Improvement of Broached Involute Gearing on Engine Components

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***Abstract*—**This paper deals with the improvement of broaching processes with respect to cost-effective solutions – e.g. less process steps. In the considered case an involute spline has to be manufactured with the flank fit “7H” according to DIN 5480 considering an orientation of one teeth pair to an outer contour. The size between pins and the run-out is considered as critical dimensions. The measurements are taken in three different levels of the spline, which brings exact results that can be used for a conclusion. When the goal is to avoid an additional process after broaching with an orientation of the spline to an outer contour there is there is a need for sophisticated fixtures.

***Keywords*—**Broaching, Gear Measuring, Involute Spline, Size between pins.

I. INTRODUCTION

THIS paper is focusing on the production process of involute splines. Nowadays involute splines for bigger quantities are produced via broaching technology. For smaller quantities also the slotting process is used, which not as economically as broaching because every teeth of a spline is produced separately. In the broaching process the profile is manufactured in a single linear movement, which makes it a very stable, safe process, where no big size variations are to be expected. Broaching tools mainly are made of M2 (HSS) steel, which is normally hardened to 63 to 65 HRC. In cases where longer lifetime of the broaching tools is required other materials, such as M35 (with a higher temperature strength in comparison to M2) or even powder metallurgical steels (e.g. ASP30) are used [1]. Coatings are also used to increase the lifetime, but to maintain a sharp cutting edge the rake angle is sharpened after coating (also removing the coating there) in many cases for soft- (also known as green-) broaching. Exceptions are e.g. dry broaching with cutting speeds around 30 m/min and mainly multi layer coatings. Reasons are higher temperatures at the cutting edge and thus a requirement for higher wear resistance. Dry broaching was developed to adapt to estimated savings in cleaning of the produced components as the process is running without any coolant [2]. In contrast to that green broaching is processed mainly with cutting oil to achieve higher lifetime of the tools and lower surface roughness of the components. The pitch and the land width are often designed according to DIN 1416 [3]. Also the combination of pitch and chip thickness is essential for a productive broaching process [4]. In contrast to e.g. a milling process the cutting forces in a broaching process are strongly varying over time in cut [5]. Especially in the automotive sector for e.g. engine components broaching is a common process, which is often running fully automated.

II. PRELIMINARIES AND PROBLEM DESCRIPTION

In the last years the requirements for the quality of internal gears such as involute splines have been increased. The reasons are e.g. reduction of emissions and fuel consumptions of engines in the automotive sector. One of many steps to achieve these goals is seen via more quality in internal gears. E.g. the German involute spline standard features several types of side fit. Former for the hub it was common to use the “9H” fit, today the hubs with flank fit “7H” do increase significantly, which results in less circumferential backlash when pairing with the shaft. For the considered case respectively diameter in this paper this means a tolerance in the size between pins of 55 µm. With respect to the characteristics of a broaching tool it is normally designed 10 – 20 µm below the upper limit of the size between pins. The reason is that the resulted size between pins on the component will decrease with every sharpening process of the broach due its back taper – which is in contrast to modern statistic controlled processes – compare accepted literature e.g. [6].

The flank fit “7H” DIN 5480 [7] does also include the tolerances for the gear quality, which cannot be achieved with secure repeatability with a “standard” broach. To achieve this gear quality at least five full-form respectively relief grinded teeth are required. The grinding process for the teeth takes much longer thank standard spline grinding with back taper. This makes a broach expensive and in conclusion often the decision is to adapt to the small tolerance for size between pins on the component but with enlarged tolerances for the gear quality – so it is for the descripted component here.

Another critical consideration for a broaching process should be the requirements regarding run-out or coaxiality, which is often referenced from the pitch diameter of the spline to an outer contour of the component. It is possible to choose between two options to achieve the required quality.

1. Broaching of the pre-bore (minor diameter), clamp after the broaching process on the minor diameter and grind or turn the outer contour (after a hardening process). This implements one additional process step to a finished component.

