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Research Article

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Design and Development of Flexible Vacuum Clamping System for Thin Walled Cylindrical Object for CNC Machines

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Abstract

In this article, vacuum pressure for holding thin walled cylindrical object in vacuum clamping system on a computer numerical control machine (CNC) is studied. In this work, thin walled cylindrical object in vacuum clamping system is designed and different parameters for the vacuum clamping system are calculated. CNC rolling and flow farming machines are being employed for the thin wall and complicated objects. It is very challenging to make various thickness thin walled objects at high precision with help of jig and fixture at large scale. A lot of time is consumed for non-operational activities and skilled operator is required. In this work, this problem is resolved by replacing the machines built with 3-jaws hydraulic chucks with traditional made flexible clamping system. It would increase production rate and accuracy of object as compared to other conventional manufacturing processes. Designing imprecision may lead to process tolerance that caused to enhance manufacturing expenditure. In this work, optimum cutting parameters: feed rate, surface roughness and depth of cut of vacuum clamping system are deliberated. The main focus of this research is to design alternate clamping system for holding thin walled work piece with variable thickness and to save time, men power and raw material.

Keywords: Vacuum clamping system; CNC; Feed rate; Depth of cut; Surface roughness

Introduction

In contemporary manufacturing processes, high-dimensional accuracy and fine surface finishing play significant role. Accurate dimension is not conceivable to achieve by manual cutting. CNC machines are used for automation of machining process for massive production. Different machining operations can be finished on CNC machines that caused to increase productivity, improved quality, reduce the scrape rate, reliable and safe operation.

Chuck system in CNC for work pieces, machine tools which has a series of vacuum pods for safe degree of clearance during machining operation through the work piece. These additional pods are arranged around work table just like array. Pressure regulated by the selected pods to rise above the table to support the wok piece, without offering any interference to the operation of the cutting tool [1]. Utilization of vacuum pressure for holding of work pieces for machining that is provided the support to work piece between the lower surface of the work piece and the non-planar surface of the bed [2]. It was described that the designing and assembling of a custom vacuum chucks for lathe including a vacuum connector assembly which is mounted within the spindle bore of a lathe machine. Such type of vacuum chucks was utilized in wood turning lathe. The end face plate of the vacuum chuck can be altered to accommodate the variety of styles making it flexible [3]. It was described that positionable vacuum clamping system includes a vacuum table and one or more positionable vacuum clamps which can hold different shape of work pieces. It contains of base plate, positionable center plate and attached top plate sliding secured by a retainer washer to the base plate. Vacuum passages within and about the positionable vacuum clamp communicate between the vacuum table and the upper vacuum mating structure of the top plate to vacuuming a work piece to the top plate for subsequent machining by machine tool [4]. Comparative study of both improved and new clamping mechanisms for CNC lathes can be used for better cutting speed and better surface roughness. The most effective clamping mechanism for holed workpiece is ball compensators which provide better centrifugal forces [5]. It was concluded that minimum clamping force is calculated for dynamic stability of workpiece during different machining operation. Static and dynamic modal for determining the optimal set of clamping force was solved by using the particle swarm optimization (PSO) technique highlighting computational intelligence [6]. By means of theoretical calculation, hydraulic clamping system for CNC Machine was designed for safety and reliability of workpiece such as guide disc. The machine has not only acquired the national utility models patent but also has been put into production [7]. It was presented a prediction model of a workpiece for geometric inaccuracy and setup error for fixture with one or more locating surface. Machining error can be predicted due to locating error on a multi-body system and homogeneous transfer matrix. Cutting test modal is effective and practicable [8]. The finite element method technique was applied to support modeling work. Chuck stiffness and critical bending force can be enhanced by clamping length [9]. For high cutting speed, greater spindle speed of machines is required. The theoretical modal was presented for conventional and modern chuck that ensures a safe high-speed turning process, and makes it conceivable to completely utilize the potential of jaw-chucks at high rotational speeds [10]. Optimal machining parameters were obtained for turning cylindrical stocks into continuous finished profile using six non-traditional techniques (GA, SA, TS, ACO, MA and PSO) that for reducing manufacturing cost in profile turning [11]. It was concluded that increase feed rate that due to cause of cutting force. Increase negative tool rake angle and cutting speed as to decrease of tool chip friction [12]. It was concluded that the better surface finish may be acquired by turning carbon alloy steels at low feed rate and high spindle

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speeds. The study exposes that the surface roughness is directly influenced by the spindle speed and feed rate. It is observed that the surface roughness increases with increased feed rate and is higher at lower speeds and vice versa for all feed rates [13]. It was experimentally determined that material removal rate in CNC turning process is influenced by cutting speed and depth of cut. Surface roughness (Ra) is influenced by Feed rate and nose radius of tools. Optimization of Surface roughness (Ra), material removal rate (MRR) and depth of cut is the most significant parameter affecting the performance followed by the nose radius [14]. Surface roughness profile depends of feed rate. Increase in roughness is generally measured to be a function of square of the feed rate. At low feed rate the micro roughness is more seen in the existence of several frequencies. Chip thickness and coil radius increase with increase in feed rate. The roughness appear like a screw thread profile representing chip removal to be the dominant mechanism of roughness generation at high feed rate [15]. Surface roughness is known to be inversely proportional to cutting speed but directly proportion of feed rate. Surface roughness is proportional to depth of cut and inversely proportional to nose radius [16].

Experimental Setup

CNC specification

In this study, JOHNFORD SL-60 CNC Lathe machine is used. It has built-in 3-jaws hydraulic chuck with all accessories, in which 3-jaws hydraulic chuck was exchanged with vacuum clamping system for experimentation.

Chuck measurement

It is necessary to find out dimension of chuck assembly because vacuum clamping system is adjusted on this chuck assembly with accurate dimension. Chuck measurement of different component is taken in Table 1.

Hydraulic chuck is mounted on chuck base plate. Figure 1 indicates three pair of bolts which is in between jaws. These bolts were loosed through device and separated hydraulic chuck from base plate as shown in Figure 2. It showed front view of base plate where clamping system would be installed. Figure 3 indicated the side view of base plate where new vacuum clamping system to be installed.

