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Design And Finite Element Analysis Of Broaching Tools

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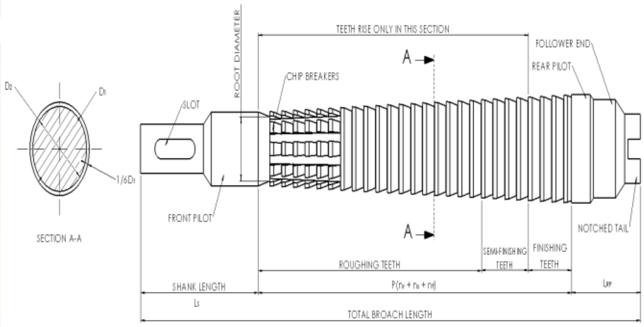
ABSTRACT

Broaching is a machining process in which a cutting tool, having multiple transverse cutting edges, is pushed or pulled through a hole or surface to remove metal by axial method. Broaching, if properly used, is a highly productive, precise and extremely versatile process. It is capable of production rates as much as 25 times faster than any traditional metal removing methods. Objectives are to lower the cost of design process by reducing the time required to design and fabricate broach tools which was materialized by the parametric design of the broach, where the design intent of the broach tool geometry is captured. Another objective is to predict the strength characteristics of the broaching tools in the preliminary stage for the tool engineer which was to evaluate the stress characteristic of the broach tool subjected to the cutting conditions. This would be useful for the tool engineer to keep a check on the tool's strength characteristics during every stage of the tools life and also on improving its characteristics during the wear out period. This was achieved by meshing and performing analysis using the Finite Element Modeller package called IIFEM. The model built from the parametric design was utilized to make a finite element model and analysis was performed to predict the stress and deflection in the tool. This would reduce time to design different broaches. By just changing the dimensions and the constraints when required, a new broach can be designed, thus allowing a lot of flexibility in the design. Further the solid model can be used to perform the finite element analysis which would help in knowing the characteristic of the broach tool under various cutting loads. This would also assist in improving the performance of the tool.

1. INTRODUCTION

Broaching is a machining process that uses a toothed tool, called a broach, to remove material. Broaching is used when precision machining is required, especially for odd shapes. Commonly machined surfaces include circular and non-circular holes, splines, keyways, and flat surfaces. Typical work pieces include small to medium sized castings, forgings, screw machine parts, and stampings. Even though broaches can be expensive, broaching is usually favoured over other processes when used for high-quantity production runs. The interesting aspect of broaching is that the feed is built directly into the broach (cutting tool) and has the machine provide only one function -speed, for metal removal, unlike in the other processes such as milling, planning, etc., where the speed and feed are the metal removing functions that machine tool is required to provide.



BROACH GEOMETRY

2. OBJECTIVE

The first objective was materialized by the parametric design of the broach, where the design intent of the broach tool geometry is captured. A geometrical relationship is developed on the broach tool geometry which is very flexible and can be altered for most of the tools with very little user intervention. This was achieved using the software called I/EMS, a design and modelling product from Intergraph Corporation.
The second objective was to evaluate the stress characteristic of the broach tool subjected to the cutting conditions. This would be useful for the tool engineer to keep a check on the tool's strength characteristics during every stage of the tools life and also on improving its characteristics during the wear out period. This was achieved by meshing and performing analysis using the Finite Element Modeller package called I/FEM. The model built from the parametric design was utilized to make a finite element model and analysis was performed to predict the stress and deflection in the tool.

3. FINITE ELEMENT ANALYSIS

3.1. INTRODUCTION- This chapter focuses on the concept of finite element analysis and the development of finite element model and analysis of a round hole broaching tool, performed to predict the affects of maximum force on the cutting teeth geometry. The static analysis was performed on the broach teeth to check the maximum stress, the teeth can withstand before failing. Also the analysis was carried out to simulate the deflection, the broach teeth are subjected to during the cutting operation, which forms criteria as whether the amount of tolerance on work piece is being met. The finite element modeling and analysis was done using the Intergraph's Finite Element Modeler (I/FEM) which is integrated with EMS. The broach teeth geometry which might change slightly due to the wearing of the tool after repeated cutting operations, can be modified and the rigidity of the teeth can be analyzed thus keeping a thorough observation on the tool which helps increase the tool life by taking proper care when the chances of failure is imminent due to fatigue.

