# Deflection Prediction of Aluminum Alloy7075 of a thin Walled Component and Optimization of Parameters

Muhammad Qasim, Lei he, and Hu Xiao

***Abstract*—**Accuracy of machined components is one of the most critical considerations for many manufacturers especially in aerospace industry where most of the part used a thin-walled monolithic structure. However, because of the poor stiffness of thin-wall part, deformation is more likely to occur in the machining process. The paper proposed for mainly predicting the mean cutting force by mathematical model and statistical analysis. In this study, to response the Surface Methodology is used by the determination of average cutting forces at different feed rate in tangential and radial directions per tooth. This model and analysis is useful for predicting and selecting optimum process parameters for the stability of end milling process, also deflection prediction for the thin wall part and dimensional error. Secondly a new method Deflection prediction during machining thin walled features with reduced analysis time from days to hours.

***Keywords*—** Aluminum alloys, Deflection prediction, Thin-wall part

## I. Introduction

IN the modern manufacturing processes, there is a continuous demand for higher productivity and product quality asks for better understanding and control of machining processes by reducing machining time with the increase of cutting force and material removal rate. Many of these complex shaped components have the characteristics of thin wall monolithic parts that are machined out of one large Aluminum block. Thin-wall machining of monolithic parts allows for higher quality and precise parts in less time, impact business issues including inventory and Just-In-Time (JIT) manufacturing. Due to the poor stiffness of thin-wall parts, deformation is more likely to occur during machining, which results in dimensional form errors [2].

The first objective of the paper is to develop is a reliable method for predicting cutting forces for arbitrary process conditions by a mathematical model [1]. These developed models are very useful for the users to predict the cutting force components in all the directions for the proposed values of input variables, to select an optimum combination of input variables for the optimum cutting force condition and to automate the milling process through the development of a computer program.

The Second objective is to apply the developed deflection prediction model for the optimization of machine parameter like feedrate, cutting speed, axial depth of cut and radial depth of cut and analyze their effects. Optimize the material removal rate and to improve the surface dimensional error.

## II. Hybrid Modeling And Simulation System

The system consists of several models, namely, the machining load computational model, the feature-based geometry model, the material removal model, the deflection analysis model. The MATLAB software is used in machining load computational model, while other models are implemented using modules of the CATIA V5 software including Mechanical Design, Advanced Meshing, and Generative Structural Analysis. The simulation is performed by automating the task by modeling solid object, material removal, and deflection analysis with CATIA V5. Finally, the methodology is validated with a set of machining tests. In the following sections, we will describe the models in the system.

### *A. Material Removal Model*

To model the material removal process, first, the created master component from the Feature base geometry model is called. Using the CATIA sketcher workbench, a sketch of cutter geometry starting with the circle profile is created on top of the master component plane. Once the cutter starting location is defined, by using the Sketch-Based Features (Pocket)' the materials in the master component which is coincidence with the cutter shape are deleted. The first material removal model is saved as a new *.CATPart* file.

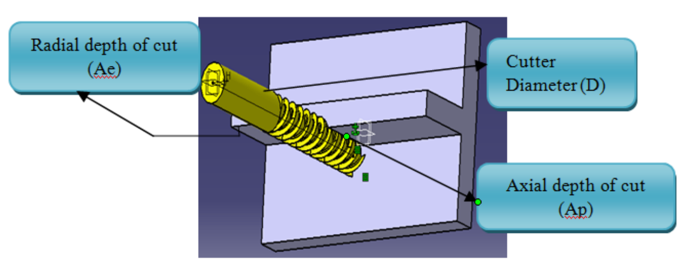


Fig. 1 Cutter profile transformation for modeling the material removal process for T-Shape Component

