Design and Development of Broaching Machine for Splines: A Case Study

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Abstract: *Broaching machine is mainly developed for special purposes where cycle times are less and number of job quantity is very high. Only at such points development of broaching machine is justified.*
Design of such broaching machine is totally customizable. This paper discuss about frame design of machine, selection of guideways, design of hydraulic power pack for hydraulic operated machine and also selection of various cylinders, pipe fittings, mandrels, pump, motor, etc.
So, main purpose of this paper is designing the broaching machine which includes all its components. This paper focuses on selection of bought out parts too.

Keywords: frame design of machine, selection of guideways, design of hydraulic power pack, selection of hydraulic cylinders, pipe fittings, mandrels, pump and motor.

1. Introduction

Broaching is a manufacturing process designed to make custom, precision parts at high speeds. There are many types of broaching machines, but they all use tools to remove a certain amount of material from a blank or machined component. Depending on the broach being used, the process can create a circular hole, irregular exterior shape, a keyway or more irregular shapes. Similar to reaming, shaping and milling, broaching is a highly specialized, precise manufacturing process. Each broach machine is designed to create a single hole with maximum precision, speed and uniformity. In these regards, broaching is a highly competitive machining process, particularly when using soft metals and plastic components. Of course, there are certain applications where a broach machine may have reduced efficiency. Particularly hard metals may require routine tool conditioning, and every specialized cut requires a new broach tool [1].

Basically, broaching machines are used to increase the production rate and to increase the quality of process. Broaching machines are actual special purpose machines and can be made for the exact requirement in order to have higher production yield. This paper describes the actual designing that is required to build a broaching machine. Basis for this project is conceptual design of machine is being done and it is going to be a vertical broaching machine which is hydraulically operated. This is based on customer'srequirements and inputs which are regarding cost and space availability [2].

1.1.1 Objectives

1. Cycle time of job with this machine should be within 50-60 sec.
2. Machine should require less maintenance.
3. Machine should be robust enough. And should have less vibration, noise and can be run in automatic mode.
4. Machine should have a cleaning arrangement for the job.
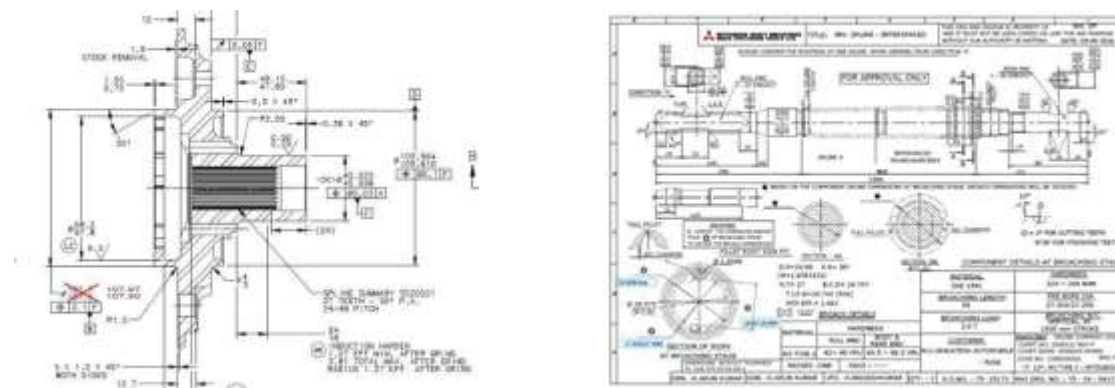5. Machine should have arrangements for easy chip management.

1.1.2 Methodology

While designing any SPM machine customer's requirements are the key agenda. By keeping those at most priority, an exact problem statement is defined and then by brainstorming various possible solutions are discussed. After that, the best suitable solution is decided. Conceptual design for the same has been made. This step includes selection of various parts and their rough placements and it also comprises the sequence of operations that must be followed.

Then parametric design must be carried out where actual values of the parameters have been decided e.g., cutting speed, Actuator dimensions, Bearings, Structural member sizes, etc. By simulating the decided model various corrections have been made for possible fouling. Then final modeling is done where various aesthetic and safety considerations are incorporated. Once the Final model is prepared the manufacturing phase starts and is followed by testing and validation. This whole process is shown in fig.1 below.

