Modeling of morphology and deflection analysis of copper alloys

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Abstract - *In this paper, an experimental investigation to predict the optimum cutting conditions for the thin wall machining of copper plate on conventional end milling machine and applications of thin wall machining are presented. Earlier the optimal values for speed, feed rate and depth of cut are taken using Taguchi technique. Taguchi methods are statistical methods developed by Genichi Taguchi to improve the quality of manufactured goods by using a fractional-factorial approach whenever there are several factors involved and is accomplished with the aid of orthogonal arrays. It is a lengthy and time taking process. In this model, by comparing all the experimental results, optimum cutting conditions are found for obtaining a good surface finish and un-deflected thin wall. The part deflection and surface roughness are predicted using a model, which gives the quadratic output equation in terms of three input parameters called feed rate, spindle speed and depth of cut. This paper consist of two parts, prediction of surface roughness and deflection when machining a thin-wall low rigidity component that is copper and secondly, the ANOVA analysis to determine the correlation between the output variables (such as deflection and surface rough roughness) and input cutting parameters from there we found the optimum cutting conditions for thin wall machining of copper plate. Therefore, in this work, the main objective was to investigate and develop an optimum process for conventional-milling of copper thin-wall features. The scope of this work was to optimize the process parameters for conventional-milling of metallic thin-walls with application in micro-heat-sink fabrication. The experiment was conducted on copper using conventional milling machine. The results have shown that by choosing appropriate process parameters, it is feasible to successfully end-milling of a thin-wall down to the thickness of 0.5mm with the height of 2.4mm (aspect ratio of 48). The proposed model would be an efficient means for analyzing the root cause of rough surface induced during machining of thin-wall parts.*

Key Words: **Thin wall machining, Copper, Deflection, Surface roughness, Heat sink**

1. INTRODUCTION

Now a day's copper alloys are widely used in thermal industry owing to their excellent thermal and electrical conductivities. They exhibit outstanding mechanical properties and are low in cost. Therefore, Thin walls of copper-based alloys are most popular and preferred choice for heat sinks for the purpose of heat dissipation from the Semiconductor devices and computers microchips etc.,. Semiconductor devices which generate large amounts of heat during operations, as semiconductor power modules, employ heat sinks for releasing heat generated from heat producing components, such as IGBTs, computer chips etc.,. Generally aluminum will soak up more heat per weight, but copper still beats it for size/volume. So, for volume Copper will soak up 142% more heat than Aluminum. It will have half the thermal resistance at the same time. Copper will also have 2-3 times less thermal resistance than aluminum. Pure Aluminum's electrical conductivity is only 62% that of copper.

1.1 Thin wall machining Applications

- Copper heat sinks
- Aluminum heat sinks
- Composite heat sinks
- aeronautics and astronautics
- Micro drilling
- Housing and enclosures
- Adapters and connectors

1.2 Key Properties of Copper Alloys

Copper is a tough, ductile and malleable material. These properties make copper extremely suitable for tube forming, wire drawing, spinning and deep drawing. The other key properties exhibited by copper and its alloys include:

- Excellent heat conductivity
- Excellent electrical conductivity
- Good corrosion resistance
- Good bio fouling resistance
- Good machinability
- Retention of mechanical and electrical properties at cryogenic temperature
- Non-magnetic

2. LITERATURE REVIEW

Many researchers have devoted their efforts to investigate the analysis and prediction of cutting force and deflection in end milling of thin-walled work piece There were few reported work been done in predicting the deformation and surface roughness of thin-wall part. Budak and Altintas [1] used the beam theory to analyze the form errors when milling using slender helical end mill for peripheral milling of a cantilever plate structure. The slender helical end mill is divided into a set of equal element to calculate the form errors acting by the cutting forces on both tool and the work piece. Experimental investigations to study end-mill deflection and surface accuracy quantitatively are reported in [2]. These studies offer solutions to these problems, such as using the shortest possible end mill for greatest rigidity and reducing feeds for finishing cuts. Error comes from deformation of thin-walled during machining and has been largely ignored by CAD/CAM software developers.

Tang Aijun [3] predicted the part deformations are using a theoretical deformation equations model, which is established on the basis of reciprocal theorem when the linear load acts on thin-walled plates. The part deformations in end milling process are simulated by using FEM software ANSYS10.0. In the process of simulating, the influences of linear loads, location of the cutter (including x and y direction), and thickness of the plates on the deformations of the thin-walled plates are analyzed. Sadasiva Rao., et al., used Taguchi based Grey Relational Analysis in optimizing multiple characteristics during Face milling process [4]. A consistent method for the analysis of bifurcation instabilities in shells of arbitrary thickness has been proposed by Triantafyllidis N [5]., et al. Debastien Seguy [6] examine the link between chatter instability and surface roughness evaluation for thin wall milling. Garimella Sridhar [7] presented an experimental device using non-contact displacement sensors for the investigation of milling tool behavior. R. izamshah R. A., et al [8] , in their experimental study series of machining experiments were carried out using Taguchi design of experiments to find the effect of important machining parameters (speed, feed, depth of cut, width of cut, tool path layout) which influence distortion of the parts during machining.

3. EXPERIMENTATION

3.1 Taguchi Method

Classical experimental design methods are too complex and not easy to use. Furthermore, a large number of experiments have to be carried out as the number of the process parameters increases. To solve this important task, the Taguchi method uses a design of orthogonal array to study the entire parameter space with large number of experiments. The experimental results are then transformed into a signal-to-noise (S/N) ratio. The S/N ratio can be used to measure the deviation of the performance characteristics from the desired values. The categories of performance characteristics in the analysis of the S/N ratio depend upon output parameters to be controlled.

Minimum experiments = L^4+1 = 81 i.e., nearly L81.

The S/N ratio of the smaller the better characteristics can be expressed as:

S/N = −10 log 1/j. yi^2

Where,

j is the number repetition of experiments.

yi is the average measured rate of experimental data

L81 orthogonal array by carrying out a total number of 81.

3.1.1 L81 Orthogonal Array:

In L81 (3^4) array 81 rows represent the 81 experiments to be conducted with 3 columns at, 4 levels of the corresponding factor. The matrix form of these arrays is shown in Table.1

Input Factors:-

1) Speed

2) Feed

3) Depth of cut

Table1: Design of experiment (L81) is shown in

Experiment No	Factor 1(Feed)	Factor 2 (Depth of cut)	Factor 3(Speed)
1	1	1	1
2	1	1	2
3	1	1	3
4	1	1	4
5	1	2	1
6	1	2	2
7	1	2	3
8	1	2	4
9	1	3	1
10	1	3	2
11	1	3	3
12	1	3	4
13	1	4	1
14	1	4	2
15	1	4	3
16	1	4	4
….	….	….	….
….	….	….	….
….	….	….	….

Number of experiments are 81 here.