2. Use of a tight tolerance for the pre-bore of the component to eliminate the space between diameter of centering-entry of the broach and the pre-bore to avoid the broach have the

possibility to move as less as possible out of the center. In the considered case this option was chosen with H6 tolerance for the pre-bore, which results in having 15 - 21 µm space on each side between the centering-entry of the broach and the pre-bore of the component. The reason for trying to achieve the required qualities regarding run-out and coaxiality are estimated cost savings by avoiding an additional process step (grinding or turning of the outer contour).

Another considered criteria for a successful broaching process has to be the orientation of the spine to the outer contour, which has to be within +/- 0.5° here to avoid an additional process step after broaching.

Summarizing for the considered component the goal is to achieve high quality with lowest costs as possible.

III. TEST SETUP

A. *Description*

The components are broached using a fixture on the machine table. The broached component is static positioned on the fixture – no clamping of it to keep it as cost efficient as possible. The outer contour is not rotationally symmetric. During the complete linear broaching process cutting oil is running out of three nozzles on the top of the component.

Next is to be found the exact data for the component, the process and the broach.

B. *Component Data*

This subchapter features the component data:

Material:	100Cr6 (1.3505) modified,
Pre Bore:	24,2 H6 (ground),
Broached Profile:	Involute spline with flank fit 7H according to DIN 5480 (modified),
Broaching length:	65 mm,
Orientation:	Orientation of one pair of teeth to an external contour is required within +/- 0.5°.

C. *Process Data*

This subchapter features the process data:

Broaching machine:	Vertical, electro mechanic broaching machine with ball screws,
Cutting speed V_c:	3 m / min,
Movement:	Broaching tool is pulled by the DIN 1418 pull head in a linear movement, no clamping of tail end,
Coolant:	Gleser Fluid 009 (Cutting oil with high sulphur content),
Fixture:	Static fixture with positioning of outer contour.

D. *Broach Tool Data*

This subchapter features the broach tool data:

Tool material:	M2 (HSS),
Coating:	None,
Rise:	0,0233mm,
Rake angle:	15°,
Clearance angle Roughing:	2°,
Clearance angle Finishing:	0°30°,
Lands:	Straight lands, length 0,3 mm on 5 finishing teeth.

IV. MEASUREMENTS

In the following is to be found the used measuring equipment, as well as the evaluation of the measured values.

A. *Equipment*

This subchapter features the measuring equipment:

Equipment 3D:	Wenzel LH54 with self-centering probe tip for measuring of the size between pins, Zeiss Calypso 5.2.24 without self-centering probe tip,
Equipment Gear measuring:	Klingelnberg PNC 30 with active compensation of setting error,
Measuring levels:	Level 1: Entry of broach - 7 mm, Level 2: Entry of broach - 48 mm, Level 3: Entry of broach - 58 mm,
Quantity:	30 components are analyzed,
Equipment Size between pins:	Subito internal gage on a stillage with a splined ring gauge for setting of the tip dial.

B. *Evaluation of measured values*

30 components are arbitrary taken for qualified measurements out of a bigger batch. It is ensured that at least 50 pieces are broached before components for the measurements are taken to avoid the remaining grinding burr on the broach influencing the measured results.

One of the most important values, which can easily be checked in the production environment, is the size between pins. This value will be used to ensure the required quality of the spline. Fig. 1 shows the measured values. It is obvious that there is one teeth pair that has a deviation of 30 – 40 µm in comparison to the other teeth pairs, although the broaching tool is manufactured according to its specifications.