Figure 1. Design Methodology

1.1.3 Actual customer requirements and inputs

Figure 2. Input Drawings from Customer

Customer has provided various inputs like material of job, hardness, spline dimensions and specifications, current cycle time, required cycle time, no. of broach teeth, space availability and height of shed available. Some of these details are in the drawing shown in fig.2 and some of them are documented separately. From these inputs the basic understanding is that splines are to be made on SAE 1541 material of given dimensions and broaching tools are going to be provided by customers whose dimensions and specifications are given in the sheet above. Current cycle time of a given job is 100 sec which is supposed to be reduced to 50-60 sec. Customer also has a space constraint of 100 sq.ft. And Height constraint of 18 ft.

Modern vertical broaches are offered with both hydraulic and electro-mechanical drives. But hydraulic drives are the most common because they cost less [3]. Customer is having a floor constraint and wanted the system at an affordable price hence a vertical broaching machine with hydraulic controls is selected. Pneumatics is used for light operations like door closing and opening of job cleaning, etc.

1.2.1 Basic concept design
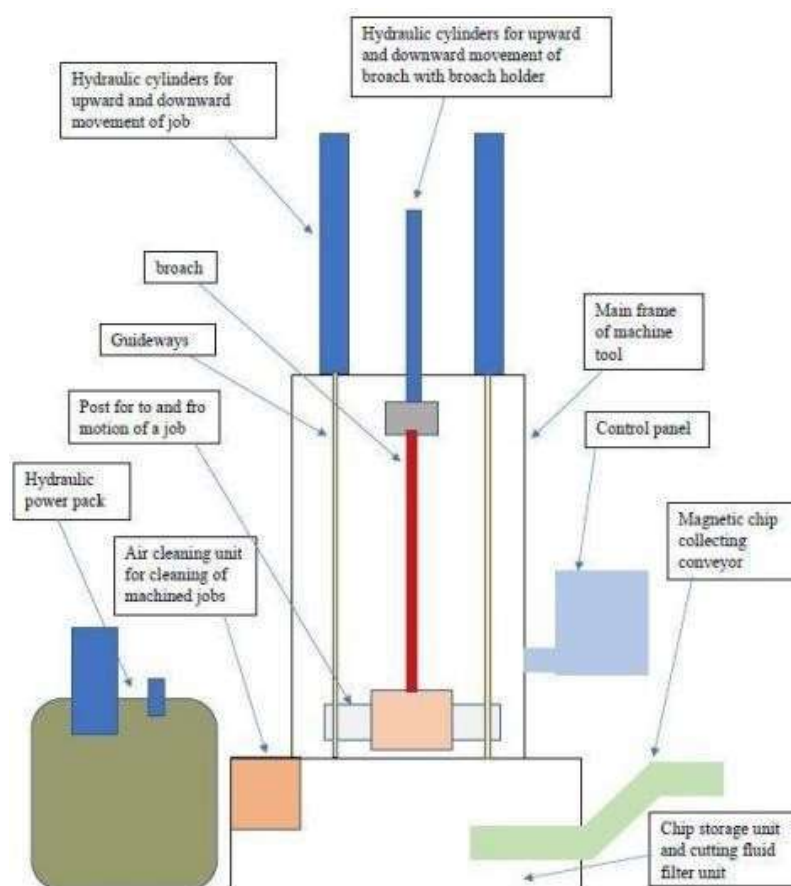
Figure 3. Basic Concept Drawing

Above fig.3 gives basic idea about essential components of machine tool. Machine frame is base of all the components which allows fixing of all the components on it and it is a stationary body. In order to facilitate the cutting operation there is need of relative motion between tool and workpiece and this is achieved with help of hydraulic actuators and the collets. Main hydraulic actuators are used for the movement of workpiece. And auxiliary actuator is used to facilitate the upward and downward movement of broach tool.

Collets are used for holding the broach stationary. Cross guide attached with actuators are used to provide transverse motion of workpiece. To give hydraulic power to circuit hydraulic power pack is used. Air cleaning unit and chip collection units are extra accessories provided with the machine.

1.3.1 Calculation of broaching force

To decide whether a particular work can be broached on a given machine and also to verify the strength of broach. It is essential to know the required broaching force [4, 5]. Following formula gives us the broaching force in kg, For Splines:

P= Ks *S*W*Z*C*K   (Machine tool design handbook by HMT)

Where,

P: Broaching force, kgf

Z: Number of teeth cutting at a time C: Rise per tooth, in mm from fig.4

S: No. of   splines

W: Width of spline, mm

Ks: Specific cutting force, in Kgf/mm2 from fig.4

K: Blunt broach factor (can be assumed to be 1.25 to 1.4)

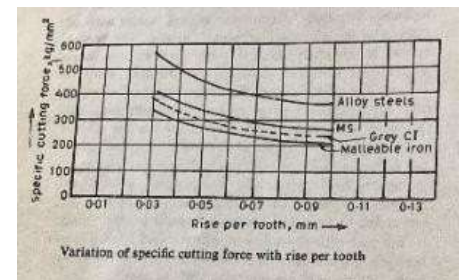The value of Specific cutting force varies with the depth of cut as shown in table and accompanying graph.