3.2. FEM FOR BROACH TOOLS- More appropriate analytical approach can be made to calculate the stress distribution and check the performance, shape and loading factors of the teeth. Only the broaching teeth were analyzed as the other parts such as the pull end, follower end and shank length are not subjected to the force that broach teeth are subjected to. Moreover, there is more probability that a broach may fail at its teeth during the cutting operation. So only the broach teeth were modeled for analysis.The finite element method breaks the broach teeth geometry into a specified number of elements formed from nodes. These groups of elements represent the model through the finite element mesh. The process of generating the finite element mesh is meshing.

3.3. MODEL DESCRIPTION

3.3.1. ROUND HOLE BROACH

The mapped mesh on the broach teeth profile was rotated 360 degrees along its axis with 12 sectors. This was done using the rotate mesh option in the mapped mesh generation menu. Tetrahedron elements were used for meshing purposes.

The model contains

Nodes : 1587

Wedge Elements : 5989

3.3.2. FLAT BROACH

The mapped mesh on the broach teeth profile was projected to a distance equivalent to the width of the flat broach using the Project mesh option in the mapped mesh generation menu.

The model contains

Nodes : 4744

Brick Elements : 3472

Wedge Elements : 480

3.3.3. OCTAGONAL BROACH

The solid model generated had a complex shape, so the model for finite element generation was approximated at the back angle and front angle radius in the octagonal shape vicinity. It was approximated to shape close to the one which would be generated with a finite element mesh and the integrity of model was maintained. This model meshed using auto mesh which places tetrahedron elements.

The model contains

Nodes : 1860
Brick Elements : 6502

3.4. MATERIAL PROPERTY- The finite element models are assigned the material properties which are the physical properties of the model.

The properties assigned to the model were:

Material Type : Isotropic
Material Name : SAE Steel 4140
Young's Modulus :
3.0*E + 7 Psi or 206884*E + 6 N/m^2
Poisson's ratio : 0.26
Maximum Yield Stress :
91000 psi or 627.42 * E + 6 N/m^2

The material can be created using the Create Material command which invokes the form driven database. The above mentioned properties are typed in the form. The material can be placed using Place Material command. The material properties were placed on all of the elements.

3.5. BOUNDARY CONDITIONS- A boundary condition is a specific physical limit - an action for a restrain – applied to the model. The boundary conditions are used in such a way that they represent the motion of the broach model under cutting operation. The boundary conditions used in this analysis are the constraints and forces. In this research three different types of models were analyzed. They are round hole, flat and octagonal broach tools. Three different load cases were used and they are Maximum force, required force and the intermediate force. The boundary conditions applied to the tools can be visualized from the figures given below.

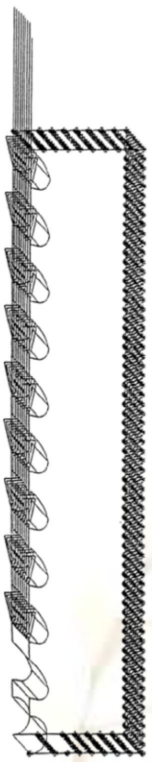


Fig. 1

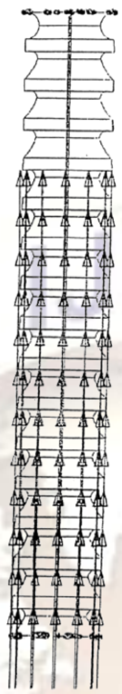


Fig. 2

Fig. 1 : Boundary Condition on Flat Broach
Fig. 2 : Boundary Condition on Round Broach

3.5.1. CONSTRAINTS

The movement of nodes along all the six degrees of freedom can be controlled by using this feature in finite element method. The procedure for constraining the three models are discussed below

- Round Hole Broach:

Since only the cutting teeth were modeled, the first surface which begins before the first tooth and the last surface after the finishing tooth were constrained. This means that the broach teeth are fixed at the two ends and movement in any direction is prevented. The nodes that were in the planes at the two ends were constrained in all the degrees of freedom. This was done from the I/FEM by using the Command Place Constraint on the node and identifying the nodes existing those planes.