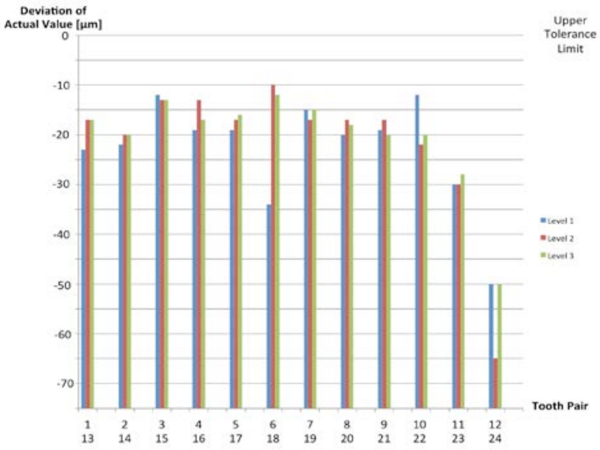

Fig. 1 Diagram for size betw. pins on level 1,2,3 for one component (component no. 1 measured with Subito)

Fig 2 and Fig. 3 show the same component, although the smaller teeth pair cannot be recognized on the same position. One of the main reason for the deviation between the two measuring devices should be a non self-centering probe tip used on the coordinate measuring machine plus small, internal calculation errors because the size between pins can only be calculated with a coordinate measuring machine.

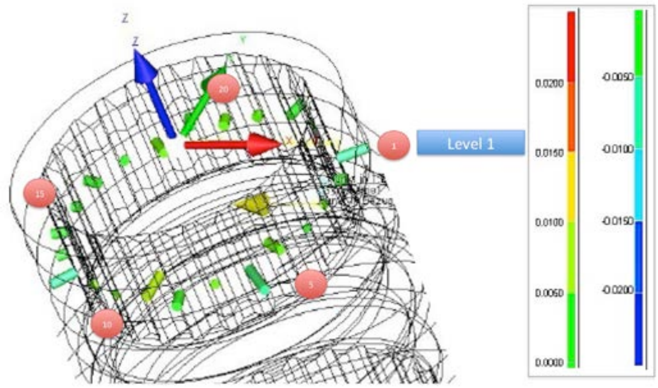

Fig. 2 Visual presentation for size betw. pins deviation from middle of tolerance in mm for one component on level 1 (component no. 1 measured with Zeiss machine)

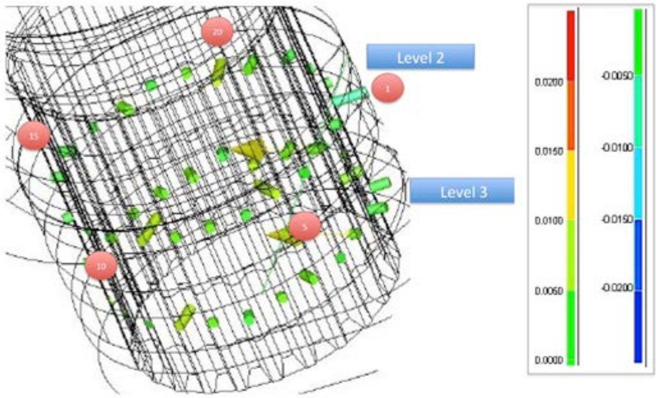

Fig. 3 Visual presentation for size betw. pins deviation from middle of tolerance in mm for one component on level 1 (component no. 1 measured with Zeiss machine)

Next is to be found Fig. 4, which presents measured values for another single component no. 2. It is obvious that the teeth pair 12 / 24 is 30 – 40 µm higher than in component no. 1.

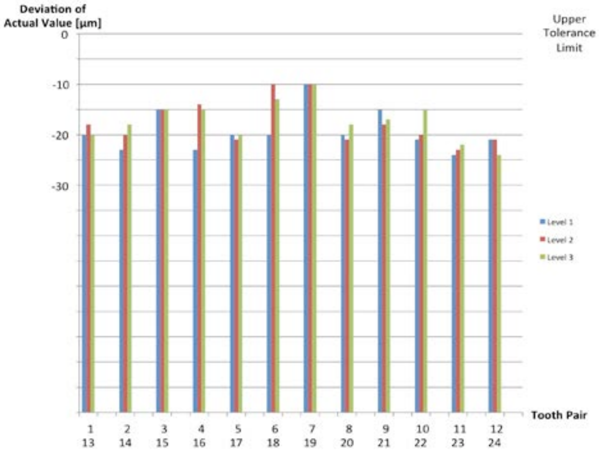

Fig. 4 Diagram for size betw. pins on level 1,2,3 for one component (component no. 2 measured with Subito)

Fig. 5 presents a histogram for the size between pins on level one. The standard deviation σ is 0,00373.