Figure 4. Specific Cutting Force and Depth of Cut References

Ks= 350kg/mm2 (Given by customer) Pitch=1.4*(length of cut in mm) 0.5 Broaching length=54 mm Pitch=1.4*(54)*0.5=10.41mm

Z = (L max / pitch) +1

  = (54/10.41) +1

  = 6.1873

S = 27

W= 1.66mm K = 1.25

C = 0.0385 (as per customer broach)

P = Broaching force= Ks *S*W*Z*C*K

  = 350*27*1.66*6.1873*0.0385*1.25

  = 4671.02kg

By considering factor of 1.30 for any irregularities and then the design broaching force becomes = 4671*1 is equal to nearly 6000kg = 6 ton

Therefore, 6 Ton load machine tool needs to be designed and broach cutting length is= 969+41=1010

And by considering some gap for start run and end run of tool, designed stroke length=1200 mm, Design Stroke length=1200 mm. After calculating the broaching force, cutting speed needs to be calculated in order to select the cylinders and design the hydraulic power

1.3.2 Selection of Cutting Speed

Proper cutting speed depends on the work material and also on the type of broaching. Cutting speed is mainly decided by the hardness of tool materials and the surface finish requirement of the job. This is the reason why cutting speeds for various materials lie in the range of 3 to 30 m/min with high-speed steel tools. Moreover, increase in cutting speed does not substantially reduce the cycle time as the cutting time is quite compared to non-cutting time in most of the broaching operations.

The recommended cutting speed ranges for different work materials are as follows:

Table 1. Cutting Speed Selection Table (Machine Tool Design Handbook by HMT)

Material	Hardness BHN	Cutting speed m/min	Rise per tooth mm	HSS tool grade
Free Machining steel	100-200	10-12	0.1	M2, M7
Carbon steel	120-375	3-8	0.08	M2, M7
Grey cast iron	110-320	7-30	0.08	M2, M7
Malleable CI	110-400	10-20	0.08	M2, M7
Aluminium alloys	30-150	10-20	0.15	M2, M7
Magnesium alloys	40-90	10-18	0.15	M2, M7
Copper alloys	40-200	8-10	0.12	M2, M7

As per customer requirement cycle time should be near 60 sec for one job so the cutting speed for carbon steel should be between 2-8 m/min. Hence, it is decided to keep this speed as 5.25 m/min (as per experience) initially [6].

1.3.3 Hydraulic Cylinder selection

Before selection of the cylinder, highest power required must be known. So, let's calculate the power of machine: Power = (Cutting Force * Velocity) / Efficiency

= (6*1000*9.81*5.25) / 0.95

= 7.26 hp

So, let's go for 7.5 hp power to be on safer side.

Now, decide the cylinder as per requirement of force and power available.

It is decided to keep system pressure to be 7 MPa. To transmit force of 3 ton, bore area of cylinder should be:

= (3*1000*9.81/0.8)/7*106

= 5255 mm2

Which gives an idea that bore diameter should be (5255/3.14) ^ 0.5=81.81 mm. Hence, selected bore diameter =100 mm 1000mm stroke length is required as per above discussions but let's go for 1200 mm stroke in order to accommodate variety of jobs in the same machine. Hence the selected hydraulic cylinder is CH2F B 100 C 1200 by SMC [7].

The cylinders selected are going to use for actual pulling operation which is cutting operations but there is need of one more cylinder for the lifting of broach tool and its platform (Assembly for fixing/holding the tool)

While selecting this cylinder consideration is weight to be lifted and this weight includes weight of broach tool holder assembly + weight of upper collet + weight of tool = 48+6+7= 61 kg. These weights are calculated by drawing rough and exaggerated models of the same in CAD software.

Let's select the cylinder piston which bears 7 MPa pressure and able to exert a force of 61*10 = 610N Area required = Force / Pressure

= (610) / (7*106)

= 87.14 mm2

After going through the catalogue of SMC, it is found that minimum possible c/s area is 550 mm2

which gives the force value of 550*7 = 3850 N

Which can ultimately give us the factor of safety = 3850 / 610 = 6.31

Hence, a cylinder with bore size 32 mm, pressure 7 MPa, Stroke 600 mm is selected. Stroke calculation is made from cad drawing of a broaching machine.