Flexible vacuum clamping system

There are different components of vacuum clamping system which were discussed below. It has following different machines parts:

Chuck base: Chuck base is main component of vacuum clamping system which receives and retains vacuum pressure. Proper materials selection for chick base plate is necessary to attain required pressure for experimentation. Mild steel were used with desirable mechanical properties such as hardness, tensile strength and Impact strength. Some material properties are shown in the Table 2. Required hardness, tensile strength and impact strength can be attained through heat treatment mechanism. Micro structural analysis was carried out through scanning electron microscopic. Micrograph exhibits proper materials division and stability of grain structure. SEM image was taken as X500 up-to 10 μm Scale (Figures 4). Mechanical design was prepared through solid

Description	Value
Chuck diameter	300 mm
Total chuck height	250 mm
Length of the tensioning tube	1500 mm
X-axis travel	250 mm
Z-axis travel	900 mm

Table 1: Chuck measurements.

Item	Description
Material	Mild steel
Hardness requirement	15~18 HRC
Material porosity	Radiographic testing
Tensile strength	400 N/mm^2
Impact strength	75 Joules (IZOD)

Table 2: Chuck base properties.

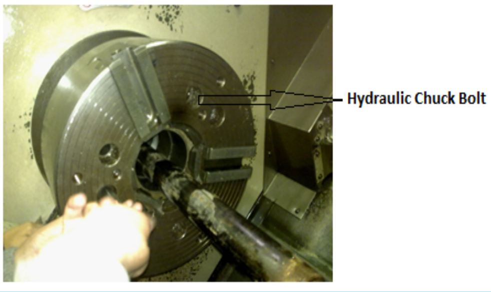

Figure 1: Hydraulic chuck.

Figure 2: Hydraulic chuck base plate.

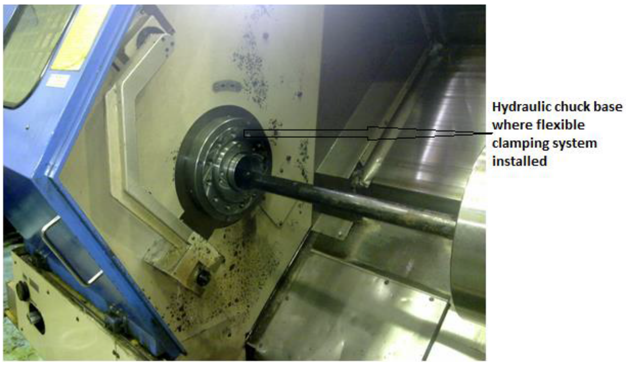

Figure 3: Base plate where clamping system to be installed.

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work according to our requirements as shown in Figures 5 and 6. The chuck base plate has six bolts which were fitted on Machine's inbuilt chuck assembly base.

Front holding plate: A good design of front holding plate is suitable for better machining operation. It has ability to hold the thin walled cylindrical work piece in suitable position and provide sufficient vacuum on the surface of the work piece for proper clamping and holding during the machining processes. Front plate materials specification is given in Table 3. The front holding plate is an essential portion in the whole structure design, because the this plate is responsible to clamp the thin walled cylindrical work piece in better adjustment and deliver appropriate vacuum on the surface of the work piece for suitable compressing in operational processes. Figure 7 represents the work piece is fitted in front holding plate (Figure 7).

Production Method

Conventional manufacturing method

Manufacturing of complicated objects with CNC machines increases the production rate and quality of products. In this method, there are five different machining steps for acquiring the final products. In each and every step, different tools and inserts are used for performing operation functions.

This research work comprises on practical solution for getting an alternate more flexible and precise clamping mechanism that is used to clamp properly the highly critical and precise thin walled cylindrical work piece for its machining operation (Tables 4 and 5).

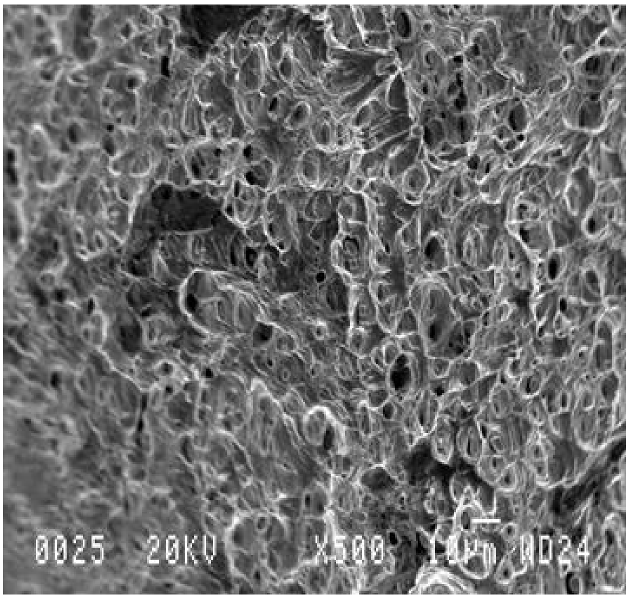

Figure 4: Microscopic view of materials.

Item	Description
Material	Aluminum
Hardness requirement	~15 HB
Material porosity	Radiographic testing
Tensile strength	60 N/mm²
Impact strength	27 Joules

Table 3: Front plate materials specification.

Process code	Process	Cutting tools and geometry	Process time t_p min
A_1	Blank cutting	Band saw	60 min
B_1	Outer stepping	CNMG 160608	150min
C_1	Inner rough/finish	DCMT 150408 TP 2000	100 min
D_1	Outer rough/finish	VCGR 160408 CP 200	90 min
E_1	Outer collar milling	Dormer HSS End mill dia 10	30 min

Table 4: Different machining operations and process codes.

Process code	Feed rate f, mm/rev	n, rpm	Depth of cut ap, mm
A_1	Band saw		
B_1	0.4	1000	0.8
C_1	0.1	400~1200	0.1
D_1	0.25	200~600	0.2
E_1	0.8	1000	2.0

Table 5: Cutting speed parameters.