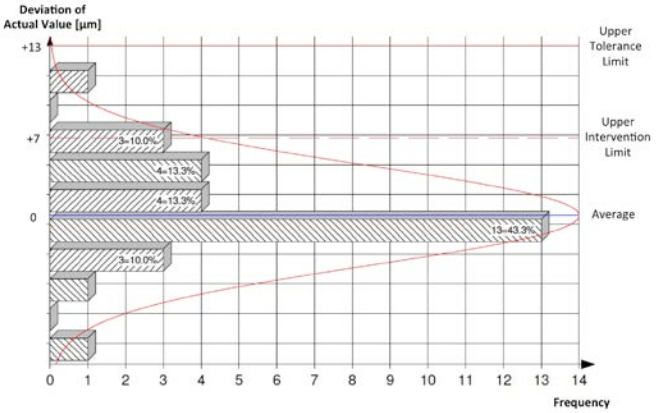

Fig. 5 Histogram for size betw. pins on level 1 for teeth pair 5 / 17 for several components (measured with Wenzel machine)

Next is to be found Fig. 6, which presents the measured values of level one in a trend diagram. Most of the values are close to average value.

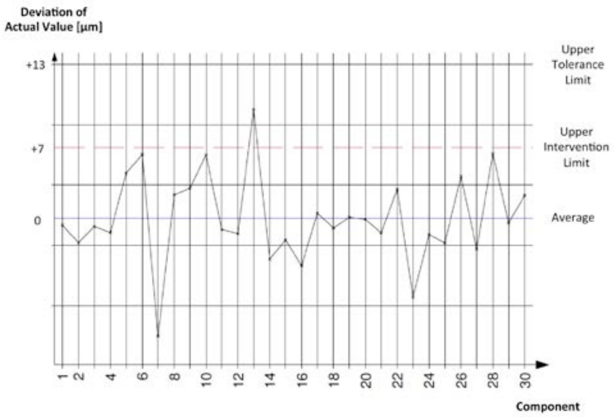

Fig. 6 Trend diagram for size betw. pins on level 1 for teeth pair 5 / 17 for several components (measured with Wenzel machine)

Fig. 7 presents a histogram for the size between pins on level three. The standard deviation σ is 0,00511 – 37 % higher than on level one.

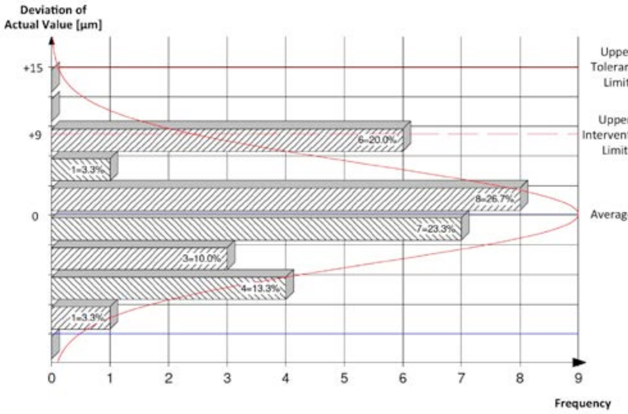

Fig. 7 Histogram for size betw. pins on level 3 for teeth pair 5 / 17 for several components (measured with Wenzel machine)

Next is to be found Fig. 8, which presents the measured values in a trend diagram. There are stronger deviations to the average than in Fig. 6, which results in higher standard deviation.