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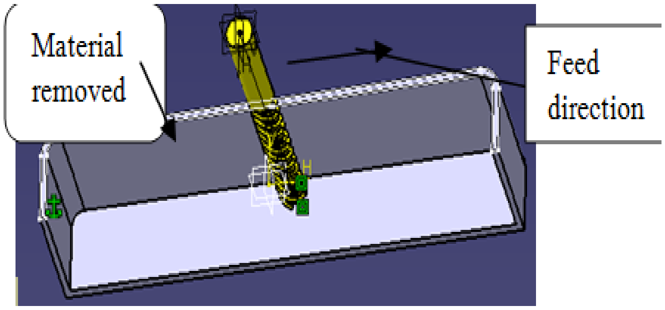


Fig. 2 Corner model of thin wall component

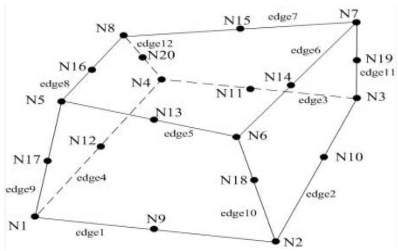


Fig. 3 Parabolic hexahedron solid element

### B. Deflection Analysis Model

catia.CATPart file is sent to the CATIA Generative Structural Analysis module to perform a static analysis for part deflection. At this phase, analysis information such as nodes, elements, material properties, boundary conditions, and the calculated machining load will be input to calculate the deflection. The structure of the thin-wall part is modeled with the three-dimensional 20 node parabolic hexahedron solid element shown in Fig. 3 and Fig. 5. For the three dimensional element, each node has three degrees of freedom, i.e. the three displacements (dx, dy, and dz). The displacements within each element are interpolated by the nodal values [1]. Fig. 2 shows the thin-wall component model for deflection calculations.

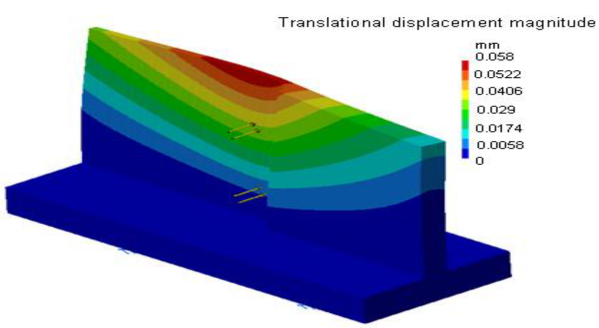


Fig. 4 Sample window shows the FEA results of the displacement values

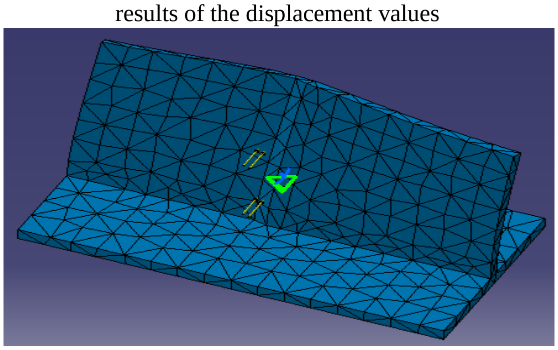

Fig. 5 OCTREE 3D isoparametric-parabolic tetrahedron mesh

## III. Cutting Force Prediction For Helical Cutting Tool And Multiple Regression Analysis

In this study, also deals with the application of response surface methodology (RSM) in developing mathematical model. With a view to achieving the above mentioned aim, Least Square method was used to calculate the average cutting to make cost effective and efficient by using Excel and Matlab to solve calculations.

Reference [13] show that five independently controllable factors affecting the cutting force and surface error were identified as the Axial depth of cut (Ap), Feed rate (f), Cutting speed (n) and Radial depth of cut (Ae). The Experiment has been conducted by milling the Al 7075 material, using Carbide end mill cutter with 12mm and 16mm diameter with a workpiece divided into three levels 1, 2, 3 in a Deckel Vertical Machining Centre [11], [12]. The level has different machining parameters as shown in Table I. The cutting force components in feed, tangential, and radial directions have been measured with a Piezo-electric three-component dynamometer (Kistler, type 9257B), a multi channel charge amplifier (Kistler, Type 9403) and a data acquisition system. Before starting each experiment the gauges have been used to set the tool height. To obtain data uniformly from all the regions of the selected working area, some selected machining parameters at different levels were selected. The secondary parameters that have been kept constant during the machining process are tool geometry, the tool height and hardness of the material. The experiments are planned as per the outline RSM method.

