FINITE ELEMENT ANALYSIS OF MICRO END MILL AND SIMULATION OF BURR FORMATION IN MACHINING Al6061-T6

A thesis submitted in partial fulfilment of the

requirements for the degree of

Bachelor of Technology

in

Industrial Design

by

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Certificate

This is to certify that the thesis entitled "**Finite Element analysis of micro end mill and simulation of burr formation in machining Al6061-T6**" submitted to the National Institute of Technology, Rourkela by PRIYANK KUMAR, Roll No. 110ID0264 and ANANYA PATEL, Roll No. 110ID0272 for the award of the Degree of Bachelor of Technology in Industrial Design Engineering is a record of bona fide research work carried out by then under my supervision and guidance. The results presented in this thesis has not been, to the best of my knowledge, submitted to any other University or Institute for the award of any degree or diploma. The thesis, in my opinion, has reached the standards fulfilling the requirement for the award of the degree of Bachelor of technology in accordance with regulations of the Institute.

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Acknowledgement

We take this opportunity to express our profound gratitude and deep regards to our guide Dr. M. R. Khan, Assistant Professor, Department of Industrial Design, for his exemplary guidance, monitoring and constant encouragement throughout the course of this project. His invaluable guidance, immense help, hearted cooperation and fruitful discussions throughout the semester are embodied in this dissertation.

We also express our sincere gratitude to Prof. B. B. Biswal, Head of Department, Department of Industrial Design, for his keen interest and unfailing inspiration throughout the course of the project.

We are obliged to the faculty members of the Industrial Design Department of National Institute of Technology, Rourkela, for the valuable information provided by them in their respective fields and acknowledge them for their cooperation during the period of our assignment.

We are extremely grateful to all lab maintenance staff for providing us assistance in various hardware and software problems encountered during the course of our project.

Finally, we thank all those who are involved, directly or indirectly, throughout the course of the project.

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Abstract

The recent technological progressions in industries have offered ascent to the continually growing requests for microstructures, sensors, and parts. Micro-milling is a promising method to create these scaled down structures, sensors, and parts. Yet, micro-milling still confronts some significant difficulties, tormenting further provision of this innovation. The most noticeable around them is micro burr formation. Burrs created along the completed edges and surfaces in micro-milling operation have huge effect on the surface quality and performance of the completed parts and microstructures. In any case, deburring of micro-parts is not conceivable because of bad accessibility and tight tolerances in micro segments. One of the methods to minimize micro burr formation in micro milling is by enhancing the geometry of the device. As minimization of micro burrs still remains a key test in micro machining, not many researchers have worked in this field. The main aim of the research work is to present finite element analysis of flat end mill micro cutters used in micro milling by varying geometry of the tools. Apart from this, study has been done in detail on burr formation in micro milling and what factors affect it. Burr formation simulation has been carried out while varying the tool geometry.

The outcome of the research will be a static finite element analysis of micro burrs formed during micro-milling which can help in determining tool life and a detailed dynamic analysis of micro burrs formed during micro-milling operation in Al6061-T6 which can benefit the aerospace industry in various ways. The results obtained during the analysis may be used for further research for burr minimization through tool optimization and process control.

Contents

List of Figures

List of Tables

CHAPTER 1

Introduction

The fabrication of a wide variety of parts and products in various fields, like aeronautics, automotives, biomedical, medical and electronics requires proper finishing for proper mating and functioning of products. A variety of operations like milling, drilling, turning, grinding, EDM and water jet cutting are utilised to fabricate and finish parts. One of the most common and important form of machining is the milling operation, in which material is cut away from the workpiece in the form of small chips by feeding it into a rotating cutter to create the desired shape. Milling is typically used to produce parts that are not axially symmetric and have multiple features, such as holes, slots, pockets, and even three dimensional surface contours. Contoured surfaces, which include rack and circular gears, spheres, helical, ratchets, sprockets, cams, and other shapes, can be readily cut by using milling operation. Recently, micro milling process has gained immense popularity due to market requirements and technological advancements which has lead to fabrication and use of micro structures. It possesses several advantages like ease of use, capability to produce complex three dimensional geometries, process flexibility, low set-up cost, wide range of machinable materials and high material removal rates.