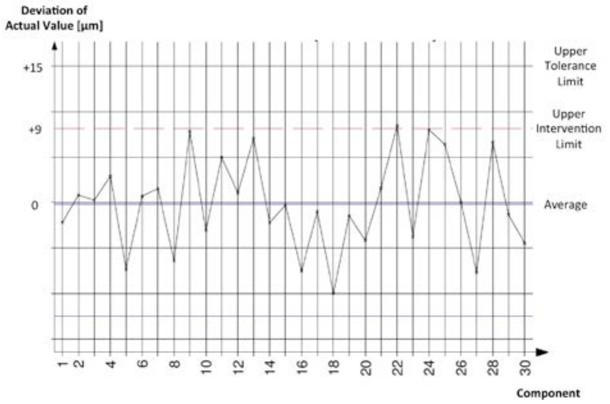

Fig. 8 Trend diagram for size betw. pins on level 3 for teeth pair 5 / 17 for several components (measured with Wenzel machine)

For further clarification why the size between pins has a larger deviation on level 3, the run-out of the pitch diameter in relation to an outer contour, as well as the run-out of the minor diameter in relation to an outer contour has been measured. The reference "A" (outer contour) is measured by scanning it as a cylinder in two levels of with 760 measured points on each cylinder – see Fig. 9.

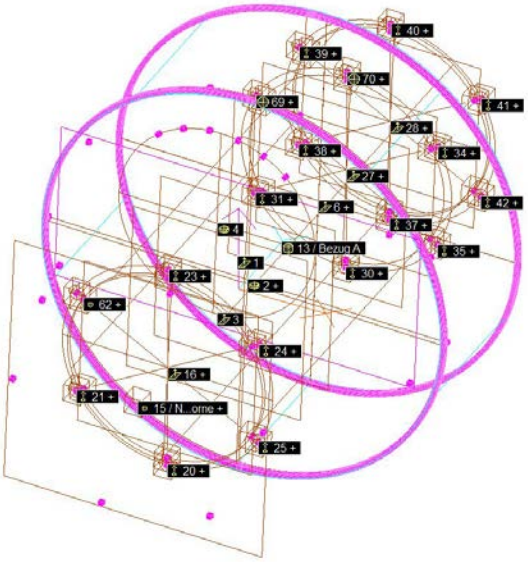

Fig. 9 Visual presentation for the reference "A" (outer contour) and measured points for the size between pins (component no. 3 measured with Wenzel machine)

The results from Fig. 10 show an arbitrary component on level one. The broached profile has a run-out of 140 µm on level one, although the run-out on level three is only 70 µm. To clarify the reason for this the run-out of the minor diameter (ground pre bore) in relation to an outer contour is measured. If the run-out of the minor diameter in relation to an outer contour is large the broaching tool also will follow the position of the pre bore.

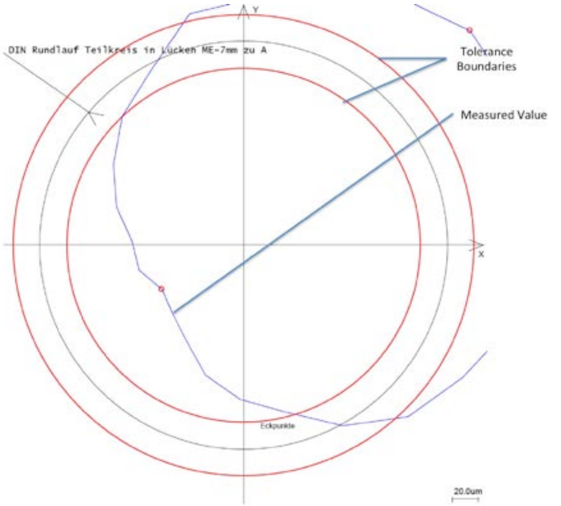

Fig. 10 Visual presentation for the run out of the pitch diameter in relation to an outer contour in µm for one component on level 1 (component no. 3 measured with Zeiss machine)

Fig. 11 presents the results for the same component on level one but it features the minor diameter instead. It is obvious that the run-out of the minor diameter is within the specifications.

