t_{a2} + (N_a - N_c - 1) \times t \quad (14.3)$$

After displaying the calculated total number of teeth and calculated total cutting length, software progresses to the Front and rear holder selection.

2.3 Front and Rear Holder Selection

The first question is whether there is a front holder or not as shown in the Figure 6. If no front holder option is selected, it means that a press type broach is designed and the front shaft length is determined accordingly.

III. Front and Rear Holder Selection

Is there a front holder?

Standard to be used:

Chosen front holder diameter: Suggested front holder diameter:

Chosen Form: Suggested Form:

Splint:

Is there a rear holder?:

Standard to be used:

Figure 6. The section where front and rear holders are selected in the program interface

If there is a front holder, the user is asked for the preferred standard information for the front holder. These standards are "DIN 1415" and "DIN 1417". These standards relate to the design of the broaching machine user and must be specified from the beginning. The loads that will come from the diameter values of the teeth that the broach will cut are calculated and the appropriate shank diameter is recommended to the user.

The recommended front holder diameter value is determined by the following algorithm;

If the chosen standard is DIN 1415;

If we briefly call the selected pre-broaching diameter " D_p ";

If $D_p < 7$ mm;

$$D_p^* = D_p - 0,21 \tag{15.1}$$

The closest value is selected among the nominal diameters of the D_p^* value as d_1^1 in the table in DIN1415 standard section 3, page 2, and this value is presented as the recommended diameter value.

If $7\text{mm} \leq D_p \leq 20\text{mm}$;

$$D_p^* = D_p - 0,21 \tag{15.2}$$

The D_p^* value is rounded up in multiples of 1, and the value found as a result of the rounding is selected as the closest value among the nominal diameters of d_1^1 in the table on page 2 of the DIN1415 standard section 3 and this value is presented as the recommended diameter value.

If $D_p > 20mm$;

$$D_p^* = D_p - 0,5 \quad (15.3)$$

The D_p^* value is rounded up in multiples of 1, and the value found as a result of the rounding is selected as the closest value among the nominal diameters of d_1^1 in the table on page 2 of the DIN1415 standard section 3 and this value is presented as the recommended diameter value.

In these sections, extracting certain values from the results and then making them is an approach of experience.

If the chosen standard is DIN 1417;

Tests are done in the same way and D_p^* values are determined in the same way. Only the D_p^* values found this time are selected as the closest value among the nominal diameters of d_1^2 in the table in the DIN1417 standard part 1 and this value is presented as the recommended diameter value.

It is desirable to select a diameter value just to the left of the proposed front holder diameter value. In order to comply with the aforementioned extreme conditions, this diameter can still be chosen non-standard, but it is also desirable to choose among the nominal diameters, because other dimensions of the shank will be determined on this nominal diameter.

After the shank diameter selection, the user is asked about the front holder form, for example, the options for the "DIN 1415" standard are "Type A Splint" and "Type B Round". The reason for this choice is that when the front holder diameter value is below 18 mm, when the circular form front holder is processed, the shank strength decreases at a high rate. In order to prevent this, if it is below or equal to 18 mm, the Splint Type is recommended.

For DIN 1417 Standard, if the selected front holder diameter value is below or equal to 18 mm, "J Type Splint" is recommended, if it is greater than 18 mm, "K Type Round" is recommended.

After this selection, the user is asked whether there will be a position split on the broach. If there is a desired fixed relation between the way the part is fixed to the fixture and the position of the involute form that the broach will create, a position cut is made on the broach front holder part and thus the broach, whose position is fixed from this position, always moves in the same position and cuts. Since the part is also fixed with a fixture, the teeth are always in the desired direction.

After this selection is made, the user is asked whether there will be a rear holder in the broach. This choice is also entirely related to the end user of the tool. If the broach is heavier than 20 kg, it is recommended that the broach has a rear holder and it is recommended to be used on a broaching machine with a rear holder system. However, due to the costs, the user may want to use it on a broaching machine that does not have an upper holder despite the weight of the broach, or may want to use it on a broaching machine, although the broach is light, if there is a rear holding system on the machine, so this choice is made according to the request of the end user. The rear holder standard must also be the same as the front holder standard, so at this point it also applies to the standard rear holder selected for the front holder.

After this selection, a rear holder diameter is recommended as in the front holder, and the preferred rear holder diameter value is taken from the user.