### A. Conducting the Experiment, Recording and Responses

The process parameters such as cutting speed (n), feed (f), Axial depth of cut (Ap) and Radial depth of cut (Ae) of Al 7075 were identified as the main factors influencing the responses cutting force component in feed, tangential, and radial directions. The selected factors and their levels are shown in Table I. The Experiment has conducted by milling the Al 7075 on a vertical Milling machine.

TABLE I
MACHINING PARAMETERS AND AVERAGE CUTTING FORCE AT EACH LEVEL 1,2,3

| Parameter | Unit | Notation | Level 1 | Level 2 | Level 3 |
|---|---|---|---|---|---|
| Feed rate | mm/tooth | f | 0.12 | 0.08 | 0.04 |
| Cutting speed | rpm | n | 16000 | 11000 | 7000 |
| Height | mm | h | 25 | 25 | 25 |
| Wall thickness | mm | a | 3 | 2 | 1.5 |
| Cutter diameter | mm | D | 16 | 16 | 12 |

### B. Mathematical Model

A mathematical Model developed to calculate the cutting force is as following by using the Least Square method as following.

$$A = \begin{bmatrix} Cp & Ap & Ae & f & n \\ 1 & a_{11} & a_{12} & a_{13} & a_{14} \\ 1 & a_{21} & a_{22} & a_{23} & a_{24} \\ 1 & a_{31} & a_{32} & a_{33} & a_{34} \\ 1 & a_{41} & a_{42} & a_{43} & a_{44} \\ 1 & a_{51} & a_{52} & a_{53} & a_{54} \\ 1 & a_{61} & a_{62} & a_{63} & a_{64} \end{bmatrix} \quad (1)$$

$$F = \begin{bmatrix} F_{11} \\ F_{21} \\ F_{31} \\ F_{41} \\ F_{51} \\ F_{61} \end{bmatrix} \quad (2)$$

The matrix A contains the values of Ap, Ae, f and n respectively and in matrix F there are the mean values of Cutting Force.

The above matrix was used with the following the mathematical formula.

$$F = Cp \cdot a_p^{\alpha} \cdot a_e^{\gamma} \quad (3)$$

As Cp, α and γ are constant

β= Cp α γ (4)

The empirical formula can be developed by this method as

F= A β (5)

Using the least square method it it is said

A' A β = A' F (6)

By this procedure we can calculation of the values of α, γ and Cp are done and put into the formula using (2) by using Matlab Software to calculate the mean value of cutting force in the specific level.

### C. Design Matrix Layout

A box design matrix shown in Table II consisting of 18 sets of conditions were selected after doing the experiment. This used central face, side face inside the cavity named three different levels [12].