- Flat Broach:

The bottom surface of the flat broach is held by the tool holding fixture and is either pulled or pushed along the work piece or is held stationary and the work piece is passed over it. All the nodes that were present in the bottom surface of the model were constrained in all directions.

3.5.2. FORCES APPLIED

Three different load cases for these models. The forces were placed on the nodes that formed on the cutting edges of the tool. The magnitudes of the forces were placed on the nodes in the X-direction which is usually the case for these types of model since they follow a linear cutting pattern. The force computed was evenly distributed on t he cutting teeth by dividing it with the number of nodes on the cutting edge.

- Round Hole broach:

The round hole broach cutting edges had 12 nodes at equal distant on them. The force computed was divided by 12 and the resulting force was placed on each of these nodes.

Maximum Force:

The maximum force that was placed was calculated as follows:

$$F(max) = A * Y$$

Where,

F= force in lbf
A= area of min cross section
Y= tensile tool strength of the material
The force that was computed from above was: 32275.265 lbf

Required Force:

The force required for a broach operation is computed as follows:
$F_{(reqd)} = 3.14 * N * D * R * C$
Where,
N= no. of teeth in contact = 3
D= starting hole diameter = 1in or 0.0254 m
R= chip per tooth roughing =
0.001006 in or 2.5 * E - 5 m
These were calculated assuming that three teeth are in contact at a time.

The force computed for the roughing teeth were: 947 lbf or 4214.15N
The force computed for semi-finishing were: 106.495 lbf or 473.90275N

Intermediate Force:

This force was deduced after the above two operations. The main criteria considered in this case were that this force when applied to the broaching teeth would not result in the yielding of the tool. This was done by hit and trial method and the safe load that would result in the below the yield stresses on the broach was deduced. This force computed is valid only for the type of model analyzed. This value changes for different tools with different material and geometry backgrounds.

The force reduced for the round hole broach in this design was: 5880lbf or 26166 N

- Octagonal Broach:

Push type broach geometry was used for the modeling of an octagonal broach. The model was meshed using the Auto meshing option because of its complex geometry. The forces were applied on the nodes that existed on the cutting edge. These were equally distributed among the nodes.

Maximum Force:

The maximum force that can be applied on a push broach is given by:

$$F_{(Max)} = (Y * D^4)/L^2$$

Where,
Y=Yield Strength of the tool= 91000 psi or $627.42*E+6 N/m^2$
D=Minimum root diameter L/2=2.676 in or 0.0679704 m
L=Length from push end to the first tooth= 8.59 in or 0.218186m
The force computed was:
63241.1 lbf or 284584.95 N

Required Force:

The force required for octagonal broach which is same as the one for round hole broach is computed as follows:

$$F_{(reqd)} = 3.14*N*D*R*C$$

Where,
N= no. Of teeth in contact
D= starting hole diameter
R= chip per tooth cutting
These were calculated assuming that three teeth are in contact at a time.
The force computed for the roughing teeth were: 2650lbf or 11925N
The force computed for semi-finishing were: 480 lbf or 2182.5N

- Flat Broach:

Maximum Force:

The maximum force a broach can withstand is computed by

$$F\ (max) = A*Y = L*W*Y.$$

Where,
A= area of min. Cross section= $6.4516 \times 10^{-4}\ m^2$
L= length of tooth= 1.5 in or 0.0381 m
W= width of tooth= 0.2 in or 0.00508m
The Force computed was:
27300lbf or 122850N

Required Force:

The required force for a flat broach is computed by

$$F_{(reqd)}\ W * N * Cd * C$$

Where,
W=Length of the tooth=1.5in or 0.0381m
N=Number Of Teeth in Contact= 3
C=Broaching Constant=
450000 Psi or $310.26*E+6 N/m^2$
Cd=chip per tooth roughing=
0.0013 in or 3.302 * E–5m
The force computed for the roughing teeth were: 877.5 lbf or 3904.875N
The force computed for semi-finishing were: 75 lbf or 333.75N

Intermediate Force:

Just like as in round hole broach, this force which is an intermediate value between the maximum force applied and required force. This force again is for the particular model which would result in the values below the yield stress and can act as a reference value as far as the forces on the broach tool resulting in below the yield point stress are concerned. This was deduced by trial and error method. Due to the limited memory requirements for the model, not many iterations could be done for the flat broach.
The force computed was:
4500lbf or 20025N

4. RESULTS USING ANSYS

I/FEM provides the information of various stress values and displacements for all the elements and nodes in X, Y and Z directions. The failure criteria used by I/FEM is Huber-von-Mises-Hencky theory.

Failure is predicted to occur in the multi-axial state of stress when the distortion energy per unit volume becomes equal to or exceeds the distortion energy per unit volume at the time of failure in a simple uniaxial test using a specimen of the same material.

On analysis it was revealed that the maximum Von Mises stress was on the elements that were at the core diameter of the round hole broach. The stress distribution on the teeth increased progressively from the top element where the force was applied to the elements at the core diameter. The stress distribution follows the same trend for all the cases. The maximum stress value occurred at the very first teeth, which implies that the first tooth is subjected to maximum stress and force during the entire operation.

The analysis also resulted in maximum displacement the teeth undergo during the cutting operation. This can be used as a criteria as to examine whether the tolerance on the work piece is being met. The maximum displacement did not exceed 0.003 in.

The result would change for different materials, i.e., once the Young's Modulus and Poisons ratio is changed, the analysis would result in different values corresponding to the type of material.

The following tables reports the maximum and minimum stress and displacement values for the three different cases discussed in the preceding chapter for the round hole, octagonal hole and flat broaches respectively. These tables are followed by the plots of Von-Mises stress distribution for the required load case in figures for the different broach models. The stress plots show that the first tooth of the broach has the maximum stress value at its core diameter.

4.1. STRESS TABLES

4.1.1. Stresses in the Round Hole Broach:

STRESS		CASE 1	CASE 2	CASE 3
MAXIMUM	Psi	8.90 * E+05	1.246 * E+04	8.3 * E +04
	N/m^2	54613. * 7 E+06	85.9 * E+06	572.2 * E+06
MINIMUM	Psi	7.316 * E +03	1.28 * E+02	1.77 * E+03
	N/m^2	50.44 * E+06	8.82 * E+09	12.203 * E+06

4.1.2. Stresses in the Octagonal Hole Broach

STRESS		CASE 1	CASE 2	CA SE 3
MAXIMUM	Psi	1.98*E+06	8.3*E+04	-
	N/m^2	13651.70 * E+06	572.26 * E+06	
MINIMUM	Psi	324.9	13.75	-
	N/m^2	2.24 * E+06	0.094 * E+06	

4.1.3. Stresses in the Flat Broach

STRESS		CASE 1	CASE 2	CASE 3
MAXIMUM	Psi	5.06 * E +05	1.50 * E +04	6.54 * E+04
	N/m^2	3488.76 * E+06	103.42 * E+06	450.91 * E+06
MINIMUM	Psi	7.62 * E +03	6.96 * E+02	3.374 * E+02
	N/m^2	52.53 * E+06	4.798 * E+06	2.32 * E+06

4.2. DISPLACEMENT TABLES

4.2.1. Displacements in the Round Hole Broach

DISPLACEMENT		CASE 1	CASE 1	CASE 1
MAXIMUM	in	1.07* E-02	4.6* E-04	3.0* E-03
	m	2.7178 x E-04	1.684 x E-05	7.62 x E-05
MINIMUM	in	0.0	0.0	0.0
	m	0.0	0.0	0.0