The rear holder diameter value is recommended as follows;

For DIN 1415;

If the selected front holder diameter value is called " D_p ";

If $D_p < 12mm$,

It is not recommended to make a rear holder, it is not necessary. If it is still desired to be used as an upper holder, any diameter value not exceeding the largest diameter of the broach teeth can be used.

If $D_p \geq 12mm$,

The D_p value is searched in the d_1^1 column in the table in the 4th section of the DIN 1415 standard and the closest value is selected.

For DIN 1417;

If $D_p < 4mm$,

It is not recommended to make a rear holder, it is not necessary. If it is still desired to be used as an upper holder, any diameter value not exceeding the largest diameter of the broach threads can be used.

If $D_p \geq 4mm$,

The D_p value is searched in the d_1^1 column in the table in the 4th section of the DIN 1415 standard and the closest value is selected.

After this selection, if there is a position cut in the broach, "C Splint Type" is recommended for the "DIN 1415" standard as the rear holder form, if there is no position cut, "D Round Type" is recommended. After this selection is completed, the "Complete Design" button becomes active, and progression after this, the force analysis of the broach and any drawbacks are indicated on the new page that will open. The required broaching machine features are also available on the page. In addition, the technical picture of the broach is prepared by reference to the standards based on the selected values and presented to the user.

2.4 Algorithm of the Software

In Figure 7 first part of algorithm three is explained. For work piece data 1st part major and minor diameter value, calibration status will be the inputs and output will be the pre-broaching diameter suggestion.

For work piece data 2nd part chosen pre-broaching diameter, part length, broaching length, and material type will be the inputs and there is no outputs, because these information will be used on quantity of teeth and pitch selection section.

On quantity of teeth and pitch selection 1st part, suggestions for pass quantity to be removed from the profile, the amount of passes to be removed from the hole caliber, total amount of passes to be removed, recommended average pass, recommended pitch, number of front caliber teeth selected, recommended number of front caliber spare teeth, recommended profile teeth number, recommended profile number of spare teeth are given and inputs will be the chosen values according to suggestions.