The dimension of the work piece under consideration is as under;

Blank thickness (B_T)=45.00 mm

Maximum profile thickness (P_{tmax})=2.53 mm

Minimum profile thickness (P_{tmin})= 1.25 mm

Profile Centre height (P_{CH})=37.00 mm

Outer diameter final (OD_F)=210 mm

Total time $T_{t=}t_{p1}+t_{p2}+t_{p3}+t_{p4}+t_{p5}$

=60+150+100+90+30

=430 min

Non-conventional operation T=50 min

Work piece per shift$_=$8 × 60/480

=1 ~ 1 Pc/Shift

=60 Pcs/Month

$$V_{c_{1\&2}} = \frac{n \times \pi \times D_c}{1000} \quad (1)\ [17]$$

Cutting Speed, Vc_1andVc_2 for Process C_1 and D_1 respectively has been calculated through equation 1. During this operation, machine is operated on 400 rpm for inner rough (C_1) and 200 rpm for outer profile (D_1) and worked on workpiece of 200 mm diameter. Cutting speed for inner profile Vc_1 and outer rough Vc_2 are 251.2 m/min and 125.6 m/mm respectively.

In turning of the inner profile of the work piece, G96 command is used which stands for constant surface speed parameter. The format of the G96 command is as: G96 S (surface cutting speed) (Figure 8).

$$R_{a_{1\&2}} = \frac{f^2 \times 50}{r_\varepsilon} \quad (2)\ [17]$$

Surface finish, $Ra_1$and Ra_2 for process C_1 and D_1 respectively has been calculated through equation 2. During this operation, machine is operated with feed rate 0.1 mm/rev and nose radius (rε) 0.8 mm for process C_1 and feed rat 0.25 mm/rev and nose radius (rε) 0.8 mm for Process D_1. Surface finish for inner profile Ra_1 and outer profile Ra_2 are 0.625 μm and 3.90 μm respectively

$$R_{t_{1\&2}} = k\frac{f^2 \times 100}{8 \times r_\varepsilon} \quad (3)\ [17]$$

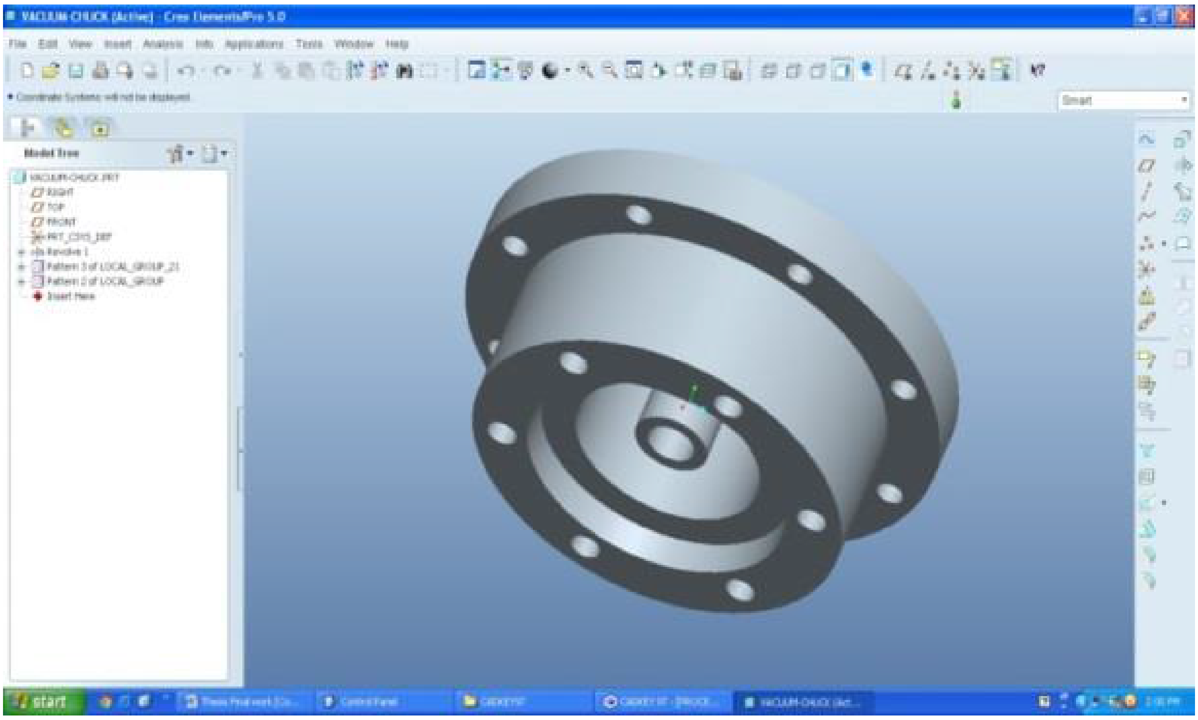

Figure 5: Vacuum chuck front side drawing.

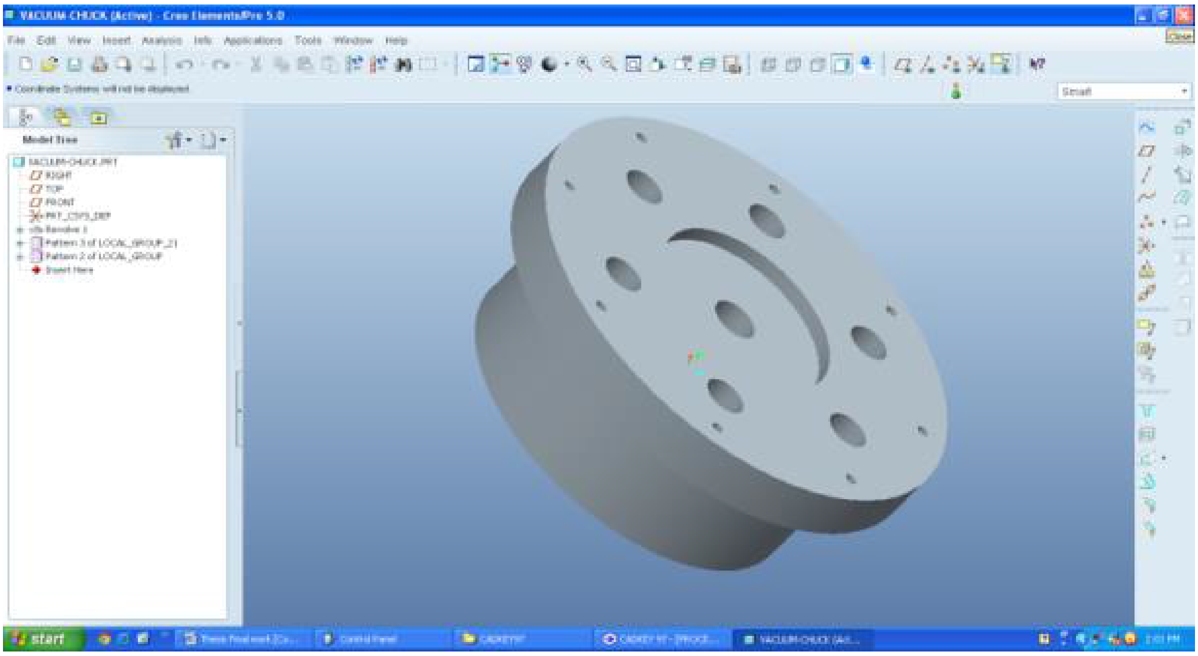

Figure 6: Vacuum chuck back side drawing.