3.1.1 Taguchi L81 Orthogonal array Design Matrix:

Table2: Taguchi L81 Orthogonal array Design Matrix

Experiment No	Feed (mm/min)	Depth of cut (mm)	Speed (RPM)
1	31.5	0.1	90
2	31.5	0.1	125
3	31.5	0.1	180
4	31.5	0.1	250
5	31.5	0.1	355
6	31.5	0.2	90
7	31.5	0.2	125
8	31.5	0.2	180

9	31.5	0.2	250
10	31.5	0.2	355
11	31.5	0.3	90
12	31.5	0.3	125
13	31.5	0.3	180
14	31.5	0.3	250
15	31.5	0.3	355
16	31.5	0.4	90
….	….	….	….
….	….	….	….
….	….	….	….

Number of experiments are 81 here. Furthermore, a large number of experiments have to be carried out as the number of the process parameters increases. This is a lengthy process. So we can for factorial method which uses power factor of 2 i.e., 2^k.

3.2 Design of Experiments (DOE)

Experiments were planned in such a way that useful inferences could be obtained by performing minimum number of experiments. DOE is an analytical tool that ensures that experiments are planned and performed in such a way that the desired conclusions could be drawn with minimum number of experiments. DOE is used to determine the impact of input parameters on the output response. This can be done by using statistical techniques. If the response or yield of an experiment be designated as 'R' and the experimental input variables as 'a', then it may be written as,

$$R\,j = \Phi(a1j, a2j, a3j, \ldots, aNj) + ej$$

Where, j = 1,2,3…N represents N observations in the factorial experiment. The function Φ is called the Response Surface. The residual ej measures the experimental error of the jth observation.

3.2.1 The Quadratic Response Surface

Usually the mathematical form of Φ is not known and has to be approximated within the range of experimental parameters, using polynomial functions in 'a'. In this experiment, chosen function is in second order and ANOVA statistical methods are used for fitting the function to the experimental results obtained.

3.2.2 Central Composite Rotatable Design (CCRD)

Central rotatable composite design (CCRD) is a modified version of 2k factorial design. In factorial design of experiment a factor is assigned two values known as levels, one higher and one lower, coded as -1 and +1 respectively. That is why the design is called 2k design and the plan in this design consists of experiments done with the combination of the parameters at these two levels. A composite design is obtained by adding some extra levels called axial or star levels. This is done to make the system rotatable i.e., standard error is same for all points. A central composite design always contains twice as many star points as there are factors (i.e.2*k) in design. Out of the parameter combinations added into the 2k plan of experiment, some are the combinations where all the parameters have 0-level values. This point where all parameters have 0-level value is called as central point. A central composite design always contains twice as many central points as there are factors (i.e.2*k) in design. These are conducted to test the consistency of the machine tool in terms of output, for the same input at different intervals of experimentation on in the Central Composite Rotatable Design (CCRD) Technique table. Central Composite Rotatable Design Technique = 2k + Axial runs (2*K) + Central Runs (2*K), since in the present work number of variables, K has been taken as 3, the total experiments required to be performed is 20, i.e., (8+6+6). The design for various input parameters are shown in the table 3.

Table3. Process input parameters

Input parameter	Input range
Feed rate (F)	31.5, 40, 50, 63, 80 mm/min
Spindle Speed (S)	90,125,180,250,355rev/min
Depth of cut (D)	0.10, 0.15, 0.20, 0.25, 0.30 mm (axially) and 0.3mm (radially).
Environment	Dry

3.3 Experimental setup and procedure

3.3.1 Material selection

The work material selected for the study was Copper alloy i.e., commercial bronze-C220. The basic work piece with dimensions 90 X 40 X 3 (mm) as shown in fig 2. The cutting tool used is 3 flutes solid carbide end mill tool with 6mm diameter.

Table 4. Chemical composition

Chemical composition- Bronze C220	
Metal	**Composition**
Copper	89-90%
Zinc	Remainder
Lead	0.05% max
Iron	0.05% max

Table 5. Physical properties

Physical Properties- Bronze C220	
Property	**Value**
Density	8.80 g/cm3
Thermal conductivity	189 W/mK

Electrical resistivity	3.92 micro ohm-cm
Electrical conductivity	0.255 mega ohm/cm
Modulus of elasticity	117 kN/mm2
Co-eff. Of thermal expansion	18.36 PPM/ºC

Table 6. Mechanical properties

Mechanical Properties- Bronze C220		
Temper	**Tensile strength N/mm2**	**Yield strength N/mm2**
Annealed (Soft)	250-290	85
¼ Hard	275-345	230
½ Hard	325-395	325
¾ Hard	360-425	370
Hard	395-455	400
Extra Hard	440-495	435

3.3.2 Experimental Setup

The machining experiments were carried on conventional 3-axis vertical milling machining center as shown in figure 3. The cutting tool used is 3 flutes solid carbide end mill tool ø 6mm. The work piece was clamped from on vice which is mounted on the long horizontal bed of milling machine as shown in figure 3.

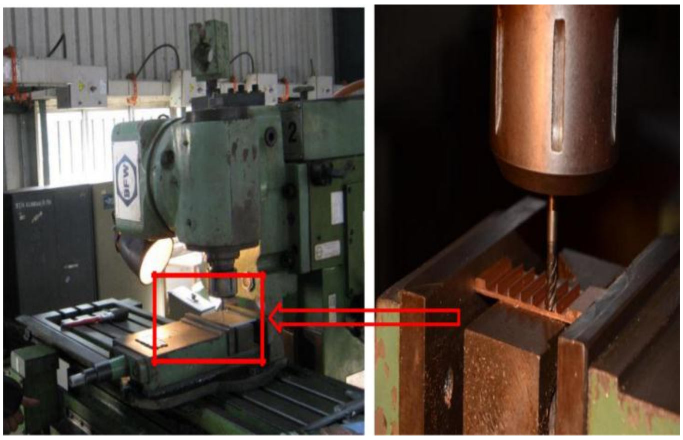
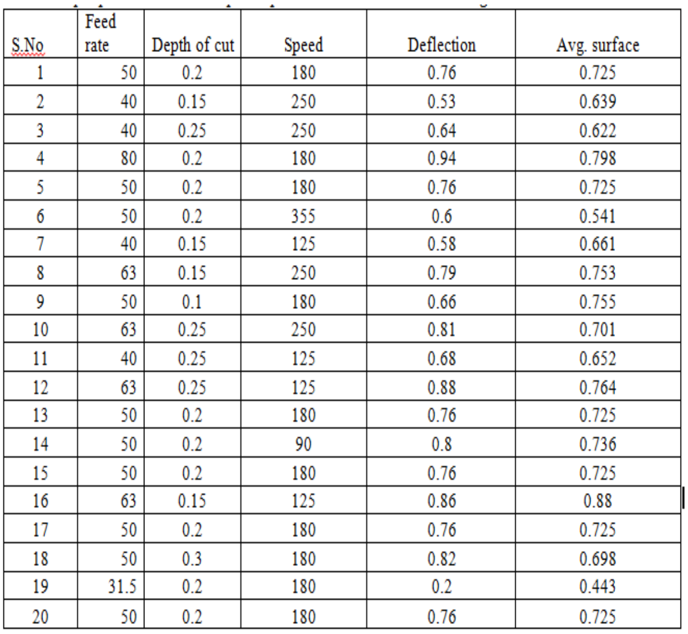


Fig. 3 An overview of experimental setup and thin wall machining zone.