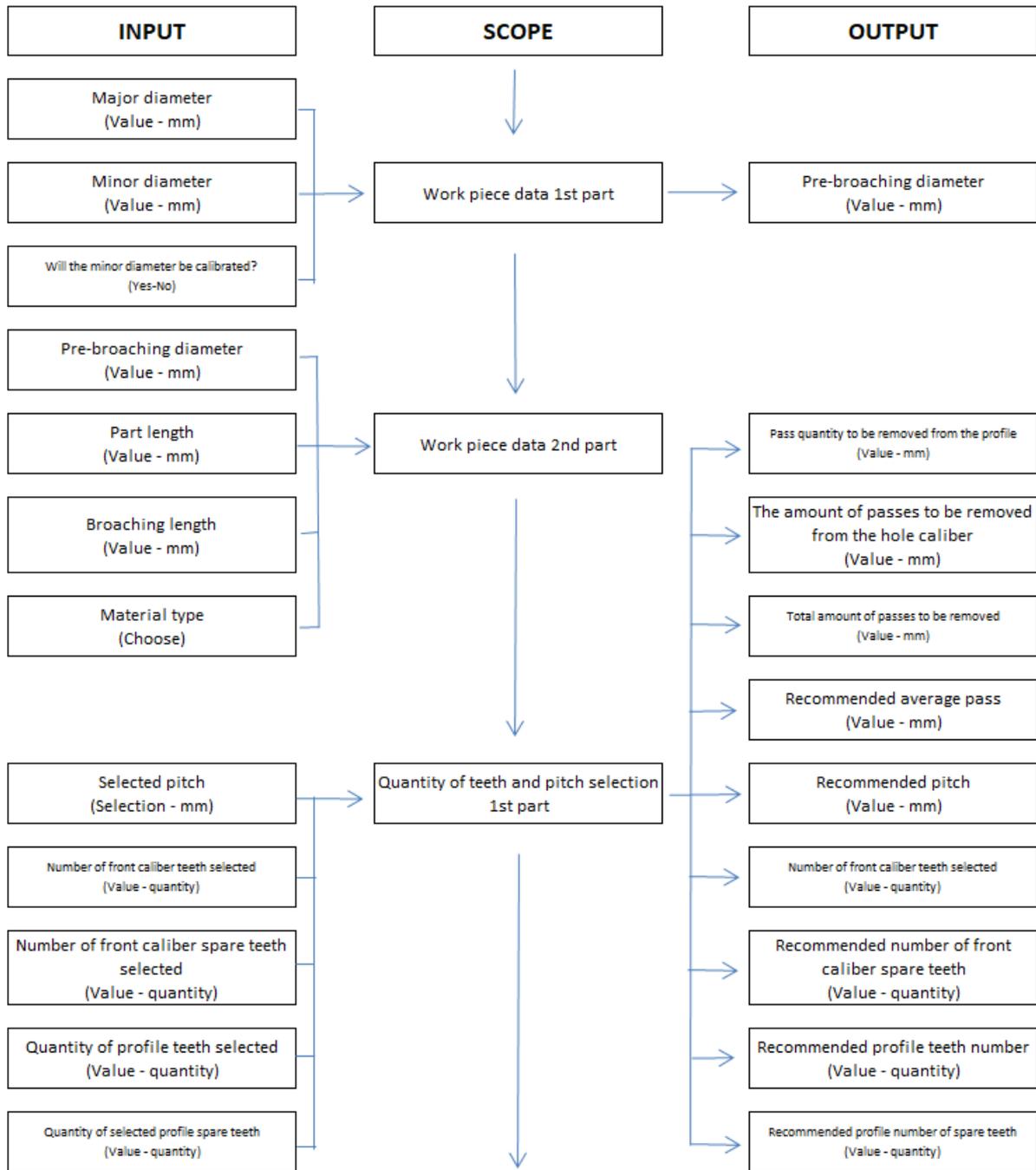


Figure 7. Algorithm Tree Part 1

These chosen values will be used in number of teeth and pitch selection 2nd part, and in this section, calculated total number of teeth, calculated cutting length, recommended total number of teeth and recommended cutting length will be the outputs as shown in the Figure 8.

All these chosen values for broaching part data and with the front and rear holder selections design will be completed.