Profile depth, Rt_1 and Rt_2 for process C_1 and D_1 respectively have been calculated through equation 3. During this operation, machine is operated with feed rate 0.1 mm/rev and nose radius (rε) 0.8 mm for process C_1 and feed rat 0.25 mm/rev and nose radius (rε) 0.8 mm for process D_1 with k=1.4 for steels and stainless steel. Profile depth for inner profile Rt_1 and outer profile Rt_2 are 0.2185 μm and 1.3671 μm respectively.

$$Q_{1\&2} = V_{c_i} \times f \times a_p \quad (4)\ [17]$$

Metal removal rate, Q_1 and Q_2 for Process C_1 and D_1 respectively has been calculated through equation 4. During this operation, machine is operated with feed rate 0.1 mm/rev, cutting speed (Vc_1) 251.2 m/min and depth of cut (ap) 0.1 mm for process C1 and feed rate 0.25 mm/rev, cutting speed (Vc2) 125.66 m/min and depth of cut (ap) 0.2 mm for Process D1.

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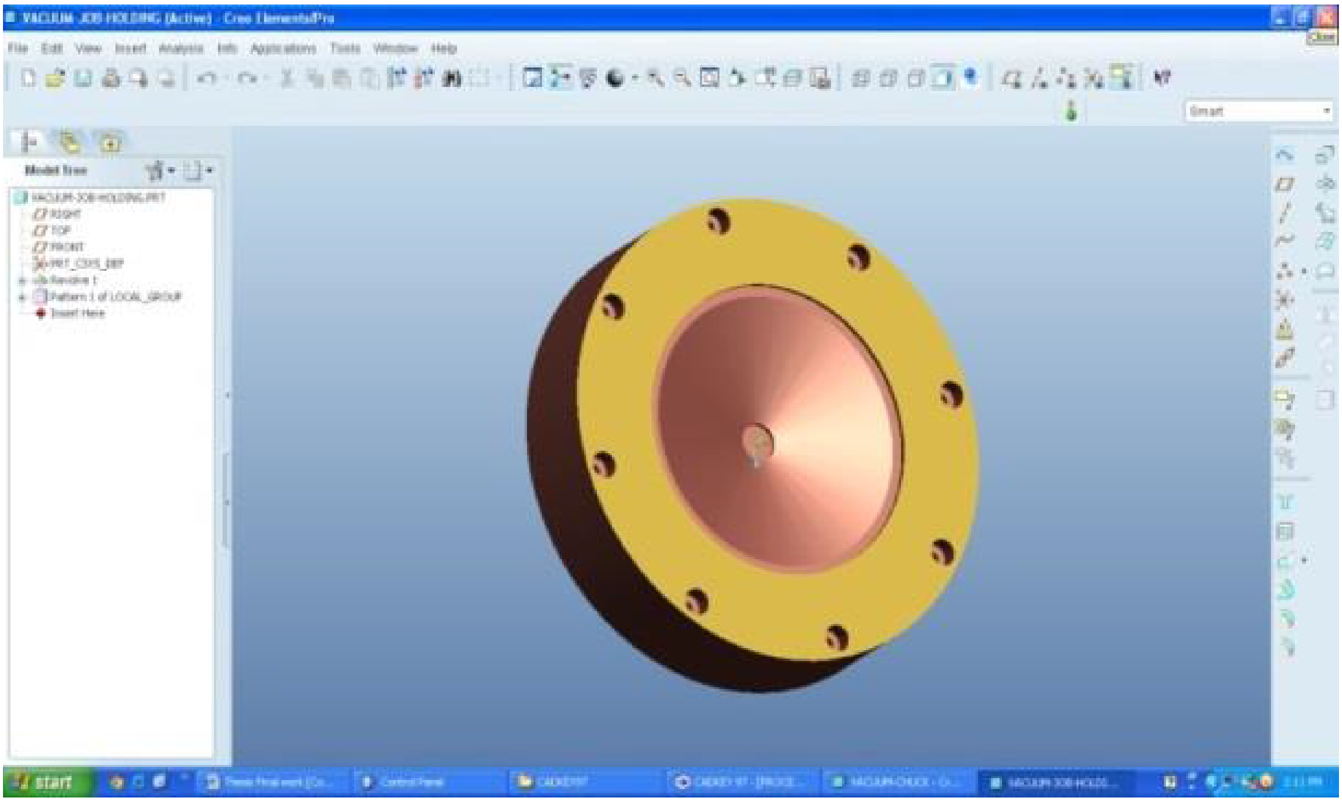

Figure 7: Front holding plate.

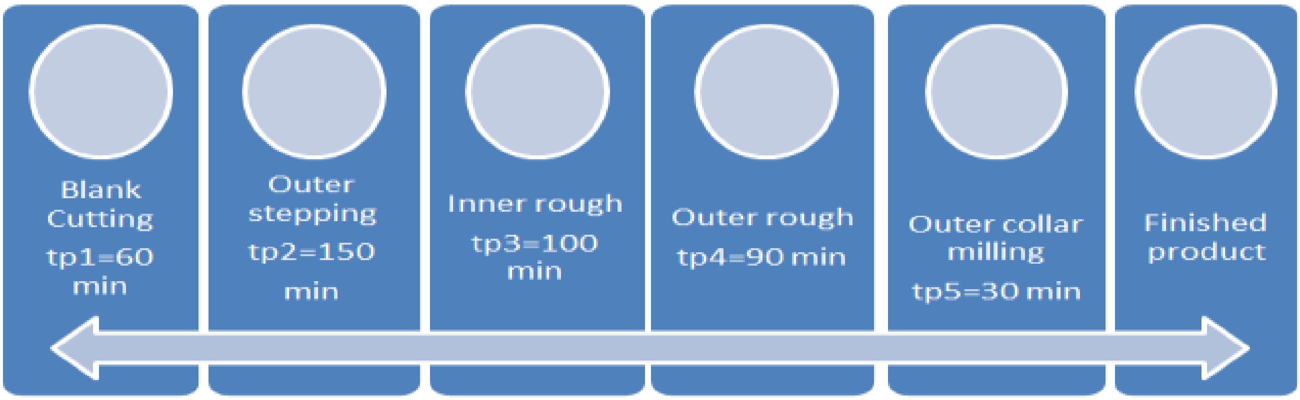

Figure 8: Machining operation time.