Selected Hydraulic Cylinder is CH2F B 32 B 600 from SMC [7].

Now selection of 3rd pair of cylinders which are for transverse movement of workpiece having frictional resistance of linear guideways and guides. And this resistance is very small compared to other forces in the machine. Hence, selection is on the basis of pressure rating and stroke availability which is 7 MPa and 140 mm resp.

So, the minimum bore diameter available is 32 mm and whose code is CH2F B 32 B 140 from SMC [7].

1.3.4 Linear Guideway Bearing Selection

1) **Selection of vertical linear guideways:** By applying moment equilibrium, effective load on linear bearings is calculated. Loading condition is as shown in fig.5 below:
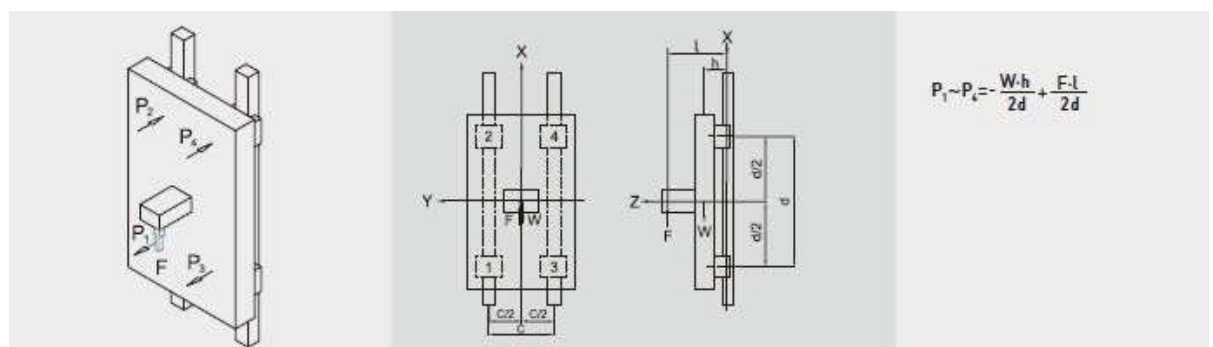
Figure 5. Effective Load Calculation Reference Diagram

In the above case cutting force is divided in two halves and calculating effective force using one half. Therefore, Effective load = 3000*9.81*250/2*200

= 18.393 KN

HIWIN is one of the trusted brands in linear guideways hence while selection their catalogue has been referred.

Let's select the linear guideway RGH45HA to check whether it is appropriate for the above use [8]. Let's use following fig.6 for reference values.

Figure 6. Linear Guideway Catalogue by Hiwin Image 1

L= (C/P) 3 * 50 Km for roller type linear guideways.

= (116/18.393)3 * 50

= 12541.53 Km

Per day usage of main linear guideways for 16 Hrs. Shift = Length of travel per minute * 60 * Hours of shaft = 2400*80*16 = 3.072 Km

Life in terms of days = 12541.53 / 3.072 = 4082.53 Days = 11 Years (Approximately).

From the manufacturer's point of view the life of 11 Years is enough and it is expected that customers should ask for service after this much period of time.

After ensuring that life is within requirements. Let's check for static rated moments.

By considering loading condition as fixed support and point load in Centre the moment that is applying on linear guideways is (PL/8) = 6000*9.81*0.5/8 = 3.678 KN.m which is less than 5.47 KN.m

Hence selected bearing is safe.

2) **Selection of cross slide linear guideways:** We have selected the cross-slide cylinders hence we know the Maximum force that can be applied

= Pressure * 3.14 * 0.25 * d^2

= $7*10^6*3.14*0.25*32^210^{-6}$

= 5.62 KN

Using Moment equilibrium let's calculate effective load = 5.62*30 / (2*200)

= 0.4215 KN

As load is very less, we will be selecting the Basic guideway from RG series

Let's Check the **RGH15CA** for our use. And calculate the life in Km. Use the following fig.7 for reference.

Figure 7. Linear Guideway Catalogue by Hiwin Image 2

L = (C/P) 3 * 50 Km

   = (11.3 / 0.4215) 3 *50

   = 963413 Km

Travel of each bearing per day = Travel per minute *60*Hours per shift

                = 0.4*80*16

                = 0.512 Km

Life in No. of Days = 3675129 days

Life in terms of Years = 10068 Years (Approximately)

This is Nearly Infinite. So, the selected bearing is appropriate. Therefore, Linear Guideway selected for cross slide is RGH15CA [8].