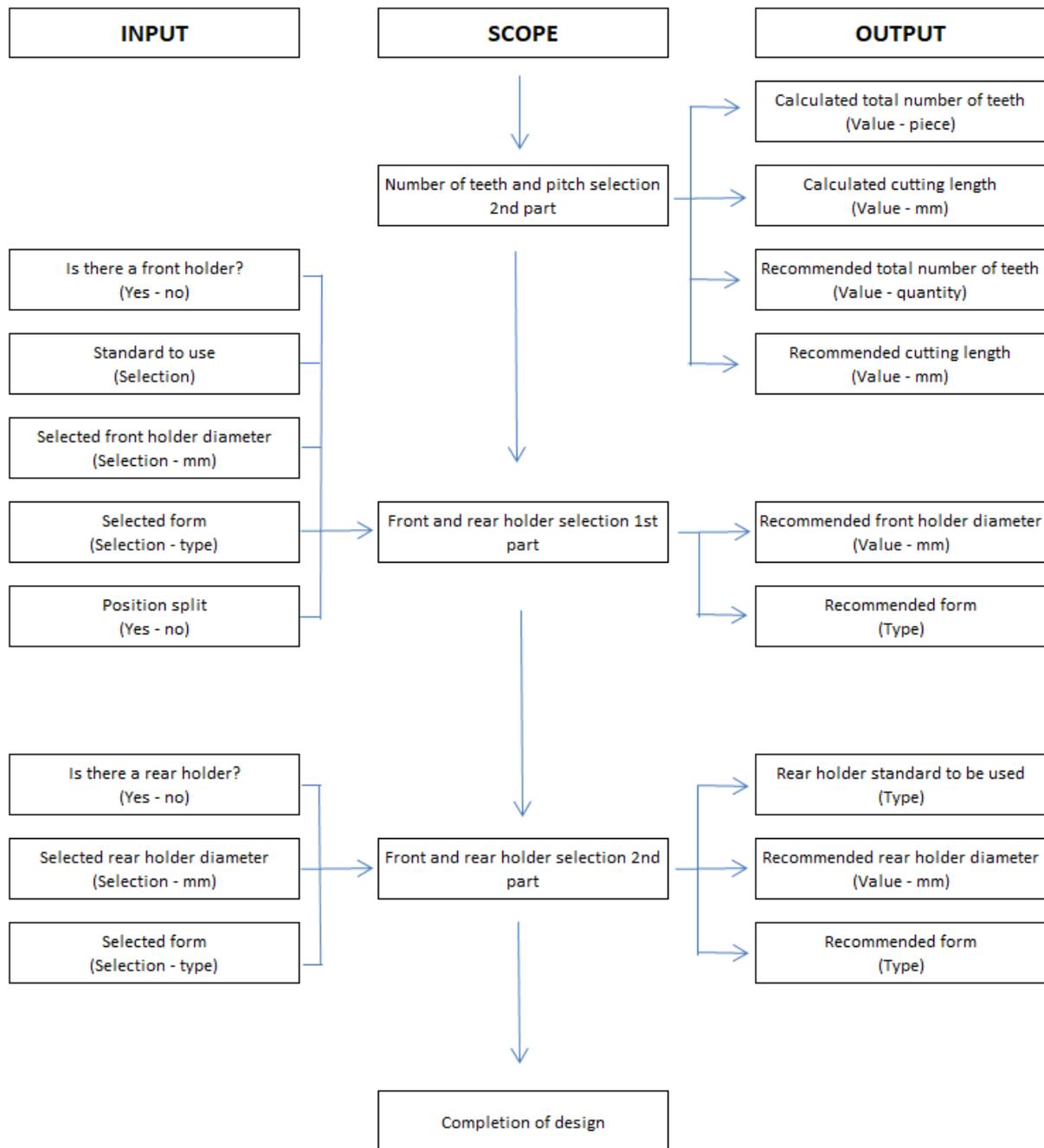


Figure 8. Algorithm tree, part 2

After all, this information can be summed up as inputs and outputs as shown in the Table 2.

Table 2. Summary for software inputs and outputs

Inputs	Outputs
Major diameter value (mm)	The amount of passes to be removed from the profile (mm)
Minor diameter value (mm)	Total amount of passes to be removed (mm)
Will minor diameter be calibrated? (yes/no)	Average pass (mm)
Pre-broaching diameter value (mm)	Pitch (mm)
Part length (mm)	Caliber and profile tooth amount (quantity)
Broaching length (mm)	Spare teeth amount (pieces)
Material type (choose)	Tooth form (mm)
Front holder included? (yes/no)	Cutting length (mm)
Rear holder included? (yes/no)	Holder lengths (mm)
Standard to be used (choose)	Holder form suggestion (choose)

2.5 Software Constraints

In order to have effective and applicable equivalents, restrictions have been made on these values in the selection of the targeted part geometry. This also aims to eliminate the effects of extreme geometries on the design part.

For major and minor diameters, 10 mm - 100 mm can be selected. This is also a range that represents 95% of the involute broaching tools used.

It is possible to choose between 8mm - 200 mm for the part length and broaching length. Again, since the distances between the teeth are very wide on the broaching length over 200 mm, the pitches on the broaching tool are generally too long and the broaching machine's stroke is not enough. In this case, broaching tools are designed in more than one for a single form, which raises the cost of the tool quite high. As a result, different methods such as wire erosion instead of broaching tools become more advantageous in terms of cost and these methods are preferred. Therefore, the broaching length for the program was determined as 200 mm as the upper limit. For part sizes below 8 mm, two or more parts must be broached at the same time, depending on the condition of the part. Since this depends on the manufacturer's preference, the lower limit is determined as 8 mm.

There is no restriction on total broach lengths, if available; broaching can be done with broaching machines where broaches can be used in very long strokes.

3. Case Study for Verifying the Software

A trial work has been done to verify the software. First a piece to be broached has chosen. Then broaching information extracted from technical drawing. This information put into the software, and software suggested a broaching tool design. Designed broaching tool has been manufactured, and 200 actual part has broached with this tool. Processes and results will be instructed in this section.

3.1 Inputs and Outputs for Trial Broaching Session

A trial is done for an automotive industry part. These values are extracted from parts technical drawing.

Table 3. Software trial inputs

Content	Value
Major diameter	65.34 mm
Minor Diameter	62.58 mm
Pre-broaching diameter	62.30 mm
Broaching length	15 mm
Material grade	CK45
Caliber type	Front caliber

With this information inputted in software, algorithm is followed, calculations are made and outputs are these;

Table 4. Software trial outputs

Content	Value
Recommended pitch	6 mm
Number of front caliber spare teeth selected	5
Number of regular profile spare teeth selected	5
Total number of teeth	71
Cutting length of the tool	420 mm
Front holder length of the tool	280 mm
Front holder diameter of the tool	56 mm
Selected front holder form	B Type Round
Rear holder diameter	50 mm
Selected rear holder form	D type Round
Required pulling force for the machine	6326.28 kg
Required minimum stroke for the machine	669 mm

Based on these information, a technical drawing was drawn and the broaching tool was produced according to the design results that determined by the software.