Metal removal rate Q_1 and Q_2 are 2.512 cm^3/min and 6.283 cm^3/min respectively.

The quality control standards for surface finish ranges for inner and outer profiles are as follows:

Inner Profile=0.5 μm to 2 μm=Ra_1

Outer Profile=3 μm to 6 μm=Ra_2

There were taken 10 random samples from the monthly production to check the quality of the final thin walled work piece (Table 6).

In conventional manufacturing process, work piece is rejected due to following reasons:

Sample no, n	Measured values Ra_1, μm	Measured values Ra_2, μm	Remarks
n_1	1.04	**2.95**	Rejected
n_2	0.8	**2.25**	Rejected
n_3	2.0	3.54	Accepted
n_4	0.75	3.10	Accepted
n_5	1.14	3.30	Accepted
n_6	**0.25**	3.03	Rejected
n_7	1.19	4.09	Accepted
n_8	**0.35**	**6.55**	Rejected
n_9	2.15	5.05	Accepted
n_{10}	0.66	5.09	Accepted

Table 6: Random sampling technique.

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1. Work piece is clamped at three different points that caused localized stresses at that region which may lead to rejection of it.

2. The carelessness of the operator during tightening of the work piece may lead to profile rejection, because unbalanced clamping of a thin walled work piece.

Analysis of the bolted ring/fixture is executed on ANSYS and shown in Figure 9.

Flexible clamping system manufacturing

Flexible clamping system has following objectives.

1. Material utilization has been reduced from 45 mm to 10 mm sheet and material saves 4 times as compared to conventional manufacturing process. It was attained nearest shape of materials as desired shape with help of pressing machines as shown in Figures 10 and 11.

2. Number of machining operations and time will be reduced that caused increase the rate of production.

3. Better surface and dimensional accuracy are attained as compared to old clamping techniques by using fixture, ring and bolts.

Vacuum clamping system has four steps to get final work piece (Table 7).

Total time T_t=tp1+tp2+tp3+tp4=30+30+90+90

=240 min

Non-conventional operation T=30 min

Work piece per shift=8 × 60/270=1.78=2Pc/Shift=120 Pcs/Month (Table 8).

The quality control standards for surface finish ranges for inner and outer profiles are as follows

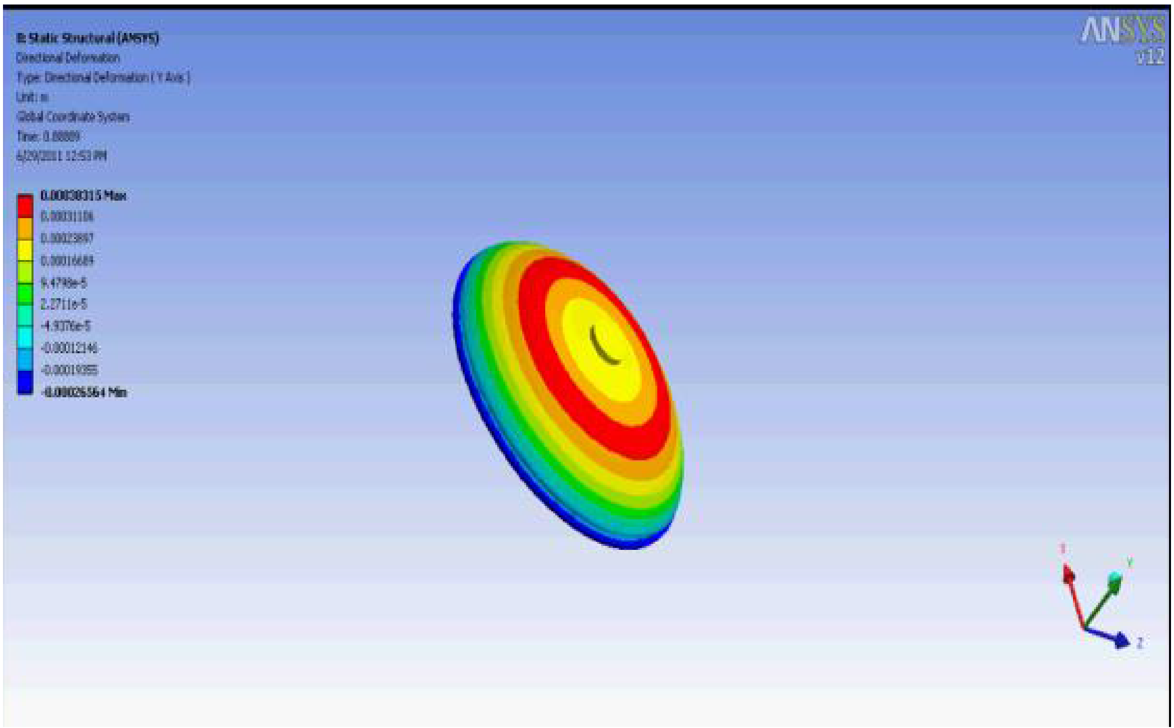

Figure 9: Analysis of conventional clamping system.