The machining parameters considered for experiments are 3 factors i.e., Speed, Feed, Depth of cut (DOC) in 20 levels as shown in table 7.

Table.7 Input parameters and output response of the thin wall machining



S.No	Feed rate	Depth of cut	Speed	Deflection	Avg. surface
1	50	0.2	180	0.76	0.725
2	40	0.15	250	0.53	0.639
3	40	0.25	250	0.64	0.622
4	80	0.2	180	0.94	0.798
5	50	0.2	180	0.76	0.725
6	50	0.2	355	0.6	0.541
7	40	0.15	125	0.58	0.661
8	63	0.15	250	0.79	0.753
9	50	0.1	180	0.66	0.755
10	63	0.25	250	0.81	0.701
11	40	0.25	125	0.68	0.652
12	63	0.25	125	0.88	0.764
13	50	0.2	180	0.76	0.725
14	50	0.2	90	0.8	0.736
15	50	0.2	180	0.76	0.725
16	63	0.15	125	0.86	0.88
17	50	0.2	180	0.76	0.725
18	50	0.3	180	0.82	0.698
19	31.5	0.2	180	0.2	0.443
20	50	0.2	180	0.76	0.725

3.4 Experimental procedure

A thin-walled copper plate is being machined in a 4mm thick plate using a 6mm solid carbide end mill. Climb (down) milling is preferable for this application with a square-shoulder end mill. The wall of the plate is machined from both sides using an alternate approach as shown in fig. to reduce the deflection of the wall. For the first wall being machined, the axial depth of cut of the first cut on one side is 0.2mm. The second is done on the other side of the wall also did with the same 0.2mm axial depth of cut to maintain the uniformity of the wall. Cutting proceeds with 0.2 mm axial depth of cut until the whole 2.4 mm is machined. This process is continued for remaining walls with varied axial depth of cuts. In this whole machining process 0.3mm,0.1mm radial depth of cuts are used for roughing and finishing cuts, respectively. Finally, all the walls obtained with a height of 2.4 mm and thicknesses of 0.5mm are shown in fig 4.

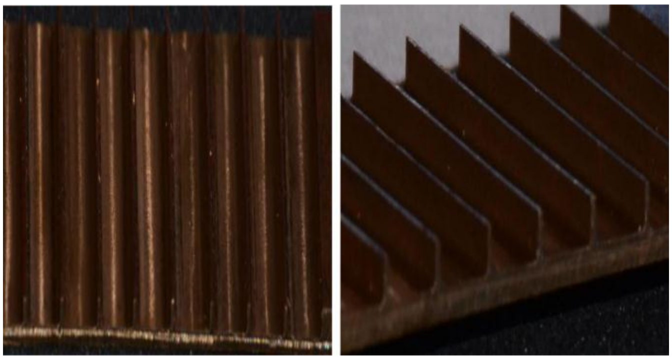


Fig.4 Machined copper thin walls

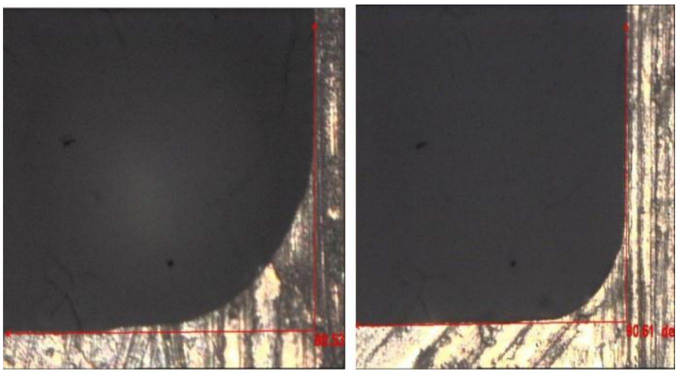


Fig.5 Optical micrographs of machined thin walls (a. Feed=40mm/min, speed=250 rpm, depth of cut=0.15mm b. Feed=40mm/min, speed=250 rpm, depth of cut=0.25mm)

The deflection is measured by using upright optical microscope. It is taken as maximum deviation from the vertical reference line as shown in figure 5. The surface roughness (i.e., R-square value) is measured by using Computerized Non-Contact Profilometer. The surface generated after machining is focused under profilometer as shown in figure 6.

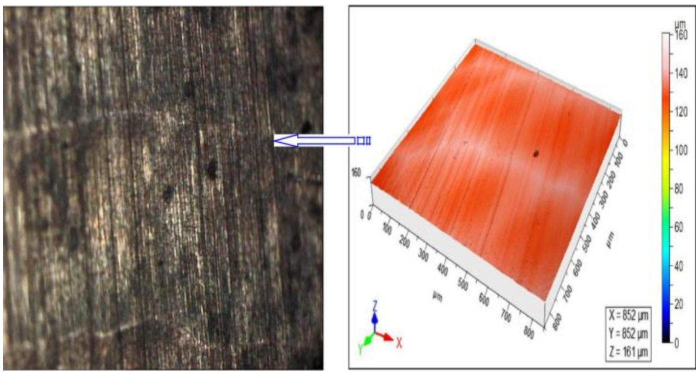


Fig.6 surface profile meter image and optical micrograph of copper thin wall

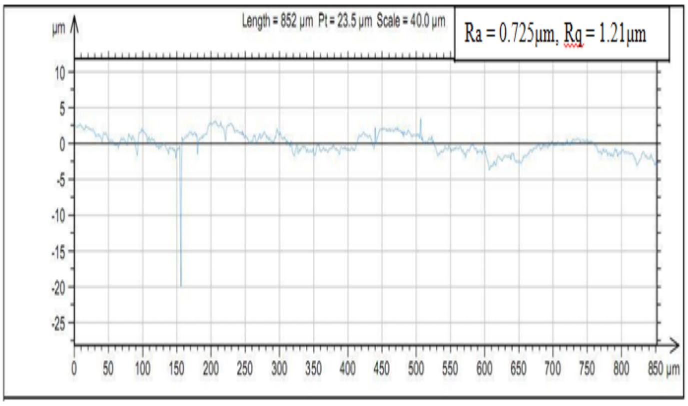


Fig.7 Surface profile of the copper thin wall

4. RESULTS VALIDATION

4.1 Validation of Deflection, Surface roughness

For the adjusted CCRD input parameters to the conventional milling machine, the deflection and the surface roughness, ANOVA was used for the regression analysis. From the ANOVA analysis, the R-square obtained for deflection and surface roughness is 0.9080, 0.9425 respectively, which indicated that the model is significant. All these evidences showed a strong quadratic relationship between the predictor variables (Depth of cut, Spindle speed and Feed rate) and the predicted variable. The results of analysis of variance (ANOVA) of the models also supported strong quadratic relationship in the model. The Model F-value of 10.97 and 18.21 implies the model for both responses is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant. Therefore, the quadratic relationship between predicted variables and predictor variables significantly existed. The coefficients of all predictor variables and constants of the models are listed. According to these coefficients, the multiple regression models for deflection and surface roughness can be written as, respectively:

Final Equation in Terms of Actual Factors:

Deflection = -1.595 + 0.063 F + 2.843 D + 8.301E-00 S - 0.037 FD - 1.562E-005 FS + 2.842E-004DS - 3.733E-004 F2 - 0.680 D2 - 1.707E-006 S2

Surface roughness = - 0.591 + 0.040 F + 0.380 D + 1.635E-003 S - 0.032 FD - 2.648E-005FS+2.079 E-003 DS - 2.089E-004 F2 + 1.170 D2 - 3.213E-006 S2

5. RESULTS AND DISCUSSION

5.1 Graphical representation and result conclusion

Figures 8 and 9 Shows the effect of feed rate on deflection with different values of the speed. By seeing the graph, as the value of the feed increases, deflection for a given values of speed also increases. Because generally increasing the feed rate reduces cutting tool life. Removing more material with this blunted tool results highly deflected thin wall.

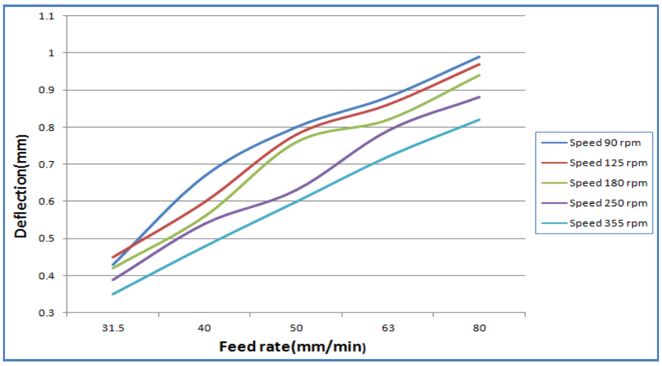


Fig.8 Variation of deflection with feed rates at different speeds

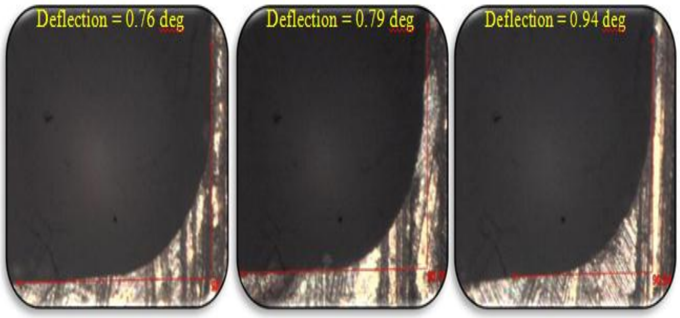


Fig.9 Optical micrographs showing deflection of machined thin walls at different feed rates

Figure 10 and 11 shows the effect of speed on deflection for different values of depth of cut. By seeing the graph, as the value of the speed increases, deflection decreases for a given values of depth of cut. As the value of speed increases cutting forces start decreasing results lower deflection of thin walls.

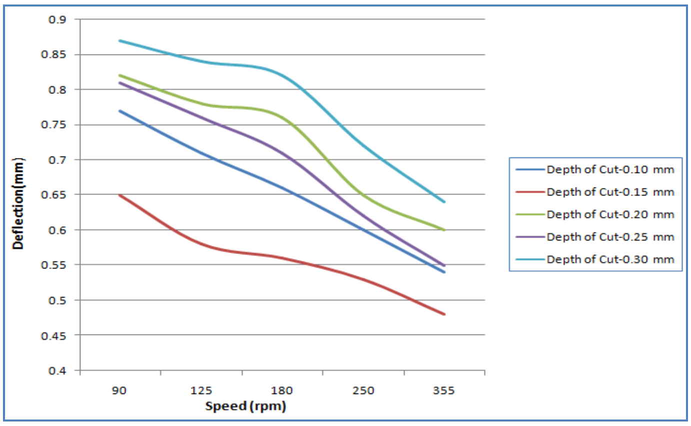


Fig.10 Variation of deflection with speed at different depth of cuts

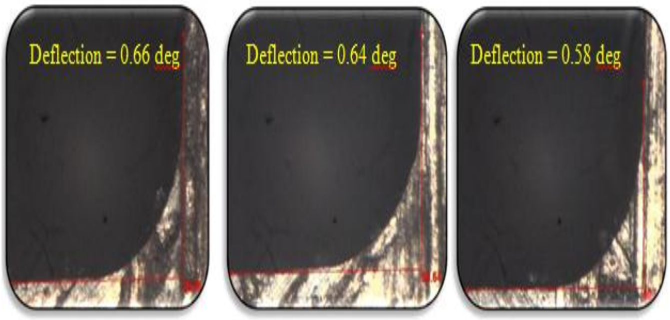


Fig.11 Morphology of deflected machined thin wall at different speeds

Figures.12 and 13.shows the effect of depth of cut on deflection for different values of feed rate. By seeing the graph, as the value of the depth of cut increases, deflection increase for a given values of feed rate. Because increasing the depth of cut can promote chatter because of higher forces. The machine tool must be rigid to withstand these forces.