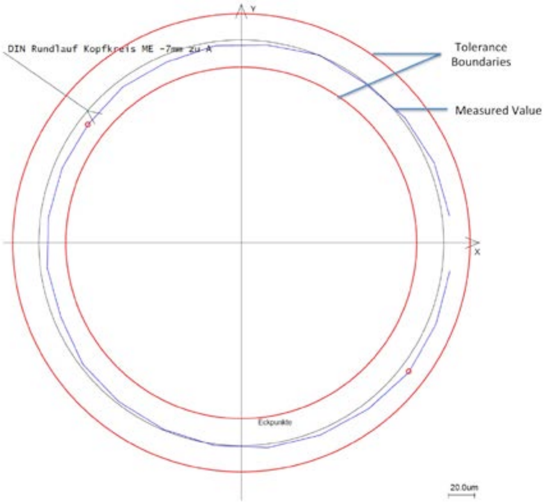

Fig. 11 Visual presentation for the run out of the minor diameter in relation to an outer contour in µm for one component on level 1 (component no. 3 measured with Zeiss machine)

The statistics over 30 parts shows that the average run-out on level one is 135 µm, where as it is on level three only 42 µm. The corresponding standard deviation σ is 0,035 on level one with values ranging from 18 µm to 168 µm, σ 0,0144 on level two with values ranging from 13 µm to 87 µm and also σ 0,0144 on level three with values ranging from 13 µm to 87 µm (measured with Wenzel machine).

V. Mathematical Approach For Run-Out Error

For an approximately calculation of the estimated run-out error of a spline broaching process the following formulas can be defined. Concluding the discussed influences from chapter IV it has to be differenced between the run-out error for a broaching process without orientation and a static fixture and a broaching process with orientation and a static fixture both for vertical broaching machines. Horizontal broaching machines will have additionally the influences of the deadweight of the broaching tool if the tail end is not clamped.

The run-out error for a broaching process *without* orientation and a static fixture can be written as:

$$R_{Max.non.o} = [p - c] \bullet h + l \qquad (1)$$
$$c < p\ ;\ c, h, l, p, R_{Max.non.o} \,\square\, \mathbb{Q}_{>0}$$

where

c	□ $_{\text{Min}}$ of the centering of the broaching tool,
h	factor for the level (height) of the to be calculated run-out,
l	summand for unpredictable, lateral shifting,
p	□ $_{\text{Max}}$ of the pre bore,
$R_{Max.non.o}$	maximum run-out error without orientation.

The run-out error for a broaching process *with* orientation and a static fixture can be written as:

$$R_{Max.o} = [p - c + d] \bullet h + l \qquad (2)$$
$$c < p\ ;\ c, d, h, l, p, R_{Max.o} \,\square\, \mathbb{Q}_{>0}$$

where

c	□ $_{\text{Min}}$ of the centering of the broaching tool,
d	summand for the deviation of the outer contour,
h	factor for the level (height) of the to be calculated run-out,
l	summand for unpredictable, lateral shifting,
p	□ $_{\text{Max}}$ of the pre bore,
$R_{Max.o}$	maximum run-out error with orientation.

The geometrical dimensions c and p as well as the moment before the entry of the broach into the component are visualized in Fig. 12. The blue arrows visualize the force of the fixture F_F to keep the component in the required position. Another blue arrow at the backside of the component has to be imagined.

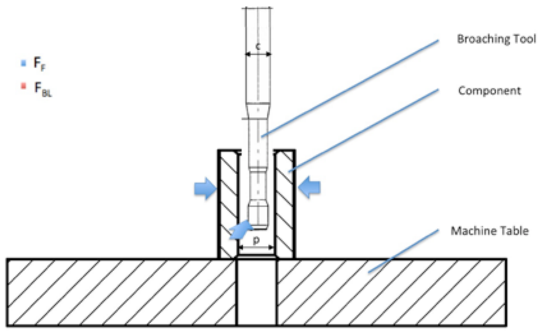

Fig. 12 Visualization for the dimensions c and p and to be considered forces for a pre-positioned component in an elastic fixture at the beginning of the broaching process

Detailed experiments are required to define actual values for the influencing summands and factors. It has also to be considered that two times coaxility can result in greater value than the run-out value [5].