4.2.2. Displacements in the Octagonal Hole Broach

DISPLACEMENT		CASE 1	CASE 2	CASE 3
MAXIMUM	in	3.706 * E -02	1.31 * E-03	-
	m	9.41324 x E-04	3.3274 x E-05	-
MINIMUM	in	0.0	0.0	-
	m	0.0	0.0	-

4.2.3. Displacements in the Flat Broach

DISPLACEMENT		CASE 1	CASE 2	CASE 3
MAXIMUM	in	9.63 * E – 03	3.0 * 10 E – 04	1.2 * 10 E -03
	m	2.44602 x E-04	7.62 x E-06	3.048 x E-05
MINIMUM	in	0.0	0.0	0.0
	m	0.0	0.0	0.0

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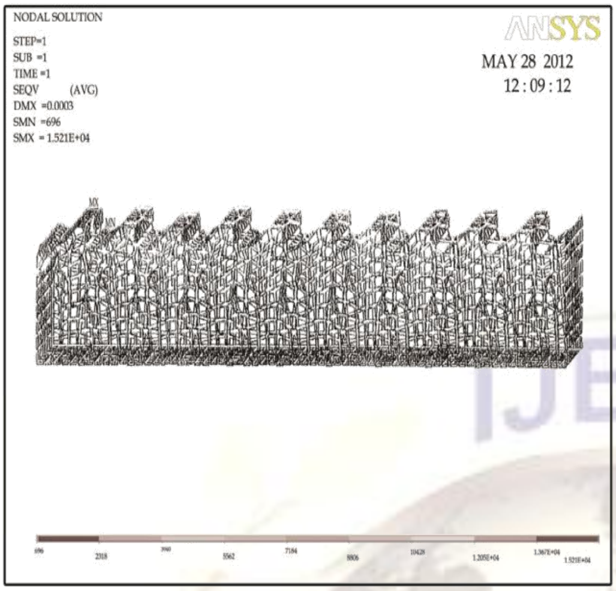
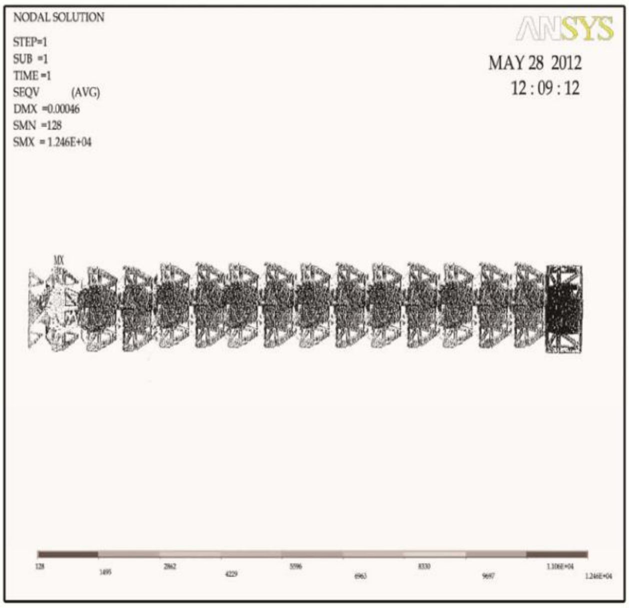