1.3.5 Design of hydraulic power pack

Designing of hydraulic power pack involves selection of all of its components like storage tank capacity, electric motor gear pump, solenoid valves oil filter, air breather and level indicator. Their selection is elaborated further in detail.

Hydraulic oil storage tank function is just to hold the oil and that must be rigid enough to sustain its own weight so as per standards and practices 5 mm sheet is used for manufacturing the tank and minimum welding is done in order to close it to avoid the leakages.

Let's summarize the selected hydraulic cylinders and their speeds in order to know the size of the hydraulic fluid tank to supply sufficient amount of fluid to the system.

Table 2. Selected Hydraulic Actuators Details

Sr. No.	Model No.	Name	Quantity	C/s Area (mm^2)	Velocity (m/min)	Discharge (l/min)
1	CH2F B 100 C 1200	Main Hydraulic Cylinder	2	5388	6	64.65
2	CH2F B 32 B 600	Auxiliary Hydraulic Cylinder	1	804	6	4.82
3	CH2F B 32 B 140	Cross Slider Cylinder	2	804	6	9.64

From Above table 2 total discharge required per min = 64.65 + 4.82 + 9.64 = 79.116 liter/min. In general, the tank capacity should be 3 times the liter per min discharge required = 79.116 * 3 = 240 liter (Approx.) so, tank of size 1200*600*500 is selected and then fill the fluid appropriately. This size of tank will have a capacity of 360 liter. Gear pump inlet level is down. So, a higher size tank is to be chosen [9].

1.3.6 Selection of Electric Motor, Gear Pump, Solenoid valves

From above calculations, maximum power that is required is while actual cutting operation which is going to be near 7.5 hp. Hence use the 3 Phase induction motor of 7.5 hp power rating. And from above value of discharge required and the pumps available in the market motor with RPM 1450 is selected.

Hence a motor from Hindustan Motors Pvt. Ltd with Power 7.5 hp @1450 RPM is selected.

By studying the sequence of operations, maximum discharge required per min is 64.65 l/min. Hence look for the available options from Yuken's catalogue.

Selected gear pump is of discharge 76 l/min capacity and which can give the pressure up to 21 MPa from Yuken. Part Number of the selected gear pump is PG3-525-U1-3-FVR.

In this way the gear pump and electric motor is selected and the maximum pressure that can be produced by the pump is 210 bar. Hence, solenoid valves of the rated pressure capacity 210 Bar are selected.