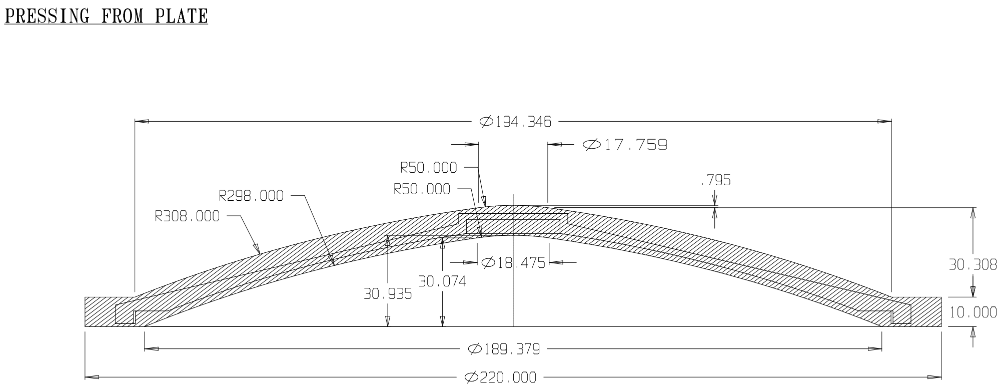

Figure 10: Desired shape after pressing.

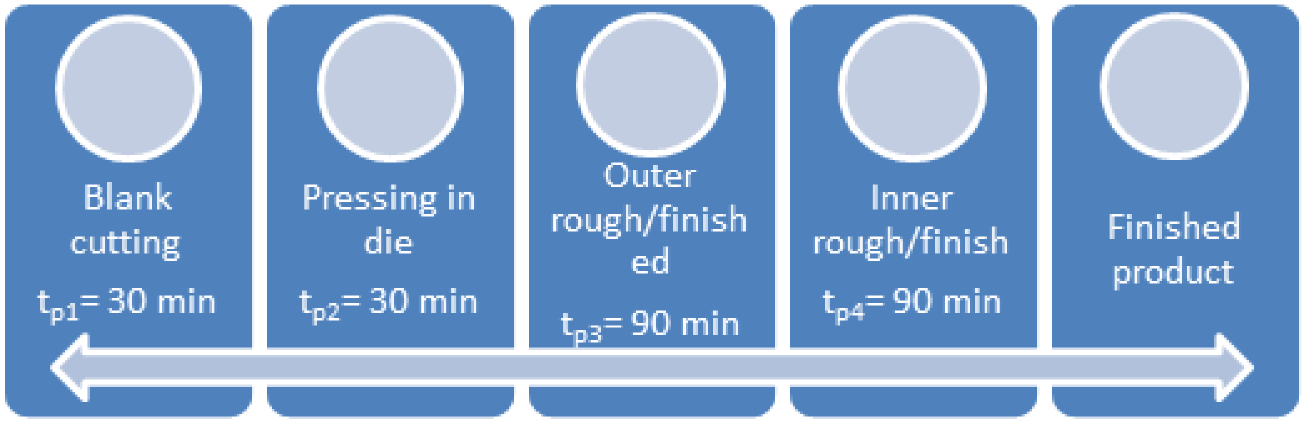

Figure 11: Time flow chart of different process.

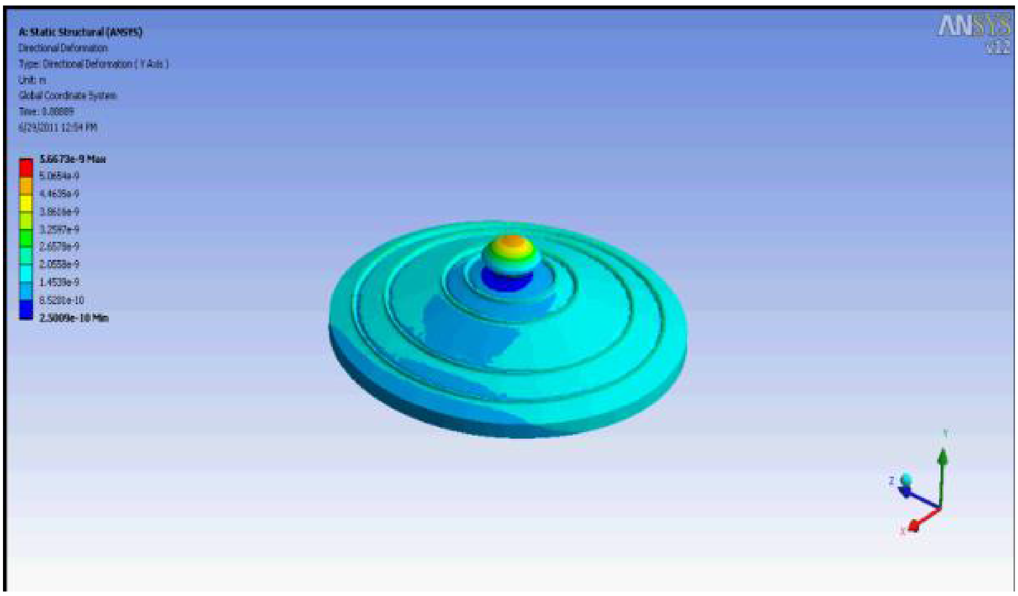

Figure 12: ANSYS analysis.

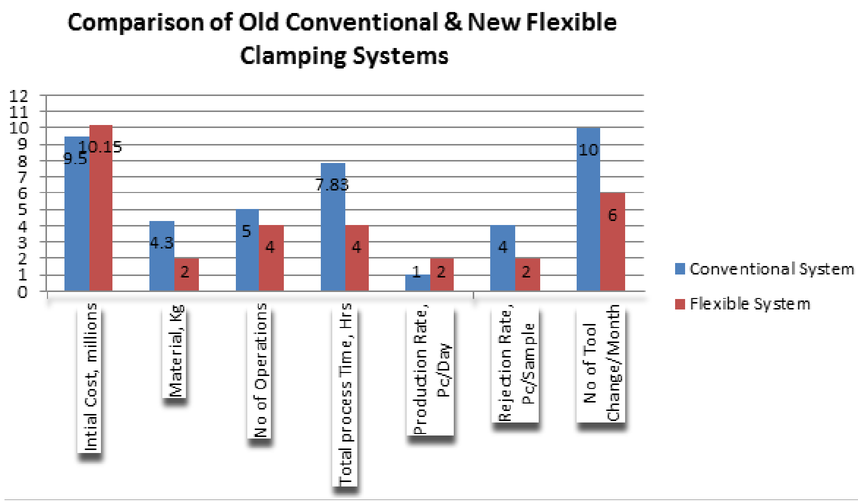

Figure 13: Graphical comparison.

Process code	Process	Cutting tools and geometry	Process time t_p min
A_1	Blank cutting	Band saw	30 min
B_1	Outer stepping	Pressing machine	30 min
D_1	Outer rough/finish	DCMT 150408 TP 2000	90 min
C_1	Inner rough/finish	VCGR 160408 CP 200	90 min

Table 7: Different machining operations and process codes.

