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Machining of Thin wall component on a CNC machine

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Abstract

In modern times as the industry is pushing the limits of conventional manufacturing, the product is getting more and more intricate in size and functioning. Thus,the manufacturing of such products with delicate and complex profiles has become a challenging task. This paper presents a detailed process plan to manufacture a thin walled (350 μm thick) component (diaphragm) through conventional machining for the Thirty Meter Telescope (TMT) project. The manufacturing process was accompanied by design and development of a special Fixture to hold the component. A programming strategy was also developed to counter the crown chip formation. A mathematical model is proposed for process parameter standardization. The results show that the diverse cutting parameters should be selected at each machining layer to satisfy the machining efficiency and precision in the process of machining thin-walled component.

Keywords:Thin walled plate, vacuum fixture, Toolpath optimization, programing strategy, mathematical model, turning parameters**.**

1. INTRODUCTION

With rise in the complex products in the global market, the manufacturability, accuracy and precision of such components has become a key issue. The need for close dimensional and geometric tolerance is directly proportional to the product's functional requirement. Due to thepoor stiffness of thin-wall parts, deformation is morelikely to occur during machining, which results indimensional form errors. In current industry practice,the resulting errors are usually compensated throughone or more of the following techniques: (i) using arepetitive feeding and final 'float' cut to bring themachined surface within tolerance, (ii) manual calibrationto determine 'tolerable' machining conditions,and (iii) a lengthy and expensive trial and errornumerical control validation process [1]. Thin wall micromilling is critical since cutting forces produce wall bending or vibrations which reduce the feature final quality in terms of flatness and straightness. Macro scale strategies for thin wall machining are a good starting point, but they must be redesigned in case of micromilling operations in order to cope with the low stiffness not only of features but also of toolsM. Annoni et al [2].

M. Annoni et al [3] presented thin wall micromilling of 0.4% carbon steel (C40) that evaluates two approaches for the thin wall geometrical quality improvement: a direct approach (relating process parameters, material and nominal workpiece characteristics to the workpiece quality characteristics) and a force-based approach (relating the same quantities through the cutting forces determination). The force-based approach relates the process parameters to the workpiece quality introducing physical quantities as cutting forces, which are suitable for monitoring and controlling purposes. K. Mehdi et al. [4] studied the dynamic behavior of a thin-walled workpiece during turning process and presented cutting process simulation. Min Wan et. al. [5] and Tang et al [6] worked on the prediction of static deformation and error and presented FEM study of the process. S. Bolsunovskiy et al. [7] studied the vibration phenomenon during machining and proposed FEM methods for vibration process modeling. Wang Zhao-jun et al. [8] studied the cause and effect of residual stress and simulated the process using FEA software MSC. Sebastien Seguy et al. [9] examined the link between chatter instability and surface roughness evolution for thin-wall milling.

Although various authors have presented their work on the machining of thin-walled components in the past, howeveroptimization of cutting parameter and toolpath are seldom found in the literature. The aim of this paper is to propose an iterative mathematical model to obtain the depth of cut (DOC) in each layer of machining an Invar-36 plate.

2. EXPERIMENTAL METHODOLOGY

This section describes various process steps involved and their respective process parameters to produce a thin wall diaphragm using conventional machining. The section includes Work-piece description, Fixture description, Cutting tool description, Machining strategy, Mathematical manufacturing model and Process description.

2.1 Work-piece Material

The workpiece material used to produce the diaphragms is Invar-36. It is an alloy of Iron (Fe) with approximately 36% Nickel (Ni) content, and additional alloying elements. The alloy is a single phase Face-Centered-Cubic material and has a hardness of approximate 75 HRB (Rockwell Hardness B). Due to its chemical composition, Invar-36 exhibits very low thermal expansion that is of the order of 1-2 ppm/K over a certain operating temperature range. This makes it a strong candidate material for scientific, astronomical, and other related applications where low or controlled thermal expansion is of vital importance.Due to the presence of relatively high Nickel content, machining Invar-36 poses challenges, especially with regards to tool wear and residual stresses.