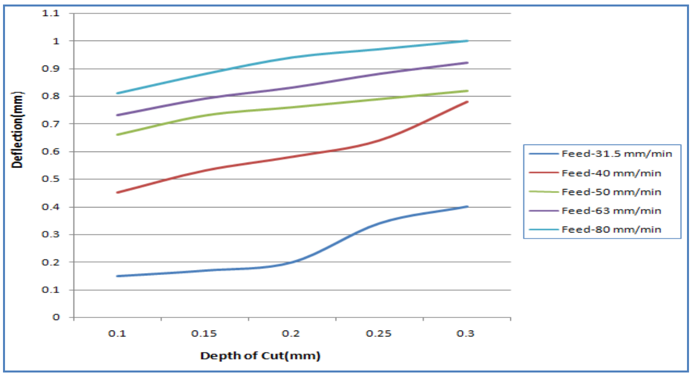


Fig.12 Variation of deflection with depth of cut at different feed rate

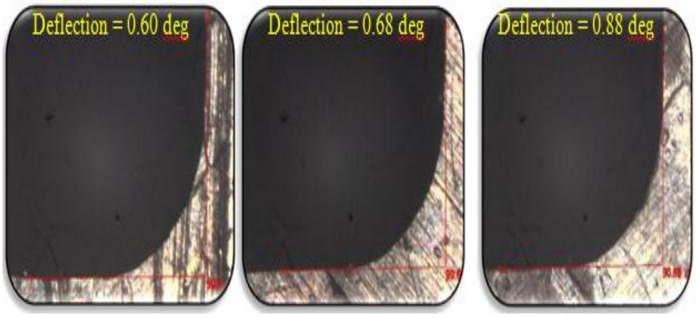


Fig.13 Optical micrographs showing the effect of depth of cut on deflection

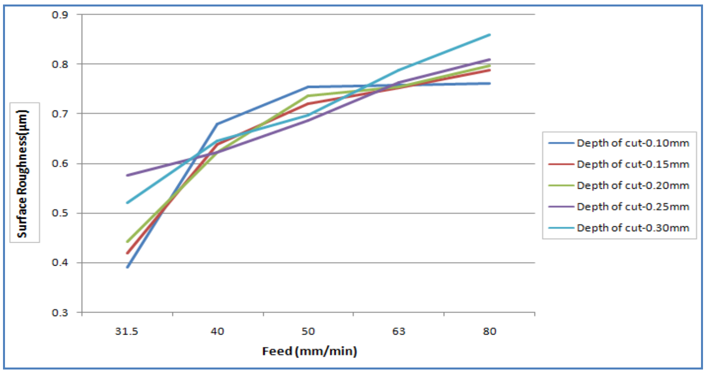


Fig.14 Variation of surface roughness with feed rates at different depth of cuts

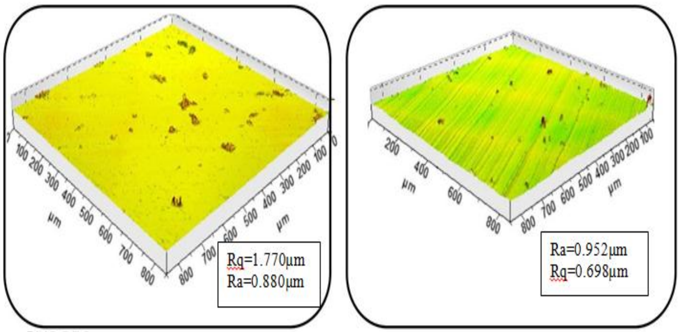


Fig.15 Surface morphology images showing surface roughness variation with feed rate

Figures.14 and 15.shows the effect of feed rate on deflection for different values of depth of cut. By seeing the graph, as the value of the feed rate increases, surface roughness also increase for a given values of depth of cut. Because of more heat generated at higher feed rates results increase in surface roughness (Ra).In fig.16 and 17 surface roughness (Ra) decreases as speed increases. Because at higher speeds generation of the heat on cutting zone reduce the built up edge formation as a result contact length between the cutting tool and chip was reduced, hence surface roughness was decreased.

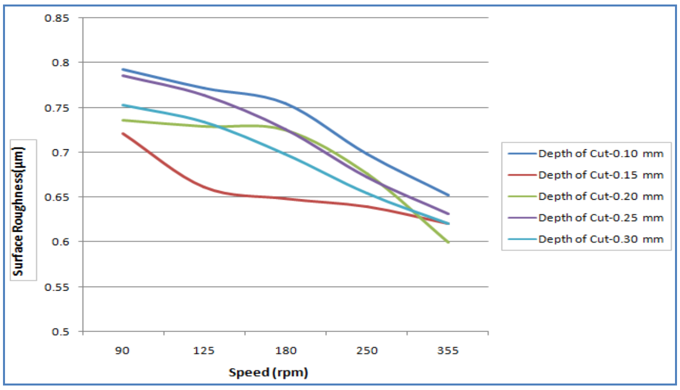


Fig.16 Variation of surface roughness with speed at different depth of cuts

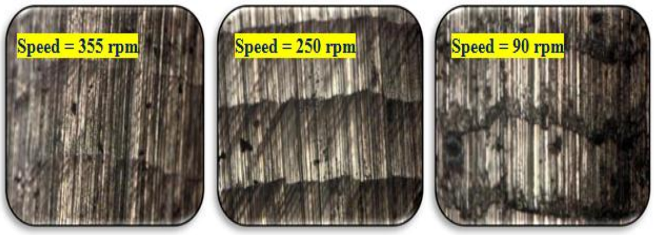


Fig.17 Surface morphology images showing surface roughness variation with speed

The effect of depth of cut with different speeds on surface roughness (Ra) as shown in Figure 18 and 19 . From the graph it is observed that if feed rate is increases surface roughness is increased at the same time as speed increases surface roughness is decreasing.

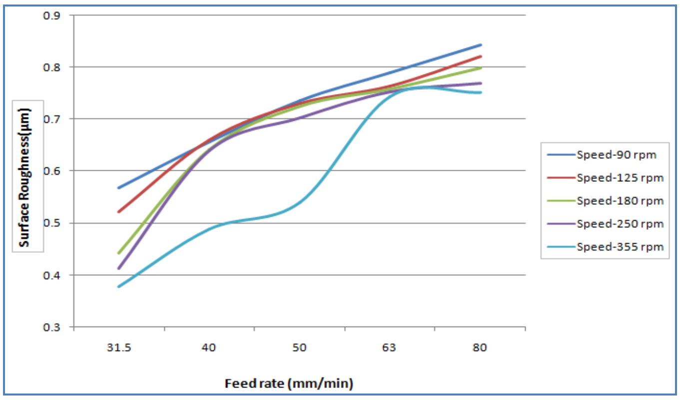


Fig.18 Variation of surface roughness with feed rate at different speeds

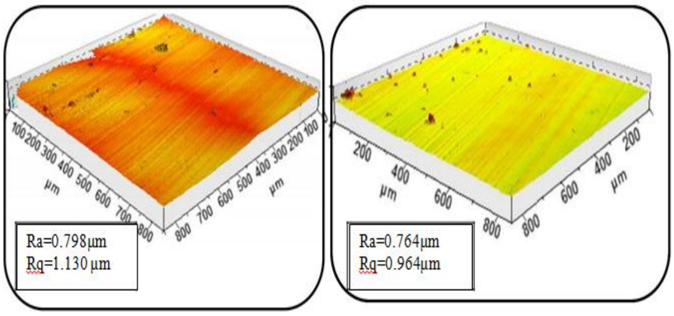


Fig.19 Surface morphology showing effect of speed on surface roughness

Fig. 20 explains the wearing of the tool flutes after the repeated machining with the same tool under dry conditions. So to reduce the tool wear and tear we need to use the suitable cutting fluids, which include oils, oil-water emulsions, pastes, gels, aerosols (mists), and air or other gases. Most metalworking and machining processes can benefit from the use of cutting fluid.