TABLE II
SELECTED PROCESS PARAMETERS FOR ANALYSIS

| Test | Ap(mm) Axial depth of cut | Ae(mm) Radial Depth of Cut | f(mm/tooth) Feedrate | n(rpm) Cutting Speed | Fx Tangential Cutting Force | Fy (N) Axial Cutting Force |
|---|---|---|---|---|---|---|
| 1 | 5 | 0.5 | 0.12 | 16000 | 287.827 | 111.8164 |
| 2 | 3 | 1.5 | 0.12 | 16000 | 270.5892 | 87.5346 |
| 3 | 3 | 0.5 | 0.12 | 16000 | 173.7264 | 104.9804 |
| 4 | 4 | 1.5 | 0.12 | 16000 | 355.4688 | 236.023 |
| 5 | 5 | 1.5 | 0.12 | 16000 | 394.48 | 97.778 |
| 6 | 6 | 3 | 0.12 | 16000 | 569.3726 | 93.0664 |
| 7 | 3 | 1.75 | 0.08 | 11000 | 120.5439 | 150.4212 |
| 8 | 3 | 0.25 | 0.08 | 11000 | 73.4592 | 117.0105 |
| 9 | 4 | 1.75 | 0.08 | 11000 | 118.9941 | 163.7207 |
| 10 | 7 | 3 | 0.08 | 11000 | 320.076 | 208.7554 |
| 11 | 8 | 1.75 | 0.08 | 11000 | 284.4086 | 259.9914 |
| 12 | 8 | 3 | 0.08 | 11000 | 243.1488 | 176.3306 |
| 13 | 3 | 3.5 | 0.04 | 7000 | 110.8093 | 95.306 |
| 14 | 3 | 1.25 | 0.04 | 7000 | 81.9397 | 77.1332 |
| 15 | 3 | 0.25 | 0.04 | 7000 | 46.2647 | 37.3078 |
| 16 | 5 | 3.5 | 0.04 | 7000 | 272.3847 | 102.6077 |
| 17 | 6 | 1.25 | 0.04 | 7000 | 101.074 | 74.3179 |
| 18 | 8 | 0.25 | 0.04 | 7000 | 56.9458 | 32.4504 |

These values are entered in (3) to obtain the constant values and to calculate the mean cutting force. This is done by using Matlab software. The values of constants are shown in Table III. Also, the cutting forces calculated are shown in Table IV.

TABLE III
FOR THE VALUES OF CONSTANTS

| Symbol | Level 1 | Level 2 | Level 3 |
|---|---|---|---|
| Cp | 4.808 | 4.481 | 4.2983 |
| α | 0.745 | 0.6289 | 0.3114 |
| γ | 0.282 | 0.1492 | 0.4961 |

TABLE IV
MEAN CUTTING FORCES AT EACH LEVEL

| Level 1 F1(N) | Level 2 F2(N) | Level 3 F3(N) |
|---|---|---|
| 138.2056 | 115.05 | 75.973 |

### D. Direct Effect Process Parameters

Fig. 6 and Fig. 7 indicates that the tangential and radial components ( $F_x$ , $F_y$) varies by changing the range of Axial depth of cut (Ap), feed rate (f), cutting speed (n) and Radial depth of cut (Ae) with the given values as shown in table I. The effect of feed rate is observed to be predominant and the cutting speed and Radial depth of cut is having linearity effect on tangential cutting force component.

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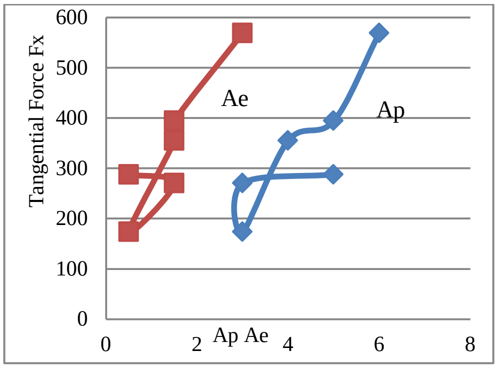


Fig. 6 Process parameters Ap,Ae and tangential force Fx

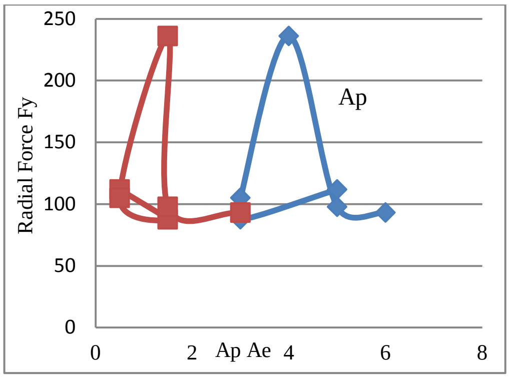


Fig. 7 Process parameters Ap,Ae and radial force Fy

Cutting force in tangential direction increases with increase in depth of cut. The rate of increase in force components with the increase in higher speed and feed rate is predominant. The cutting forces are found to be low in radial and tangential directions, when the cutter of 12mm was used as compared to the 16mm diameter. The cutting force components are more sensitive in the high speed and full immersion condition. Table I, show that as the tool diameter is reduced the cutting force is reduced. This calculation of the cutting force is not only useful in predicting part deflection as well can be used for calculate the surface form errors. The responses can be effectively controlled by substituting appropriate values of the process variables in to the mathematical model developed.