VI. Conclusion

The first inspection of the components is the size between pins. On level three the standard deviation σ is 0,00511 – 37 % higher than on level one. In contrast to that it may be expected the deviation on level three should be higher than on level one. The reason for this can be tearing of material at the end of the broaching length, due to breaking of the lubricating film. This assumption can be negated after visual inspection with a digital microscope of several components.

The next inspection "run-out" delivers the result that the run-out is much better on level three than on level one but with a large range on level three.

The space on each side between the centering-entry of the broach and the component is 15 - 21 µm, which should be roughly half of the maximum possible value for run-out if the component, the fixture and the broaching tool is aligned exactly. In contrast to the theoretically assumption the measured values of run-out are 135 µm on level one and 42 µm on level three in average with a standard deviation on level one higher than on level three.

After having inspected 30 parts and having received strong different results the set-up of the process has to be questioned. This leads to the conclusion that the outer contour has too much deviation to use a static fixture for positioning of the component. Ether the tolerances of the outer contour of the component have to be decreased or the design of the fixture has to be changed to reach the goal of saving an additional process step after broaching.

If it is chosen to change the fixture there is a need for the fixture to keep the outer contour in the correct position (Maximum tolerance of position of the outer contour +/- 0.5° to the center of a teeth pair in this case) as well as being flexible enough to allow the broaching tool to push the component in a certain direction during the broaching process if the outer contour has deviations from exact size. This is a question of the balance of the two forces F_F (fixture, blue arrows) and F_{BL} (broach lateral, red arrows), which is visualized in the Fig. 13 and Fig. 14. Another blue and red arrow at the backside of the component has to be imagined in Fig. 13

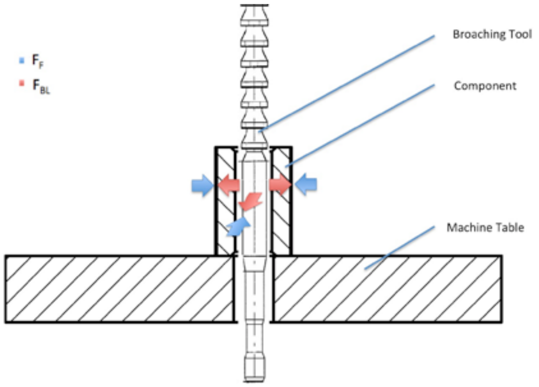

Fig. 13 Visualization for the to be considered forces for a pre-positioned component in an elastic fixture during the broaching process

Fig. 13 shows the moment when the broach is centering in the pre bore. The centering diameter of the broach is positioned at the height of the component, which results in having a space of $[p-c]/2$ on each side between the centering diameter of the broach and the pre bore.

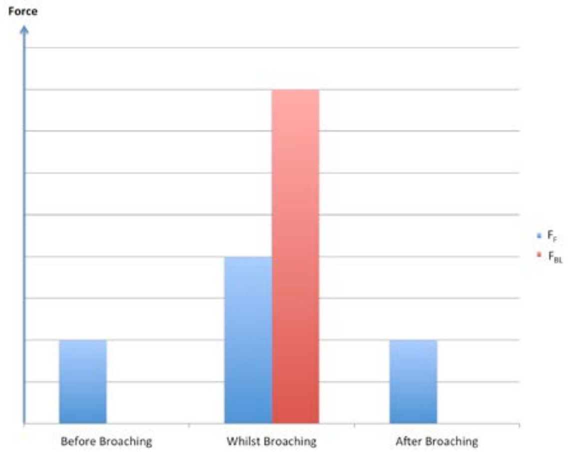

Fig. 14 Diagram for the to be considered forces for a pre-positioned component in an elastic fixture with deviation of the outer contour

Before the entry of the broaching tool in the component F_F has to push at the outer contour for pre-positioning of the component. Whilst the broaching process F_{BL} must have a greater value than F_F to have the ability to move the component lateral to avoid receiving bad run-out on level one but only if the outer contour has a deviation from the exact size. F_{BL} can only be influenced indirectly through the sizes of the outer contour of the component. F_F can be influenced directly with the design of the fixture – the results after design of the fixture finally have to be verified by practical tests.

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