2.2 Work-piece Geometric Requirements

The diaphragm is disc shaped component that measures 150mm in diameter and features variable thickness regions; a central hub; threaded holes; and slotted peripheral tabs.

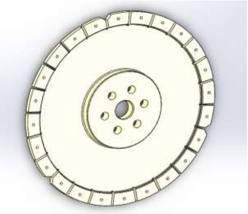

Figure 1: CAD Model of TMT Central Diaphragm

The major requirements are as follows:

- A 350µm thin membrane region that spans 35mm radially starting from ø60mm and ending at ø130mm. This region must be within a tolerance +/- 25µm.
- A parallelism requirement of 0.15 mm between the thin membrane surface and the central hub surface.
- A parallelism requirement of 0.5mm between the tab surface and the central hub surface.
- A central through hole with 14 mm diameter that has a tolerance of 27µm.
- Several other features that have a positional tolerance requirement of 0.1mm and 0.25mm
- A general surface roughness requirement of 0.8µm RMS.

These requirements make the manufacturing process a challenge. Since the diaphragm has a region of very low thickness of 350µm, it warps when it is kept in an unrestrained state. More than 80% volume of the raw material is machined to produce the diaphragm, and this leads to machining induced residual stresses which cause distortions.

2.3 Fixture Development

Given the complexity and critical geometrical requirements of the central diaphragm, and also due to machinability characteristics of Invar-36, there were several technical challenges witnessed over the course of the developmentalwork. The deflection of the membrane region (350µm thickness region) during machining was one of the major challenge faced during machining. After the Ø130-60mm membrane region had reached a thickness of 0.7mm, the membrane would not remain flat on the fixture. Due to stress induced from previous tool passes, the membrane region would buckle upwards (towards the tool) leading to extra material removal in the next cut.

To address this problem a vacuum fixture was developed to hold the part and provide necessary support to the workpiece. The vacuum fixture provided a pull force of a little more than 1000N. The vacuum fixture had several holes which provided the suction to hold the workpiece. The vacuum fixture was successful in providing the necessary holding force, howeverthe presence of holes in the fixture ended up leaving the finished part with small bubble marks. Thisproblem was resolved by designing a second version of this fixture. The second version of this fixture was designed to eliminate the issue by providing micro slots using laser machine (instead of several holes). This fixture was then tested and used to hold the work-piece and ensure that the membrane region remains flat and does not buckle during all stages of machining operations.


(a) Fixture with Vacuum holes (b) Component with bubble marks

Figure 2: Vacuum fixture with holes and corresponding deformed component

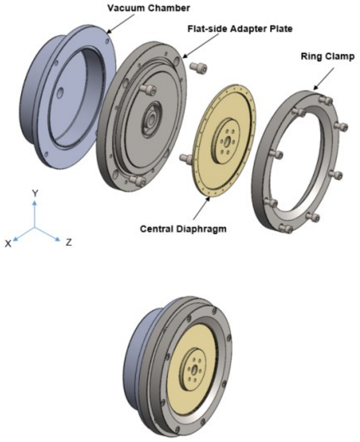

Figure 3: CAD model of vacuum fixture assembly showing exploded and assembled views

- Design of a vacuum Chamber
  The Vacuum Chamber is a one-side open circular flanged component clamped between the soft-jaws on the chuck. The closed side of the vacuum chamber is used to fasten G-type rotary union. The open-side is fastened to the diaphragm flat-side adapter plate.
- Diaphragm Flat-side Adapter Plate
  This is a circular flat component which mates with the Diaphragm Flat-side. It mates with the Vacuum chamber on its one side and with the Ring Clamp on the other side.
- Ring Clamp
  The purpose of ring clamp is to rigidly clamp the Ø150-130 mm surface of the Diaphragm Hub-side during the hub machining operation and final finishing of the Ø130-60 mm thin membrane surface.