As per market availability solenoid valves selected are of the Spica made 4DE-1-GS-110 and 4DE-06-ES-110 which are having 120 l/min and 60 l/min rating resp.
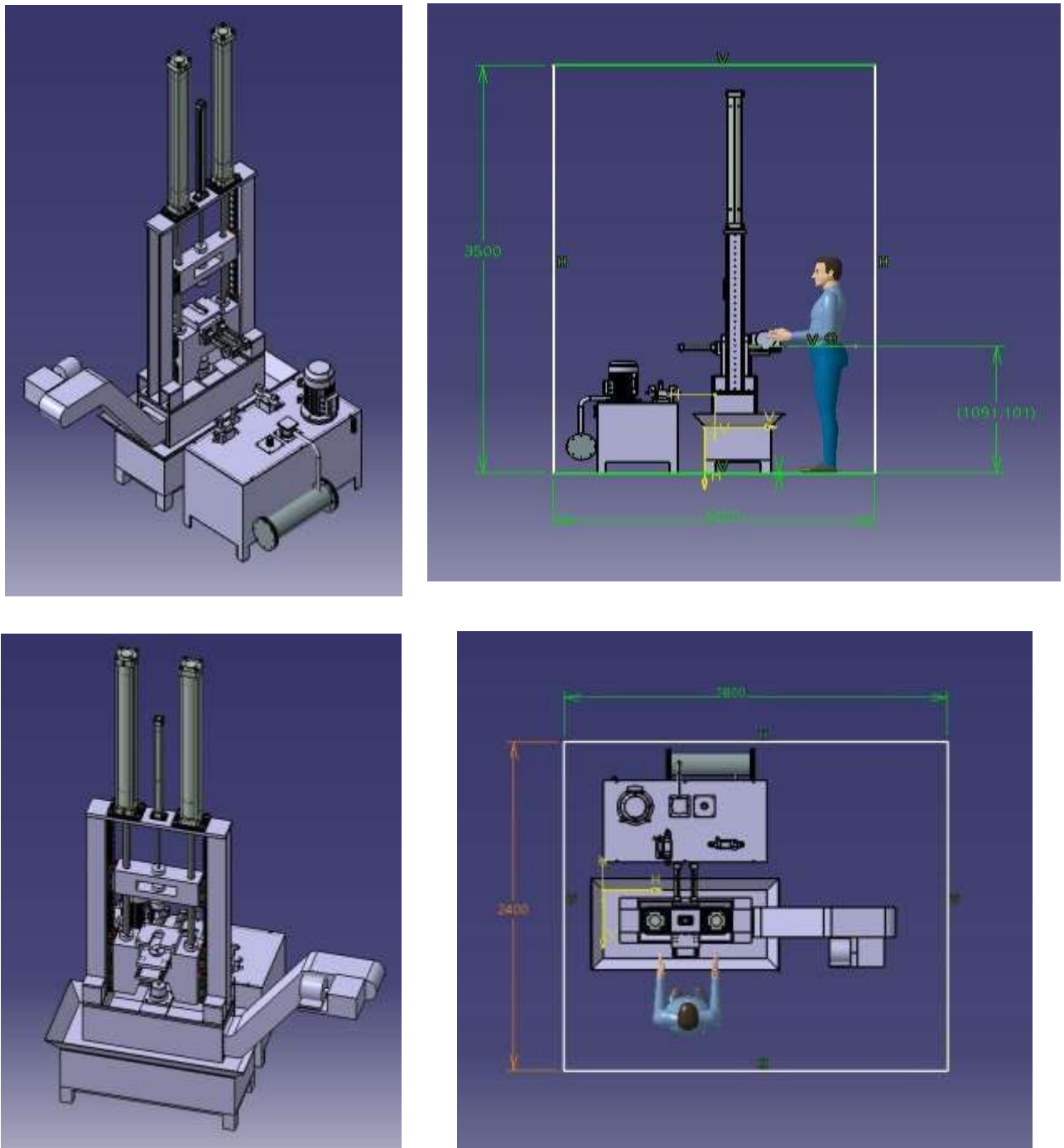
1.3.7 Final Assembly

Figure 11. Final Assembly Image

Above fig.11 shows the ergonomic considerations and general assembly of the product. By keeping standard manikin in the model machine is ergonomically modified to reduce operator fatigue. In this way final 3D modelling is done.
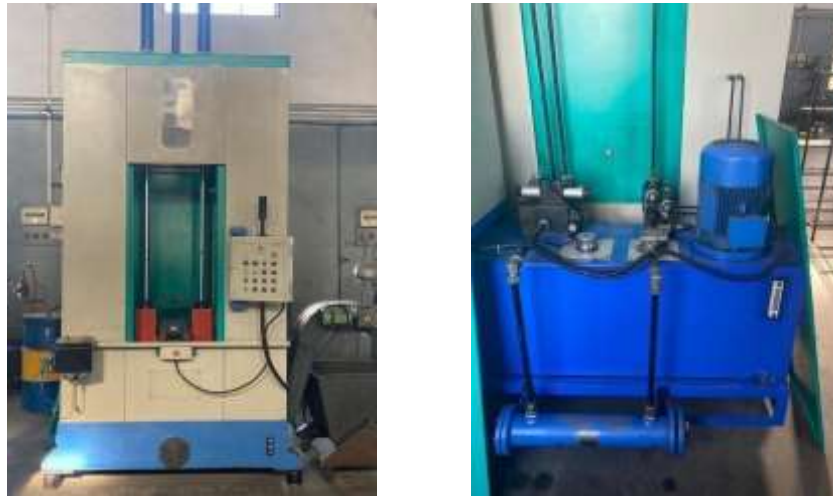
1.3.8 Final product

Figure 12. Final broaching machine

Above fig.12 shows the completely manufactured broaching machine which is exactly as per the drawings. Left hand side image shows front view of machine and right hand side image shows hydraulic power pack of machine.