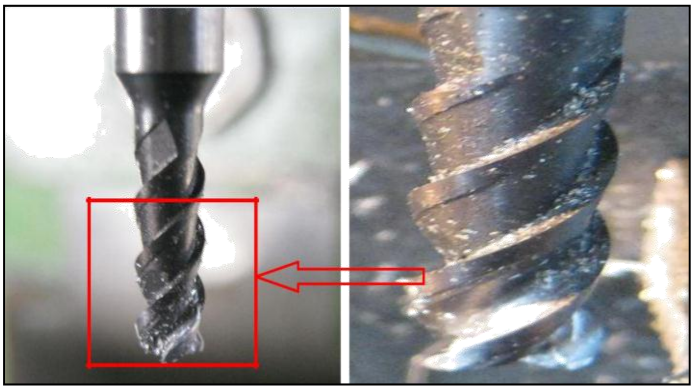


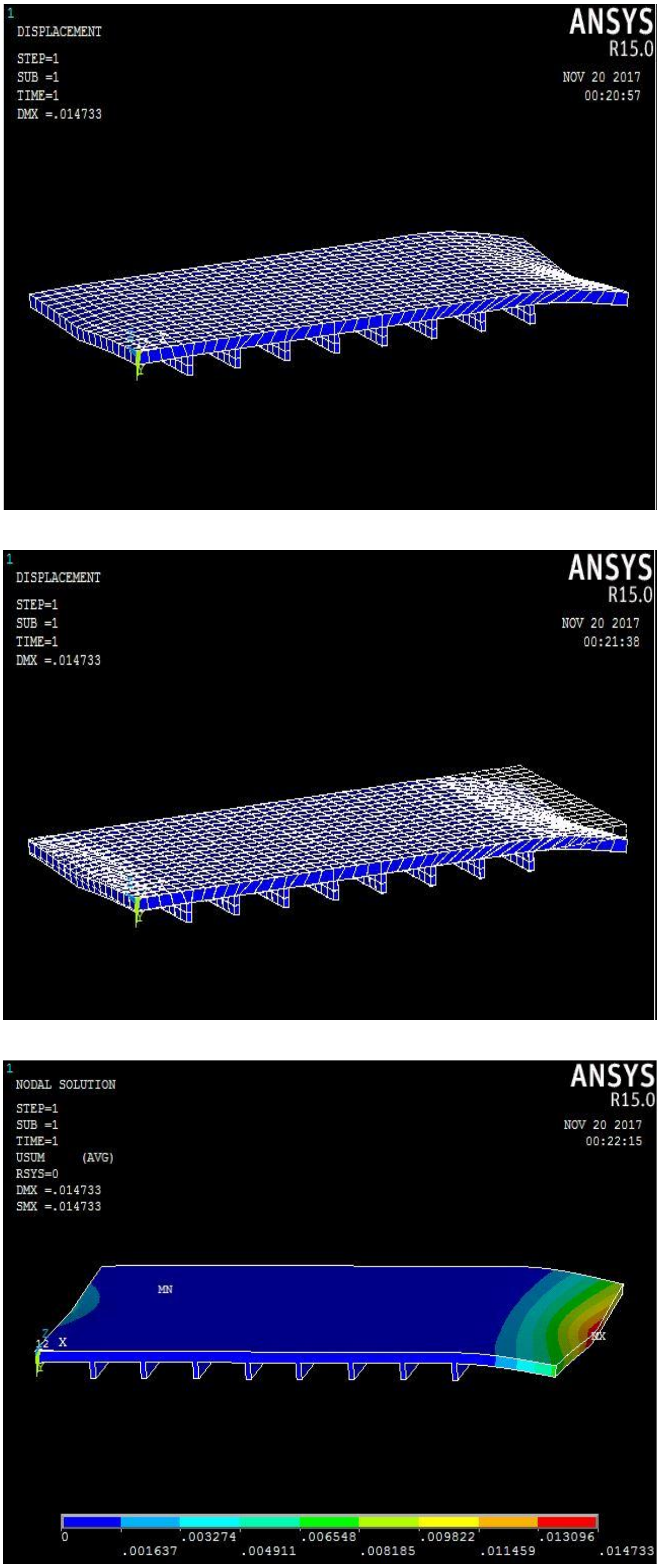
Fig. 20 Morphology showing the worn-out tool flutes

5.2 ANSYS Modeling of Thin walls base deflection

Table 8: Maximum deflection at thin wall base with different loads

S.No	Input load(N)	Maximum deflection at the thin walls base(mm)
1	20	0.014733
2	40	0.027362
3	60	0.040225
4	80	0.05293
5	100	0.065187

a) At 20N load:



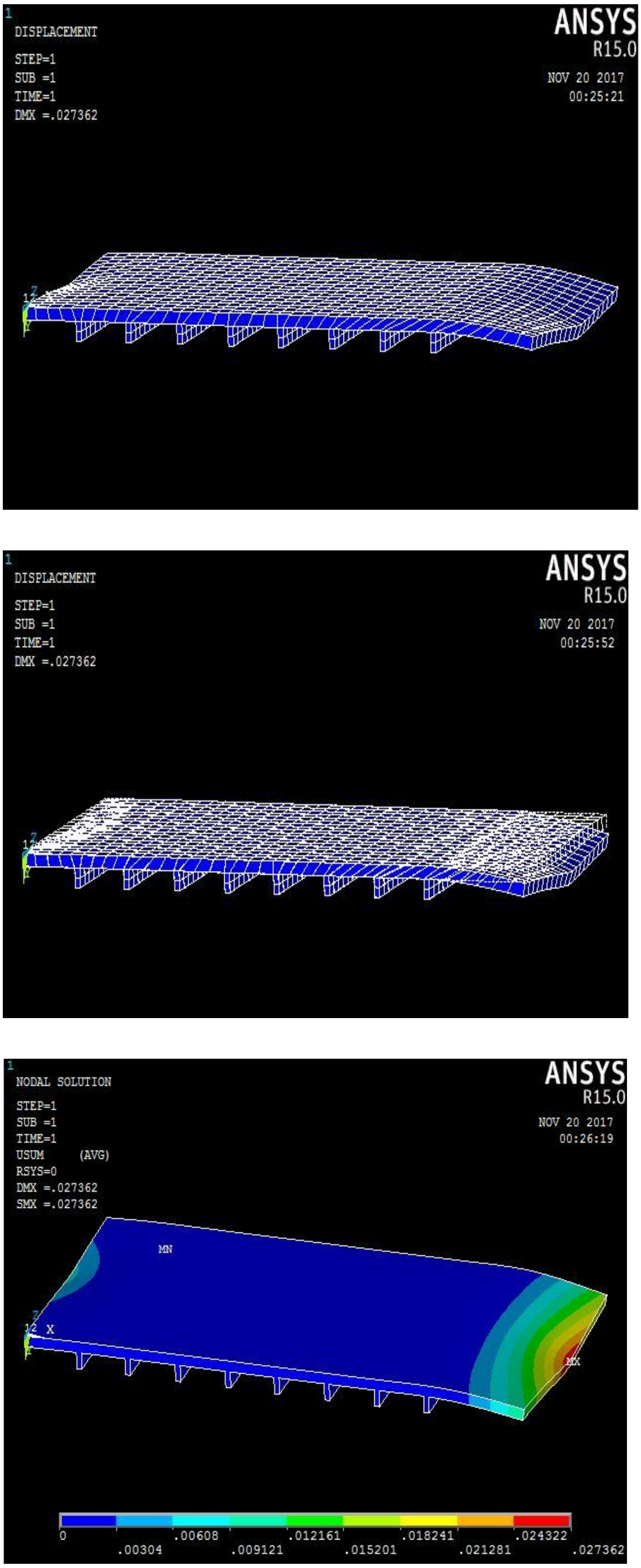
```
DISPLACEMENT
STEP=1
SUB =1
TIME=1
DMX =.014733
NOV 20 2017
00:20:57

DISPLACEMENT
STEP=1
SUB =1
TIME=1
DMX =.014733
NOV 20 2017
00:21:38

NODAL SOLUTION
STEP=1
SUB =1
TIME=1
USUM     (AVG)
RSYS=0
DMX =.014733
SMX =.014733
NOV 20 2017
00:22:15
```