2.4 Cutting Tools

The machining of diaphragm was widely done on the turn-mill machine by the use of following tools based on the type of profile:

Table 1: Cutting Tools

S.N.	Tool Name	Tool description
1	SVPBR-VBMT08R	Right hand cutting tool with 0.8mm nose radius
2	SVPBL-VBMT08R	Left hand cutting tool with 0.8mm nose radius
3	SVPBR-VBMT02R	Right hand cutting tool with 0.2mm nose radius
4	SVPBL-VBMT02R	Left hand cutting tool with 0.2mm nose radius
5	1.6 drill	For Ø1.6mm hole
6	82° chamfer tool	For 82° chamfer
7	1.5 thread mill	For M2 threading
8	60° chamfer tool	For 60° chamfer
9	5.2 drill	For Ø5.2mm hole
10	4.8 thread mill	For M6 threading

2.5 Machining Strategy

Due to metallurgical and mechanical properties of Invar-36 material, the long and continuous chips tend to entangle with the tool and form a 'nest' thus causing serious problems while machining. This damages the tool as well as the finished work-piece surface. During the roughing operation chip crown formation leads to severe tool damage.

This problem of 'nest' formation in the proximity of the tool and work-piece was overcome by developing a special purpose roughing toolpathstrategy (with invention disclosure). This resulted in reduce tool load and wear by improving chip evacuation.

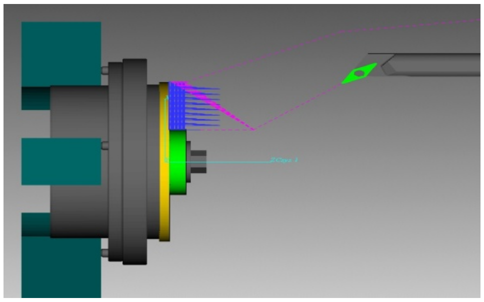

Figure 4: Optimized tool path for roughing operation

2.6 Mathematical Manufacturing Model

The turning was performed in various steps. Each step had a fixed Depth of Cut (DoC) and pre planned number of turning passes (n). This under ideal case should result in material removal, equal to DoC times the number of passes (n). The actual material removed can be calculated by measuring the surface coordinates of the work pieceafter each turning step. However, due to various non-ideal reasons, the amount of material removed would be different from the ideal value. This could be corrected in subsequent turning steps based on the feedback from the measured thickness of the workpiece.

The measured surface coordinate of the workpiece can be represented by a real valued function capital Z(r, ϴ, t).This function provides an access to the measured data z (the axial coordinates of the surface of the workpiece) for a given r, ϴ (based on the cylindrical coordinate system) and *t*. The value*t*represents the number of turning steps with *t* =0 representing the initial set of measurement before turning. By accordingly varying r, ϴ and t, one can (in principle) retrieve all possible values of z. However, the measurements were performed on only one value of r and 8 equally spaced ϴ values as given below:

Z ϵ set of real numbers
r ϵ {48}
ϴ =(n-1) π/4 for n ϵ {1,2,3,4,5,6,7,8}
t ϵ set of whole numbers

Let the total material removed after t steps be represented by y_nom(t) and let the actual material removed after t steps be represented by y_act(t).Then it can be shown that:

$$y\_nom(t) = \sum_{k=0}^{t} DoC(k) * n\_act(k)$$

And

$$y\_act(t) = \frac{1}{8}\sum_{n=0}^{8}\left\{Z\left(r = 48, \Theta = \frac{(n-1)\pi}{4}, t\right) - Z(r = 48, \Theta = \frac{(n-1)\pi}{4}, 0)\right\}$$

Where, DoC(k) represents the depth of cut at kth turning step and n_act(k) represents the actual number of turning passes at the kth step.

The deviation y_dev(t) in the material removed would be given by the difference of the two:
y_dev(t) = y_nom(t) – y_act(t)

Then, for the next step (i.e. step number t+1), the number of passes can modified to n_act(t+1) as given below:

n_act(t+1) = n(t+1)+[y_dev(t)/doc(t+1)]

Where the square bracket [ ] represents the greatest integer function and doc(t+1) is the depth of cut for the t+1 step as per the manufacturing plan. It should be noted that n_act(t+1) could be greater than or smaller than planned number of passes n(t+1).