Load on Roughing Teeth = 877.5 lbf
Load on semi finishing Teeth = 75 lbf

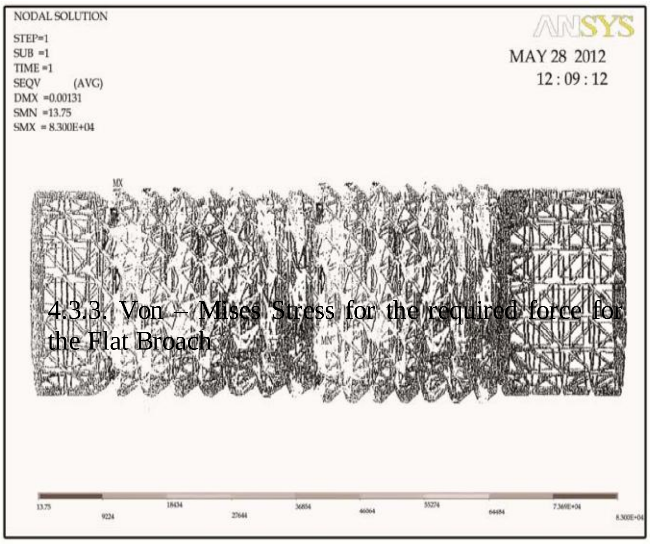
4.3. FIGURES FROM ANSYS

4.3.1. Von – Mises Stress for the required force for the Round Hole Broach



Load on Roughing Teeth = 948.312 lbf
Load on semi finishing Teeth = 106.475 lbf

4.3.2. Von – Mises Stress for the required force for the Octagonal Hole broach



4.3.3. Von – Mises Stress for the required force for the Flat Broach

Load on Roughing Teeth = 2650 lbf
Load on semi finishing Teeth = 480 lbf

4.4. ANALYSIS RESULTS OF BROACH TOOL UNDER VARYING LAND WIDTH

So far in this study, the geometry of the tool was kept constant and was analyzed under varying loads. An extension of this study may be to analyze the tooth behaviour under varying cutting teeth parameters, such as the pitch, gullet depth, land width, face angle, etc.,. The following table summarizes a brief analysis in this direction which was performed by varying the land width by 10%. A constant force of 948.312 lbf. Were applied on the first three teeth for the three different models. The stress levels reduced by 6.7% when the land width was increased 10% from .156 inches to .172 inches. Similarly the stress levels increased by 11.7 % when land width was reduced 10% from .156 inches to .140 inches.

4.4.1. Comparison of Maximum Stress for the three cases

		Baseline	**Iteration 1**	**Iteration 2**
Maximum Stress	In PSI	9,366	8,734	10,460
	In N/m^2	64.57*E+06	60.219*E+06	72.11*E+06
% Change in stress from baseline		-	(-)6.7%	(+) 11.7 %

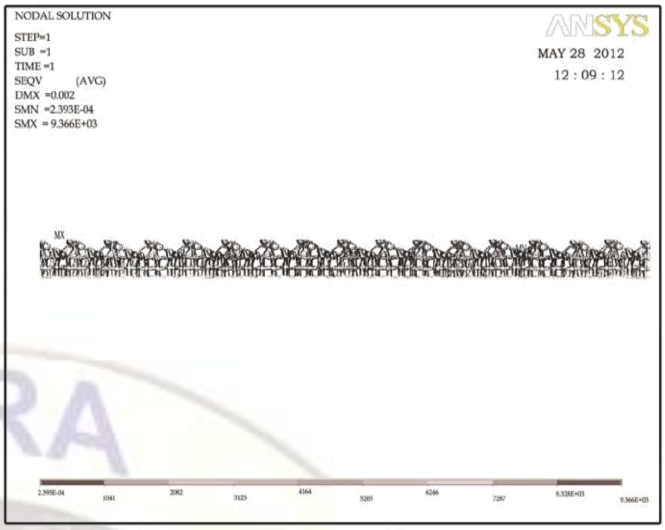
Baseline : Land width of 0.156 inches or 3.9624 * E-03 m