2. Result and Discussions

2.1.1 CAE

In this part the basic structure of broaching machines has been analyzed using software like Ansys, Hypermesh. Following are the details of constraints and results obtained during the analysis [10].
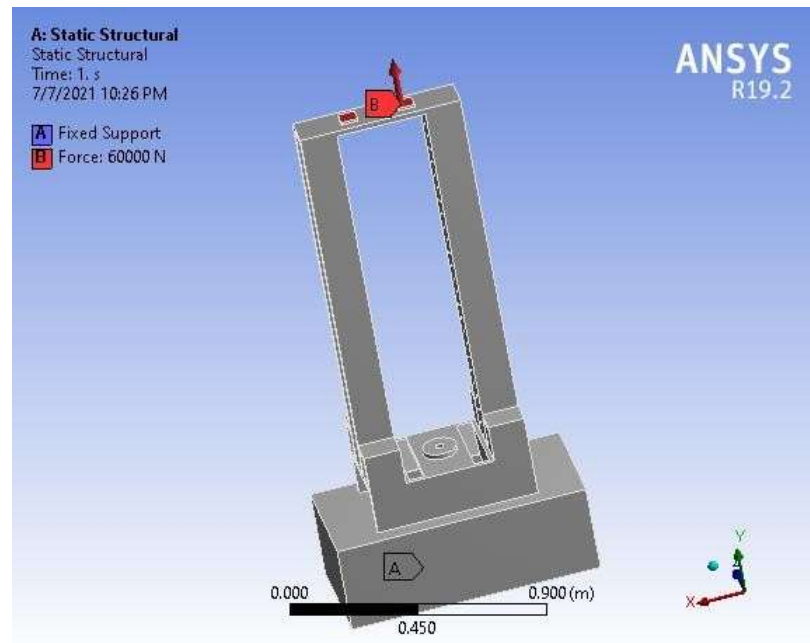

Figure 13. Static structural constraints and load

In the above fig.8, the base of the structure is fixed and the broaching force is applied at the point of cylinder mounting which is going to be a reaction force. And the magnitude of force is 60000 N. This magnitude is calculated in the broaching force calculation. After this meshing is done to appropriate limits to get accurate analysis results. The material we are going to use is structural steel with tensile yield strength 250 MPa and ultimate tensile strength 460 MPa. Structural steel is ductile in nature. So, it is more appropriate to check stress results of Von mises theory of failure for a given structure. Below fig.9 shows that maximum stress in structure is 70 MPa which gives minimum factor of safety of 3.56 which is pretty enough to sustain the loads.
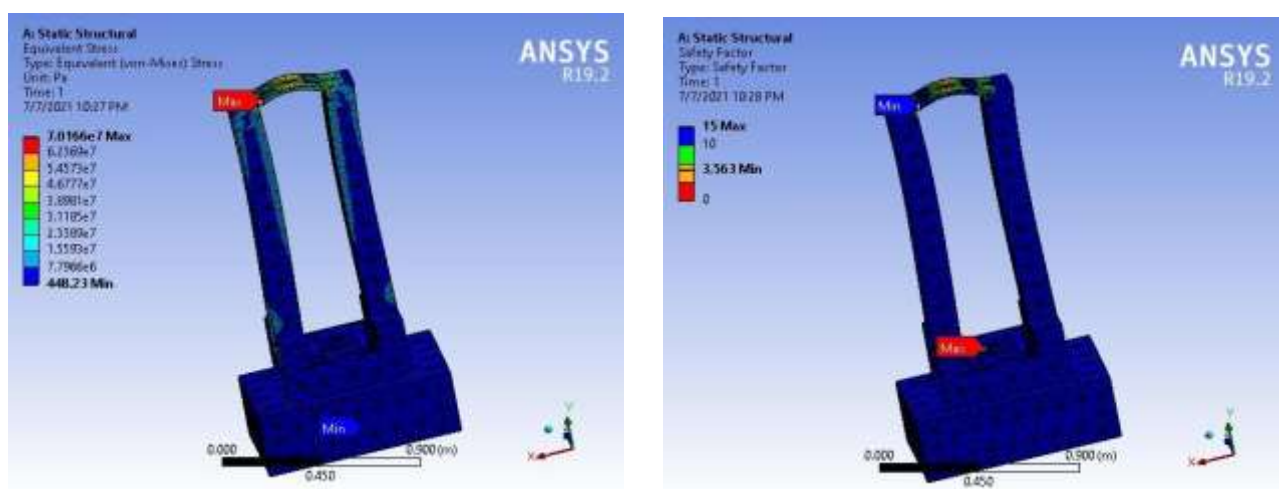