Fig: 21. At 20N load maximum deflection is observed at the thin wall base is 0.014733 mm

b) At 40N load:



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DISPLACEMENT
STEP=1
SUB =1
TIME=1
DMX =.027362
NOV 20 2017
00:25:21

DISPLACEMENT
STEP=1
SUB =1
TIME=1
DMX =.027362
NOV 20 2017
00:25:52

NODAL SOLUTION
STEP=1
SUB =1
TIME=1
USUM     (AVG)
RSYS=0
DMX =.027362
SMX =.027362
NOV 20 2017
00:26:19
```

Fig: 22. At 40N load maximum deflection is observed at the thin wall base is 0.027362 mm

c) At 60N load:

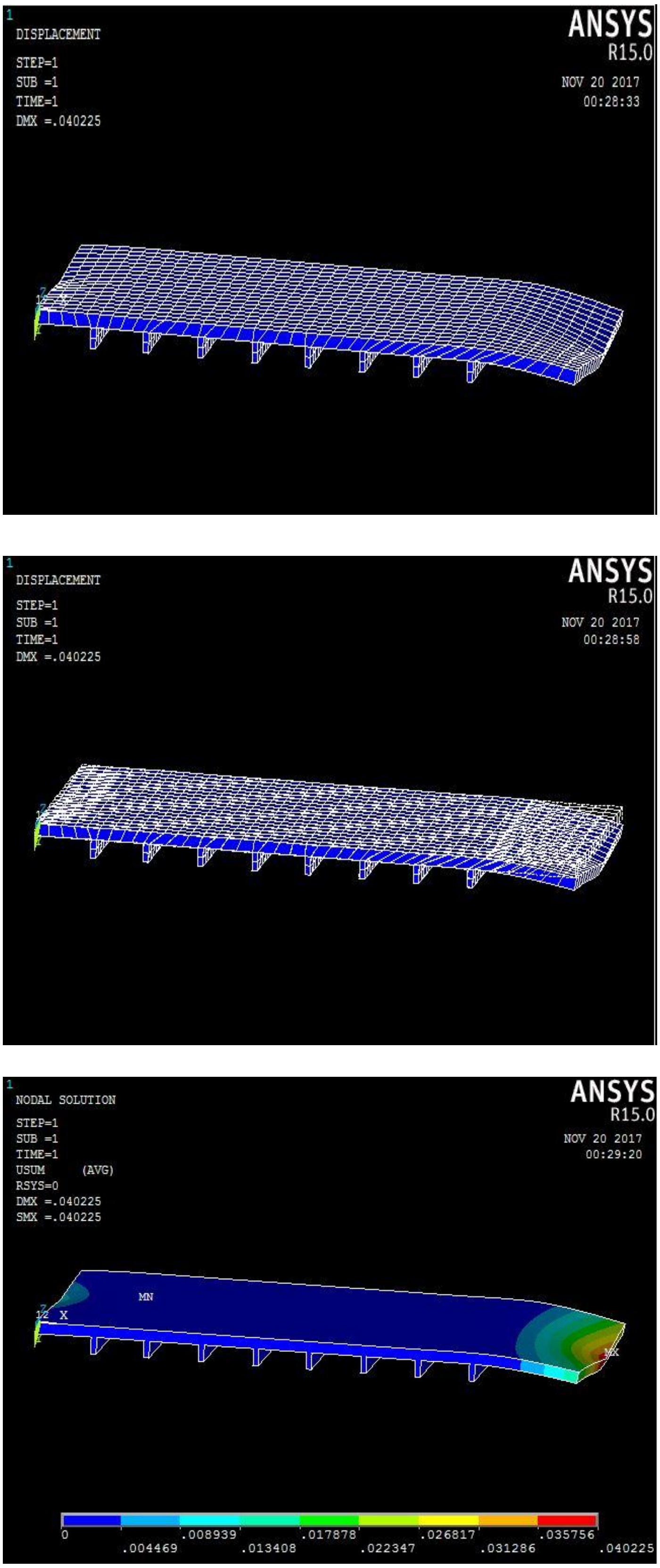

Fig: 23. At 60N load maximum deflection is observed at the thin wall base is 0.040225 mm

d) At 80N load:

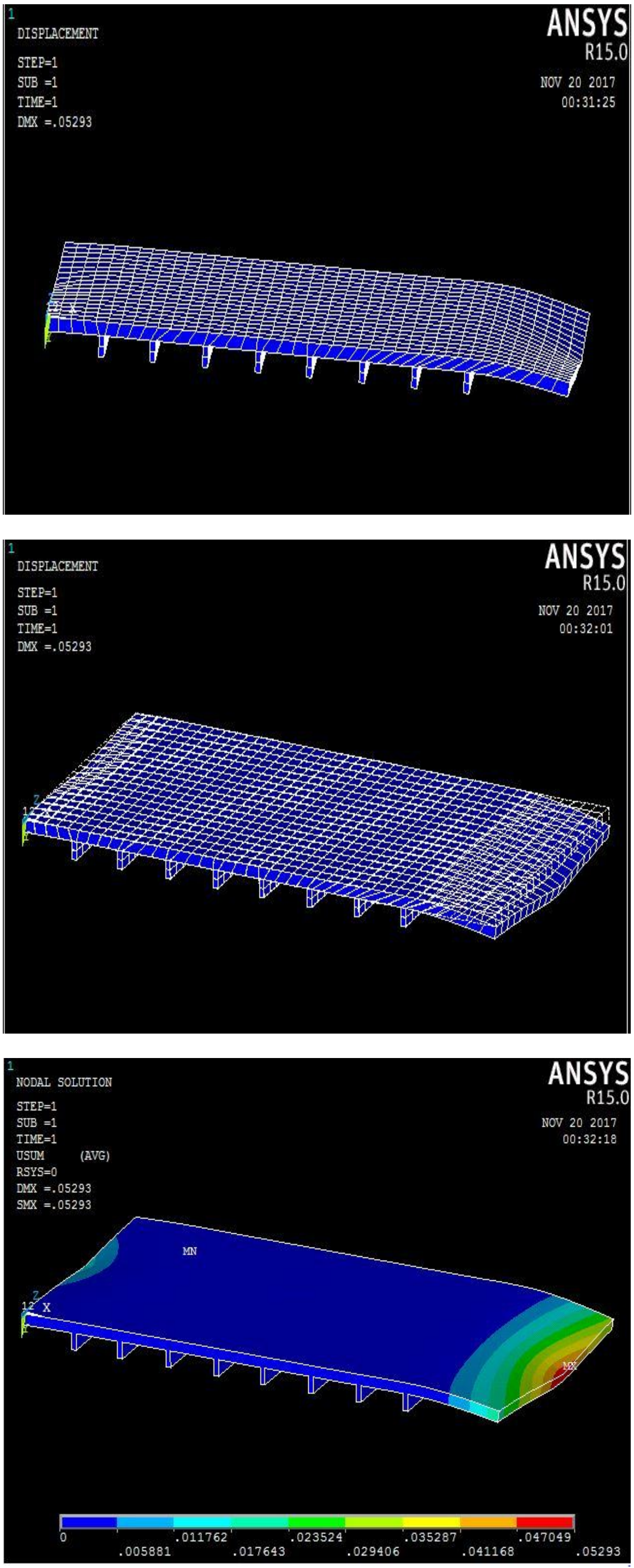

Fig: 24. At 80N load maximum deflection is observed at the thin wall base is 0.05293 mm

a) At 100N load:

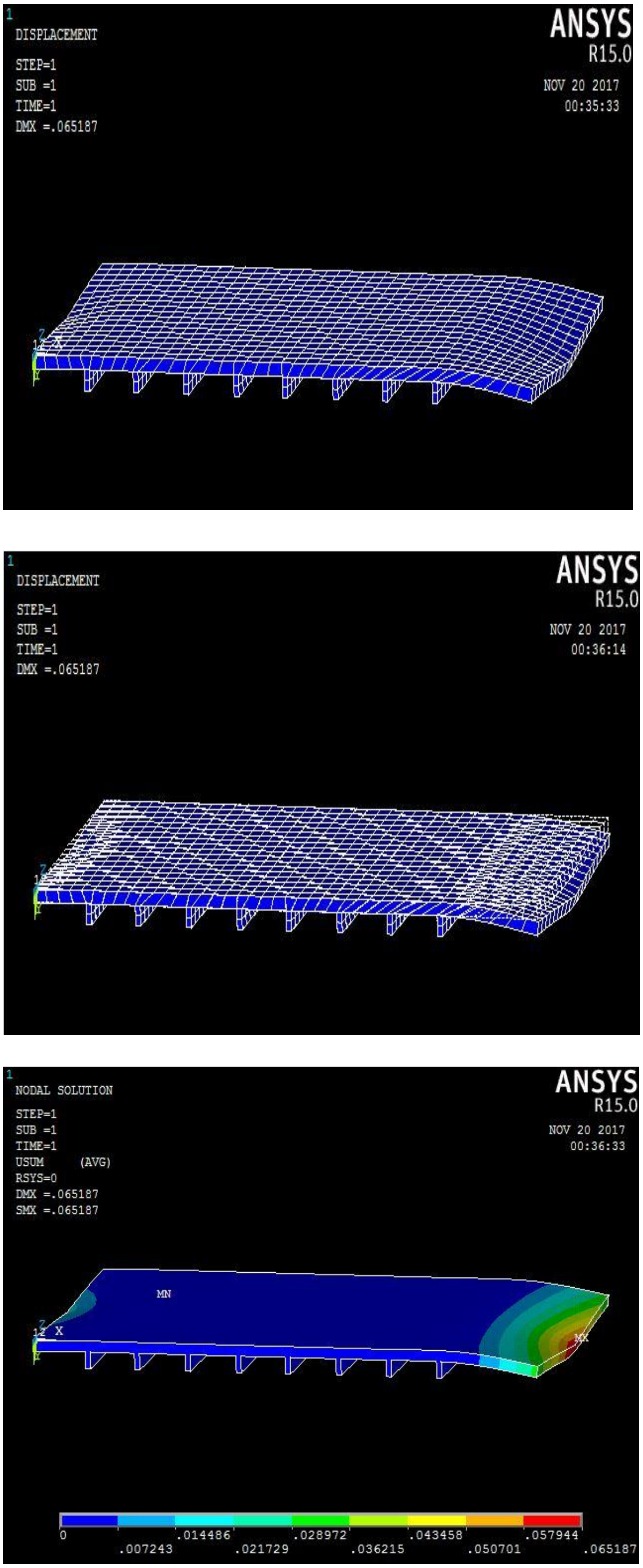

Fig: 25. At 100N load maximum deflection is observed at the thin wall base is 0.065187 mm

5.3 Results of Confirmation Experiment

Confirmation experiments were done taking the optimum factors obtained by ANOVA analysis. The results of the experiment given in table 3. It can be seen that the deflection and surface roughness of the component which are very less.

Table 9 : Optimum parameters showing less deflection and surface roughness (Ra)

Input parameters/Response		**Deflection (mm)**	**Surface roughness(Ra) (µm)**
Feed rate (mm/min)	40	0.4441599	0.496724792
Speed (rpm)	355		
Depth of cut (mm)	0.1		

CHAPTER 6: CONCLUSION

Accuracy of machined components is one of the most critical considerations for many manufacturers especially in thermal and aerospace industry, where most of the part used a thin-walled structure. Taguchi methods are statistical methods to improve the quality of manufactured goods by using a fractional-factorial