Iteration 1 : Land width of 0.172 inches or 4.368 * E-03 m

Iteration 2 : Land width of 0.1404 inches or 3.56 * E-03 m

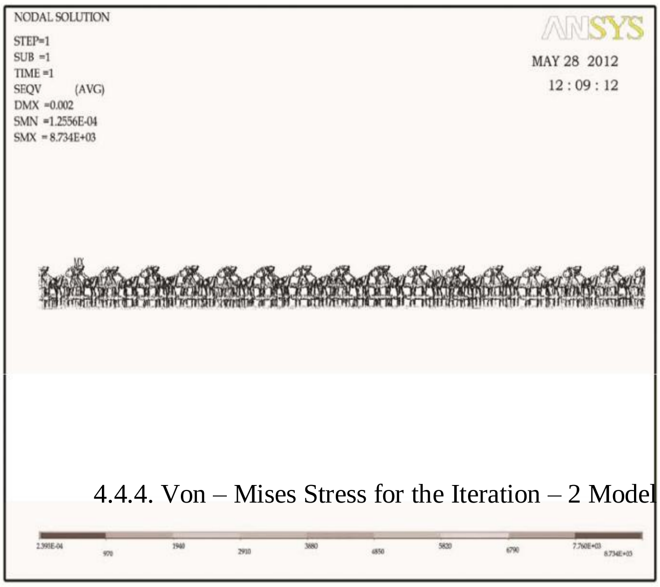
The Von Mises stress distribution for the above mentioned models can be seen from the figures given below. The maximum stress occurs at the first tooth for all the cases.

4.4.2. Von – Mises Stress for the Baseline Model



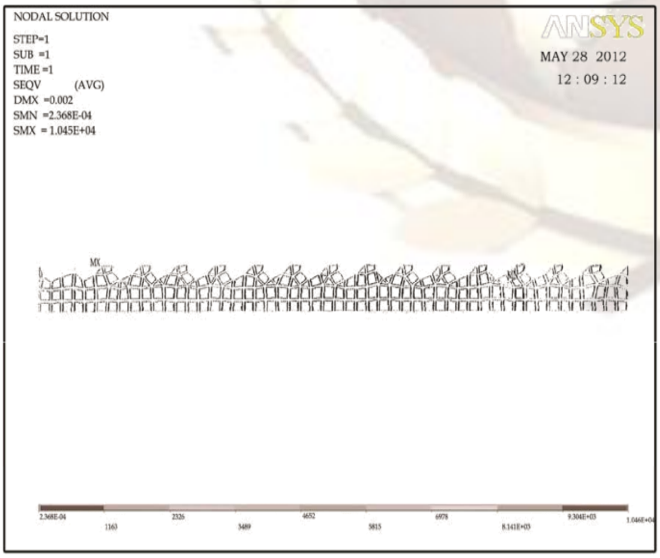
Land Width = 0.156 inches

4.4.3. Von – Mises Stress for the Iteration 1 Model



Land Width = 0.172 inches

4.4.4. Von – Mises Stress for the Iteration – 2 Model



Land Width = 0.1404 inches

5. CONCLUSIONS

The design of the broach using the parametric modelling was addressed in this research. This tool can be used for designing and modifying the broaches of various types and this would reduce time to design different broaches. By just changing the dimensions and the constraints when required, a new broach can be designed, thus allowing a lot of flexibility in the design. Further the solid model can be used to perform the finite element analysis which would help in knowing the characteristic of the broach tool under various cutting loads. This would also assist in improving the performance of the tool.

The analysis was performed on the three different solid models which were generated by the parametric modelling. The finite element model generated for the round and flat broach were done by mapped meshing while auto meshing was used for the octagonal broach.

Three different load cases were used, the first one being the maximum force the broach teeth can withstand which was calculated based on the formulae found in the literature.

The second case being the force required to do the cutting operation. This was also calculated based on the formulae found in the literature. The maximum force case for both the models, round and flat were resulting in stresses above the yield point.

The third load case which was used was the intermediate force, which was basically done by the hit and trial method to capture the value between the maximum force and required force, that would result in the stress values which are close to the yield. This force can also be kept as a check point force, that should not be exceeded for the cutting operations. The octagonal broach was meshed using the automatic option because of its complex geometry. Only two cases were run for the octagonal broach as the required force had resulted in the stress very close to the yield point stresses. The maximum stress however had a very high stress value. The high stress area were very small and occurred near the gullet which was the same for the other models too. The main concern in the octagonal broach was the stress at the square teeth. Since the maximum force is always taken by the first teeth, the stress concentration is more on it. The octagonal teeth usually starts at the end of roughing, and ends at the finishing teeth. The stresses in these areas are much below than the beginning few round hole teeth.

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