Process code	Pressing in die	Feed rate f, mm/rev	n, rpm	Depth of cut ap, mm
A_1	Pressing in die	Pressing machine		
B_1	Outer stepping	0.4	1000	0.8
D_1	Outer rough/finish	0.25	200~600	0.2
C_1	Inner rough/Finish	0.1	400~1200	0.1

Table 8: Cutting speed parameters.

Inner Profile=0.5 µm to 2 µm=Ra_1

Outer Profile=3 µm to 6 µm=Ra_2

There were taken 10 random samples from the monthly production to check the quality of the final thin walled work piece (Table 9).Analysis of the new flexible clamping system using vacuum pressure as the main holding force during machining is performed on ANSYS and shown in Figure 12.

Production System Comparison

The following table compares the old conventional method of production and the new flexible manufacturing system using vacuum. The whole month's data is compared for both the systems (Table 10).

Optimum Parameters for Flexible Clamping System

After installing the vacuum clamping system, the series of experiments are conducted to find out the optimum machining parameters such as feed rate, surface roughness and depth of cut (Figure 13).

Optimum feed rate

Optimum feed rate is calculated with the increase of feed rate and checkout surface roughness in outer and inner finish.

Optimum feed rate for process D1: Spindle RPM range is kept constant at 200~600 RPM and by changing feed rates from 0.2 to 0.45 mm (Table 11)

Surface roughness value is in acceptable range (3 to 6 µm) with feed rate vary from 0.2 to 0.25. At feed rate 0.3 and 0.35, the range is out. By increasing feed rate 0.4, it is in acceptable range. This is our optimum value where surface roughness in acceptable range (Figures 14-18).

Optimum feed rate for process C_1: Spindle RPM range is kept constant at 400 ~ 1200 rev/min and by changing feed rates from 0.1 to 0.35 mm (Table 12)

Surface roughness value is in acceptable range (0.5 to 2 µm) at feed rate 0.1 to 0.15. When we increase the feed rate to 0.2 and 0.25 mm, the range is out. By increasing feed rate 0.3, it is in acceptable range. This is our optimum value where surface roughness is in acceptable range.

Optimum depth of cut

Optimum depth of cut for process D1: At constant feed rate, surface finish changes with variation of depth of cut from 0.2 to 0.6 (Table 13).

Sample No, n	Measured values Ra_1, µm	Measured values Ra_2, µm	Remarks
n_1	1.04	3.15	Accepted
n_2	0.8	**2.25**	Rejected
n_3	1.90	3.30	Accepted
n_4	0.75	3.19	Accepted
n_5	1.19	4.18	Accepted
n_6	**0.35**	2.80	Rejected
n_7	1.29	4.27	Accepted
n_8	0.95	5.15	Accepted
n_9	2.15	5.22	Accepted
n_{10}	2.67	5.09	Accepted

Table 9: Random sampling technique.

Description	Conventional system	Flexible system
Initial cost, millions	9.5	10.15
Material, Kg	4.3	2
No of operations	5	4
Total process time, h	7.83	4

Table 10: Systems comparison.

Job dia	RPM (rev/min)	Feed rate (mm/rev)	Process time t_p min			Remarks
220	200~600	0.2	3.4	4.4	4.6	In Range
220	200~600	0.25	3.05	4.15	3.8	In Range
220	200~600	0.3	2.56	2	1.9	out of Range
220	200~600	0.35	6.02	2.95	2.5	out of Range
220	200~600	0.4	3.56	4.78	5.15	In Range
220	200~600	0.45	2.43	2	6.85	out of Range

Table 11: Feed rate and surface roughness at constant RPM.

Job dia	RPM (rev/min)	Feed rate (mm/rev)	Surface roughness (mm of turning) µm			Remarks
220	400~1200	0.1	0.54	1.19	1.78	In Range
220	400~1200	0.15	0.85	1.27	1.89	In Range
220	400~1200	0.2	1.01	2.5	2.34	out of Range
220	400~1200	0.25	1.15	2.34	2.67	out of Range
220	400~1200	0.3	0.98	1.56	1.43	In Range
220	400~1200	0.35	2.43	1.95	1.8	out of Range

Table 12: Feed rate and surface roughness at constant RPM.

Calculation of DOC (constant feed rate)				
Job dia	Feed	DOC	**Surface finish, µm**	**Remarks**
220	0.3	0.2	4	Accepted
220	0.3	0.24	4.15	Accepted
220	0.3	0.28	3.58	Accepted
220	0.3	0.32	5.54	Accepted
220	0.3	0.38	2.91	Not Accepted
220	0.3	0.4	2.54	Not Accepted
220	0.3	0.45	2.32	Not Accepted
220	0.3	0.5	2.54	Not Accepted
220	0.3	0.55	2.6	Not Accepted
220	0.3	0.6	2.3	Not Accepted

Table 13: DOC and surface finish for process D_1.

Surface finish is within the acceptable range (3 to 6 µm) as increase DOC values 0.2, 0.24, 0.28 and 0.32. DOC value of 0.28 is nominated because at this point the surface is at the lowest range of surface finish requirement.

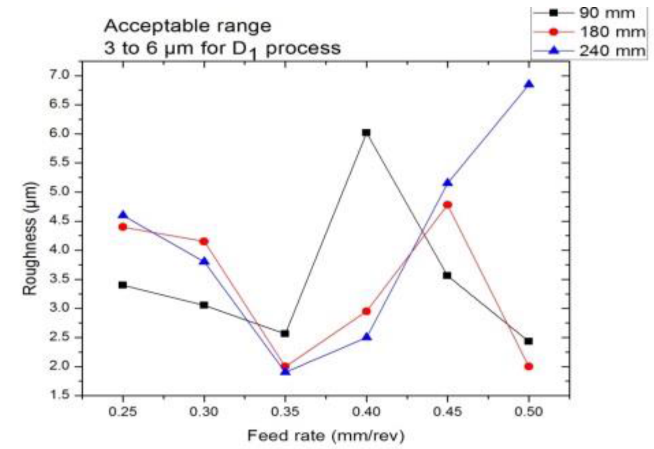

Figure 14: Feed rate versus surface roughness for process D1.