### *E. Part Deflection Validation*

In order to verify the predicted part deflection, a similar set of cutting experiment have been carried out. A number of simulations and experiments have been carried out to demonstrate the capabilities of the model. The results of the simulations are explained by the following graphs.

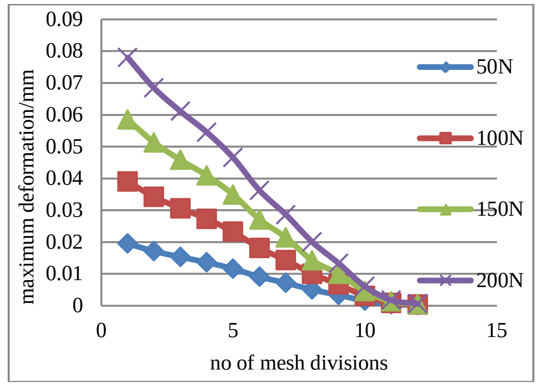


Fig. 8 Influence of linear load of 50,100,150,200 on thin walled part

As it is seen by the Fig. 8 as the cutting force of the model is increased the deformation is decreased.

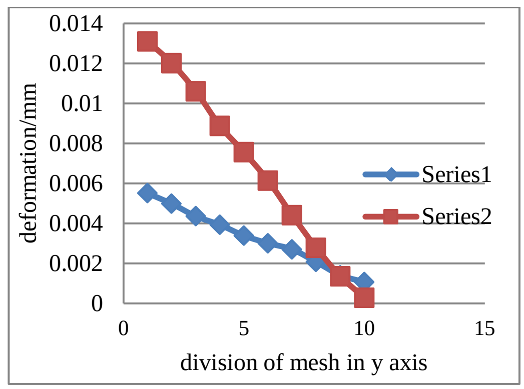


Fig. 9 Influence of deformation in the corner 6(series 1) prediction and 101(series 2) mm on the thin plate.

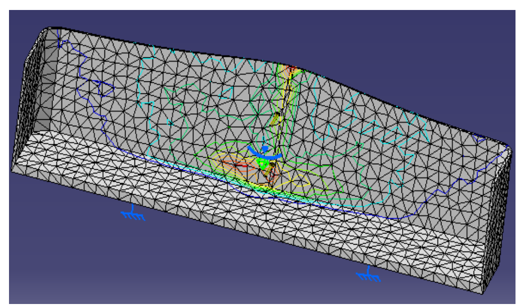

Fig. 10 FEM model for deflection

A case is considered the thin walled plate in the model as shown in Fig. 10 is divided into 42 divisions in X axis and from 6mm to 191mm and 10 divisions of the mesh on the vertical section. A force of 160N is applied to the wall. The above Fig. 9 and Fig. 10 indicates the higher part of the wall has more deformation, while lower part of the wall has less deformation. Also, the maximum deformation is in the centre of the wall as indicated by Fig. 9.

## IV. Conclusion

Accuracy of machined components is one of the most critical considerations for many manufacturers, especially in the aerospace industry where most of the parts used are thin-walled structures. In the current work, a fast methodology for predicting the surface errors when machining a thin-wall low rigidity component has been developed. The methodology integrates the statistical FEA result by statistical methods to determine the correlation between a criterion variable (form errors) and combination of a predictor variable (cutting parameters and component attributes). A set of machining tests was performed to validate the accuracy of the model. A good agreement between simulation and experimental results showed the validity of the models in handling real-field problems.

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