approach whenever there are several factors involved and are accomplished with the aid of orthogonal arrays. It is a lengthy and time taking process. . Here a set of machining tests have been done in order to validate the accuracy of the model. In addition, results from the ANOVA analysis showed a strong quadratic relationship between the predictor variables (Depth of cut, Spindle speed and Feed rate) and the predicted variables (Deflection and surface roughness). As the feed rate changes from 31.5 to 80 mm/min, deflection rises from 0.35 to 0.95 mm and surface roughness rises form 0.48 µm to 0.93 µm at 0.1 mm depth of cut showing the effect of feed rate on deflection and surface roughness is more. In the experiments conducted it has been observed that the deflection and surface roughness found are not same in all the experiments and are varying. This is due to machining is done with the various input conditions. From the above observations effect of feed rate is more and more as compared to the other machined parameters on deflection and surface roughness. So form the graphs and the surface textures mentioned above it was that the better surface characteristics was obtained by using combinations of lower feed rates, higher speeds and depth of cuts as per as chosen cutting conditions. And also load applied at the fixing jaws on the thin walls base also will cause deflection but it very negligible even at 100N load. So we can go for machining by fixing the work piece at 100N loads also. From the Optimum cutting parameters for thin wall machining of copper the better surface characteristics was obtained by using combinations of lower feed rates, higher speeds and depth of cuts as per as chosen cutting conditions.

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