Figure 14. Results of Von Mises Theory

So, from the above discussion it is clear that our structure is safe as per von mises theory. In order to get the exact tolerances on our machining job structure must be fabricated within the minimum tolerances and this structure is not supposed to deform under load hence total deformation and directional deformations of structures are analyzed under given loading conditions.
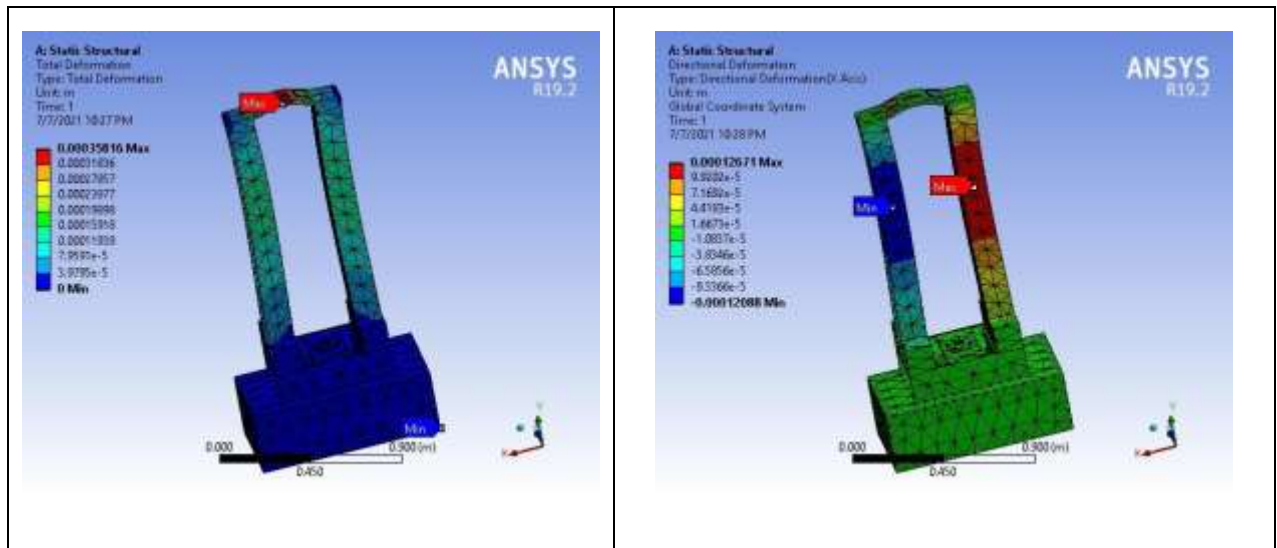

Figure 15. Deformation results

Table 3. Analysis results

Sr. No.	Results	Loading Condition 1		Loading Condition 1	
		Max	Min	Max	Min
1	Stress by M.D.E.T.	70.16 MPa	$448.23*10^{-6}$ MPa	99.62 MPa	$790.96*10^{-6}$ MPa
2	Stress by M.P.S.T.	82.34 MPa	-12.37 MPa	116.14 MPa	-8.67 MPa
3	Stress by M.S.S.T.	39.44 MPa	$253.98*10^{-6}$ MPa	50.08 MPa	$434.71*10^{-6}$ MPa
4	Directional Deformation	0.1267 mm	-0.1208 mm	$1.48*10^{-2}$ mm	$-1.03*10^{-2}$ mm
5	Total Deformation	0.3581 mm	0 mm	0.1855 mm	0 mm
6	Factor of safety using M.D.E.T.	15	3.563	15	2.5094
7	Factor of safety using M.S.S.T.	15	3.1686	15	2.4586

Total deformation is 0.358 mm and directional deformation 0.126 mm which is under limits in order to get final job within its tolerances. So, from above discussions it is clear that structure is perfectly suitable for given loads. Simultaneously structure has been checked for other theories of failure to which it is safer and their results are tabulated above. In above table, results of 3 theories of failure are elaborated. From those maximum distortion energy theory is the most appropriate theory for ductile materials under triaxial state of stress.

2.1.2 Final Machining Output

Figure 16. Before-After of Actual Job

After the broaching machine was ready, various job trials were done on it. Machined jobs were checked with help of go and no go gauges and it is found that quality parameters of 90% of jobs were confirming to requirements. Then by some fine tuning of machine this percentage has been raised to 95%. This amount of accuracy was acceptable from customer.Fig.13 Shows the before after of the machined job.

3. CONCLUSION

From above analysis results conclusion is that the designed structure is safe enough to carry all the loads. And after manufacturing and trials it is pretty clear that the machine performs well to fulfill its functionality. Machined jobs are falling within their tolerances and auto cycle is also running as per the expectation without any fouling. At the same time cycle time achieved is fulfilling the customer expectation. Machine is equipped with the air cleaning unit and magnetic belt conveyor for easy chip removal.

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