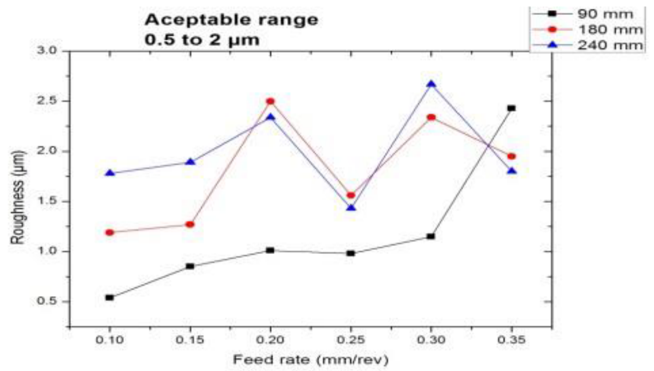

Figure 15: Feed rate versus surface roughness for process C1.

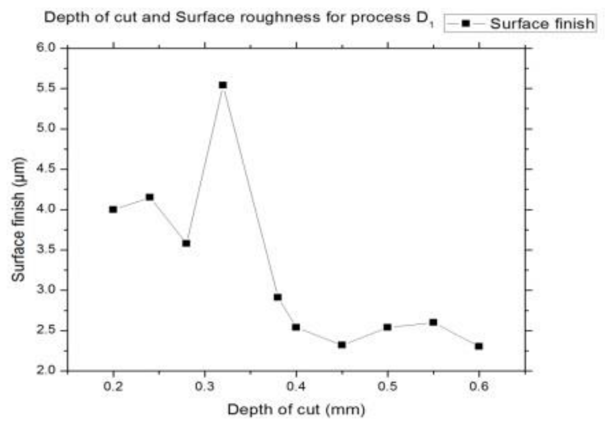

Figure 16: Surface finish and DOC for process D1.

Optimum depth of cut for process C1: At constant feed rate, Surface finish changes with variation of depth of cut from 0.1 to 0.4.

Surface finish is within the acceptable range (0.5 to 2 μm) as increase DOC values of 0.1, 0.14, 0.18 and 0.2. DOC value 0.18 is selected because at this point the surface is at the average range of surface finish requirement (Tables 14 and 15).

Optimum vacuum pressure for process D_1

At 0.28 mm DOC value, the vacuum pressure varies from 15 KPa

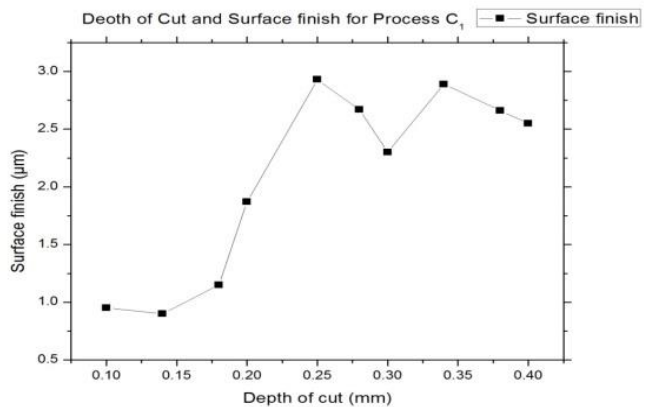

Figure 17: Surface finish and DOC for process C1.

Calculation of DOC (Constant feed rate)				
Job dia	Feed	DOC	Surface finish, μm	Remarks
220	0.3	0.1	0.95	Accepted
220	0.3	0.14	0.9	Accepted
220	0.3	0.18	1.15	Accepted
220	0.3	0.2	1.87	Accepted
220	0.3	0.25	2.93	Not accepted
220	0.3	0.28	2.67	Not accepted
220	0.3	0.3	2.3	Not accepted
220	0.3	0.34	2.89	Not accepted
220	0.3	0.38	2.66	Not accepted
220	0.3	0.4	2.55	Not accepted

Table 14: DOC and surface finish for process C1.

Calculation of vacuum pressure required			
Job dia	DOC	Vacuum pressure (KPa)	Results/Remarks
220	0.28	15	Clamping not sufficient
220	0.28	30	Poor visual surface texture
220	0.28	60	Excessive wear of tool bit
220	0.28	85	Excellent
220	0.28	90	Poor dimensional accuracy
220	0.28	100	Poor dimensional accuracy

Table 15: Evaluating vacuum pressure for D_1.

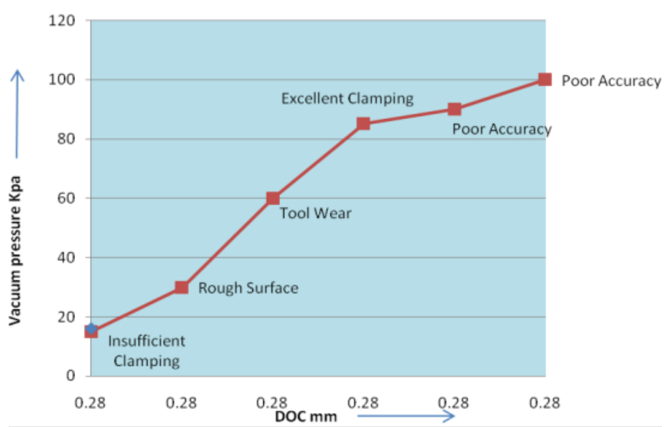

Figure 18: Graphical representation.

to 100 KPa. 85 KPa vacuum clamping pressure gives excellent results in vacuum clamping system of manufacturing.

Conclusion

The present study shows that importance of vacuum clamping system for massive production with great accuracy and dimension tolerance. This research was carried out thin walled job that is difficult to do machine using conventional manufacturing process. It is concluded that new flexible clamping system is better in different ways.

- Better control feed rate for purpose to obtain required surface finished jobs.
- To avoid severe deflection surface during inner and outer machining by vacuum clamping system. Figure 12 ANSYS give better result as compared to Figure 9.
- To save materials in which materials thickness reduced from 40 mm to 10 mm.
- Less material removal that caused the greater tool life.
- Depth of cut (DOC) improved from 0.1 to 0.18 for process C1 and 0.2 to 0.28 for process D1.

Feed rate improved from 0.1 to 0.3 for process C1 and 0.25 to 0.4 for process D1.

Conflict of Interest Statement

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