Broaching trials for 200 parts were made with the manufactured broaching tool and it was determined that both the dimensions over pins are correct and the surface quality is proper. Required surface roughness value was 3,2 μm and average result for 10 parts is 2,48 μm .

3.2 Broaching with The Designed Tool

The operation sequence for round broaches is as follows. Regardless of the outer dimensions of the part, a pre-hole area where the broaching front shaft will pass easily and will serve as a bearing should be precision turned. When the part is placed on the broaching machine, the front holder of the broach passes through this area and the front shaft region is beared in this area. Thus, the first cutting tooth of broach can move perpendicular to part and the broaching form can be processed perpendicular to the surface on which the part sits. This measure is called "pre-broach hole".

Broaching tool is designed with rear holder, because tool was heavy. It can be used without rear holder, but rear holder preferred in design to use it with a rear holder mechanism included broaching machine as shown in the Figure 9.

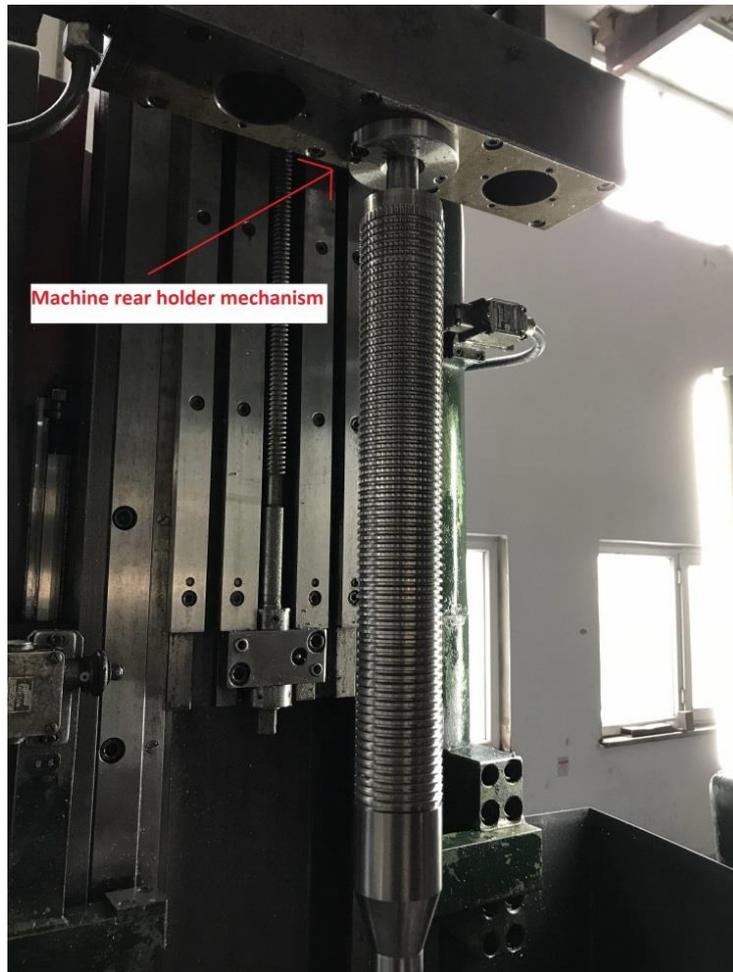


Figure 9. Connecting the designed broaching tool to the broaching machine

The parts to be broached are precision turned to pre-broach diameter as shown in Figure 10, which is chosen in the software.



Figure 10. Precision turned part with pre-broaching hole

Broaching length and broaching speed has set-up in the machine. Broaching tool came down on locking mechanism, and pilot area of the broaching tool is beared by pre-broaching diameter of the part as shown in the Figure 11.



Figure 11. Precision turned hole bearing of the front shaft area of the broaching tool

Then broaching operation has started, cutting sound was good and it is observed that tool left the part without any problem as shown in the Figure 12.

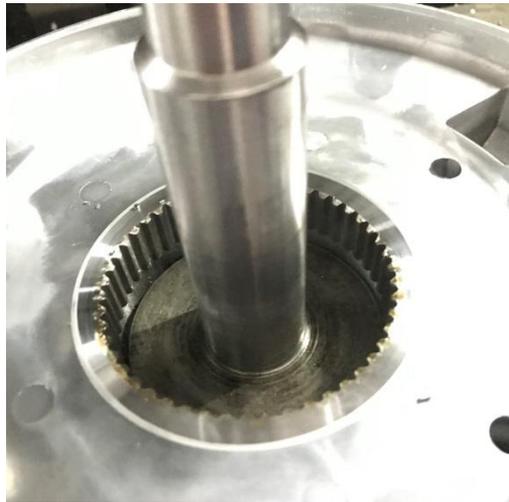


Figure 12. Tool exits from the piece while broaching operation.