This procedure would correct the deviation in thickness up to a value of depth of cut (DoC(t+1)). However, in the last turning step (the finishing step) it is not sufficient to be able to compensate for the deviation up to a whole number multiple of the depth of cut since the remainder may be very large (as compared to the required tolerance) to be ignored (although less than the DoC). Hence, a variable depth of cut strategy was invented and followed for the last (finishing) turning step.

In general, the DOC of a finishing operation cannot be arbitrarily set and is dictated by several other process conditions. Hence in general there would be a min. limit for the DOC **(doc_min(tf))** and a max. limit of DOC **(doc_max(tf))**.

The actual DOC (doc(tf)) as per the process plan would lie in between these two extreme limits. The term tf indicates the final finishing step. The compensation of the deviation y_dev(tf-1) in the final step can be achieved by a two partstrategy:

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Part I: The first part is to change the number of finishing passes as per the previous equation so as to have an effective deviation less than the final DoC(tf). As before, this is given by

n_act(tf) = n(tf)+[y_dev(tf-1)/doc(tf)]

However, as discussed this will lead to a residue

res(tf) = y_dev(tf-1) - doc(tf) * [y_dev(tf-1)/doc(tf)]. This Residue is compensated in Part II.

Part II: This Residue can be compensated by the variable depth strategy as follows:

Case 1: If res(tf) ≥ doc_min(tf) then add one more pass (over and above n_act(tf)) with DoC = res(tf). It should be noted that res(tf) will always be less than doc(tf) and positive.

Case2: If res(tf) <doc_min(tf) then again there are two possibilities:

Case a: res(tf) + doc(tf) ≤ doc_max(tf) then modify the last depth of cut of the finishing step (i.e. for n_act(tf) th pass) to res(tf) + doc(tf).

Case b: res(tf) + doc(tf) >doc_max(tf); then modify the last two depth of cuts (i.e. for pass n_act(tf)-1 and n_act(tf) pass) to res(tf)/2 + doc(tf).

3. RESULTS AND DISCUSSION

In the process of manufacturing the Invar-36 diaphragm, the main task was to achieve the final thickness of 0.35mm within given close tolerance along with other geometrical and dimensional aspects. The task was quite complicated mainly due to the unusual behavior of the workpiece material. The process went through several trial before achieving the final thickness of 0.35mm by optimizing manufacturing process including fixture design and toolpath optimization.

Design of fixture has played major role in achieving the desired geometrical accuracy of the thin walled surface by providing a uniform clamping force without any surface deformation (as shown in Fig. 2).

The use of optimized toolpath for roughing operation (as shown in Fig. 4) enables timely evacuation of chips which would otherwise result in formation of nest around the tool-workpiece engagement eventually resulting in surface damage and high tool wear due to abrasive nature of chips.

Mathematical model which was developed for depth of cut compensation helped in machining away the residual stock that is left after each machining operation due to non-ideal machining conditions. This model basically helped to keep in check the thickness of the material after each machining operation throughout the manufacturing of the diaphragm.

In the process of machining thin-walled delicate profile the diaphragm went through a no. of trials before standardizing the final set of cutting parameters.

4. SUMMARY AND CONCLUSION

In the manufacturing of thin-walled diaphragm by conventional machine many issues were encountered due to abnormal behavior of the workpiece. The issues were addressed time to time by taking several measures. Design and development of Vacuum fixture is an effective method for reducing the deformation, vibration, buckling of the component and improve the holding and machining accuracy. The issue of chip entanglement and nest formation was solved by development of a special purpose toolpath.

The paper also reports the mathematical model which can be used to address the issues of leftover or overcut stock after each finishing operation. The model provides DOC compensation to be used for subsequent machining operations.

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