Involute forms on the parts are inspected for the 1st hour of trial. Measurements over pins are within tolerance and surface quality was good as shown in the Figure 13.



Figure 13. Involute form on the part after broaching

4. Conclusion

This study was conducted to examine the results of applying the experience of design to the principles and formulas used in common designs.

Based on this trial work, it is understood that the algorithm produced gives correct design results. With the broaching tool which is designed by software, 200 parts has been broached in one set-up and with 7 meter/min broaching speed. The targeted major diameter value was 65.34 mm and the targeted

minor diameter was 62.58 mm. 10th, 50th, 100th and 200th parts are measured for these values and results are within tolerance of $\pm 0,01$ mm. Surface roughness target was max. Ra: 3,2 μ m and 10th, 50th, 100th and 200th parts are also measured for surface roughness values. Average of results is Ra: 2,48 μ m, so this means designed tool delivered good condition for surface quality too.

For future work, program parameters will be tested with more trials and whether they give correct results in extreme conditions. Correction coefficients will be added to the formulas in the program in order to adapt to extreme conditions.

In addition, in order to expand the selection constraints further, deviations occurring in extreme dimensions will be examined and coefficients to eliminate these deviations will be added to the formulas to be used for different input measurement ranges. Thus, the calculation capacity of the program will be increased.

As a result, step-by-step software was developed, and when this software was used, the design of the parameters could be decided without being affected by the decisions made later, and made the calculations easy and user friendly. Also with the trials, software has verified.

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References

- [1] www.kestas.com.tr June, 2020
- [2] Pradeep, A.V., Prasad, K.R. & Babu Victor, T. (2012). Design and Finite Element Analysis Of The Broaching Tools, 2(6), 67-74.
- [3] Akula, M., Sekhar, K.C. & Nagendra, A. (2013). Design And Analysis Of Broach Tool For Splines, Intenational Journal of Advanced Engineering Technology, 6-8.
- [4] Çelik, F., Körbahti, B. & Kucur, M. (2003). Computer Aided Design Application for Optimum Broach Design, Department of Mechanical Engineering, Istanbul University, Turkey.
- [5] Lukina, S., Krutyakova, M. & Ivannikov, S. (2018). Designing spline broaches of optimal structure, MATEC Web of Conferences, 224. 01094.
- [6] Monday, C. (1960). Broaching, The Machinery Publishing Co., London.
- [7] Nemyrovskiy, Y., Krivosheya, V.V., Sardak, S.E., Shepelenko, I. & Tsekhanov, Y. (2020). The use of deforming broaching for enhancing the efficiency of cutter chisels, Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, 51-56.
- [8] Ahmad, R., Al-Rawashdeh, H. & Hasan, A.O. (2019). Optimization of Keyway Broach Design. J Fail. Anal. and Preven. 19, 688–697.
- [9] Hosseini, Ali & Kishawy, H.A. (2013). On the Optimized Design of Broaching Tools. Journal of Manufacturing Science and Engineering, 136. 011011.
- [10] Zhed, O. Kozochkin, M. & Kazymaeva, K. (2020). Perfection of the methodology for calculating the keyway broach through the experimental data of photomechanics, IOP Conf. Ser.: Mater. Sci. Eng., 971 022027.
- [11] Özelkan, E.C., Öztürk, Ö. and Budak, E. (2011). Identifying parameters of a broaching design using non-linear optimization, Int. J. Modeling, Identification and Control, 12(3), 244–252.
- [12] Ni, J., Shi, Y., Wu, S., Guo, X. & Meng, Z. (2020). Modeling and assessment of broaching tool with grooves on the flank face, Int J Adv Manuf Technol., 107, 4531–4543
- [13] Vogtel, P., Kloche, F., Lung, D. & Terzi, S. (2015). Automatic Broaching Tool Design by Technological and Geometrical Optimization, Procedia CIRP, 33, 496-501.
- [14] Stott, W.R. (2011). State of the Art Broaching, Gear Technology, 62-66.
- [15] Islam, S. (1990). Design Of Broaches Using Computer, Department of Industrial and Production Engineering Bangladesh University of Engineering & Technology, Dhaka, Bangladesh.
- [16] Yalçın, M.K. (2018). Involute Simulation for Broach Cutting Tools Design, Hacettepe University, Turkey.