This chapter develops the background for the present work and discusses the need to take up this work. It presents a review of available relevant literature. Objectives of the present work along with methodology adopted to accomplish them are also discussed here.

1.1 Background

With the growth in technology, the expectations from products have greatly increased. More and more complex shaped parts of varying sizes are being designed, developed and used for a wide variety of industrial applications. The commercial success of a new product is strongly influenced by the highest possible quality and productivity achieved. This can be achieved only when the parts and/or products have excellent surface finish.

One of the important causes of poor surface finish is the formation of burrs along the machined edges / boundaries. The impact of burr formation on the surface finish of microstructures is much more significant than in case of macrostructures because of comparable sizes of burrs and the parts formed during micro machining. Deburring in this case is expensive, and sometimes impossible, and, hence, the only solution is to minimise the formation of burrs.

To realize any surface accurately using conventional subtractive machining process, two most important factors to be properly controlled are: geometry of the cutting tool and the kinematic structure of the machine tool. The cutting tool geometry along with the relative motion between the cutting tool and the work piece generates the profile of the cut. Even the shapes not possible to manufacture earlier are achievable due to increased control of machine tools by CNC controllers. Optimising the cutting tool geometry or the machining parameters or both, can help in the control of burr formation in micro machining.

1.2 Motivation

Conventional milling has a wide range of industrial applications and is used where there is a requirement of complex shapes, removal of large amounts of material, and accuracy. However, with the advancement in technology, more and more industries are leaning towards the use and fabrication of miniaturized parts and products. In the present scenario, micromachining is increasingly finding application in various fields like biomedical devices, avionics, medicine, optics, communication, and electronics. Among all micro-machining operations, micro-milling and micro-drilling are the two most important operations.

In today’s competitive world, every industry is dependent on the adequate functionality of its micro components. Automobile and aerospace industries need extremely good quality machined components due to greater complexity of the workpiece, tighter tolerances, miniaturization and use of new composite materials. In case of biomedical devices, there are stringent requirements for form and finish of the product like metallic optics and cochlear implants. Good surface finish of micro-components is needed for proper functioning of the products, and for proper mating of micro-parts.

Protruding edges at the boundary of the machined surface are called burrs. Burr removal is necessary for good surface finish. In case of conventional milling, surface finishing is done by either improving the machining setup or changing the tool geometry. Burr removal can be done by using various deburring processes. However, controlling burr formation in micro milling can be very challenging because of the sub-micrometer size of the burrs produced. Furthermore, in micro-milling operation, deburring solutions utilized in conventional machining are not allowed due to inherent material characteristics or limitations in part geometry. Deburring processes allowed in micro milling are expensive and can lead to microstructural damage. Optimisation of various machine parameters, like cutting speed, feed rate and depth of cut, or tool parameters, like rake and relief angle, can help in minimization of micro-burrs in micro milling operations. An accurate surface geometry of micro milling cutters is one of the essential parameters responsible for the control of micro burrs in micro milling.

Very limited work has been done on the control and minimisation of micro burrs formed during micro milling operation. Virtual finite element analysis of micro burr formation during micro milling process is a cost effective method for obtaining optimised tool parameters for minimum burr formation.

1.3 Problem Definition

This work is an attempt to optimize micro milling tool parameters for minimization of micro burrs formed during micro machining. The objectives of this work are stated as follows:

- To develop three-dimensional solid models of two flute and four flute flat-end micro milling cutters.
- To perform the static finite element analysis of the tools during micro milling.
- To perform the finite element detailed analysis of the tool and work piece combination during micro milling.
- To perform burr formation simulation in micro milling.

1.4 Manufacturing Processes and its Classification

Manufacturing can be defined as value addition processes, which produces high utility and valued products from raw materials of low value and utility. The procedure of manufacturing confers some practical capability with definite dimensions, structure and completion to crude materials of lacking material properties and poor or irregular size, shape and completion. The center of manufacturing operations is the methodology answerable for converting the shape, size and completion of the object.

Manufacturing processes can be broadly classified in three major groups, namely,

(i) substractive machining (removal processes),

(ii) additive manufacturing, (deposition of material in an empty volume or layer) and;

(iii) shaping or forming processes (plastic deformation)l.

Figure 1,1 shows the different classes of manufacturing processes. The purpose of all these manufacturing processes is shape realization.

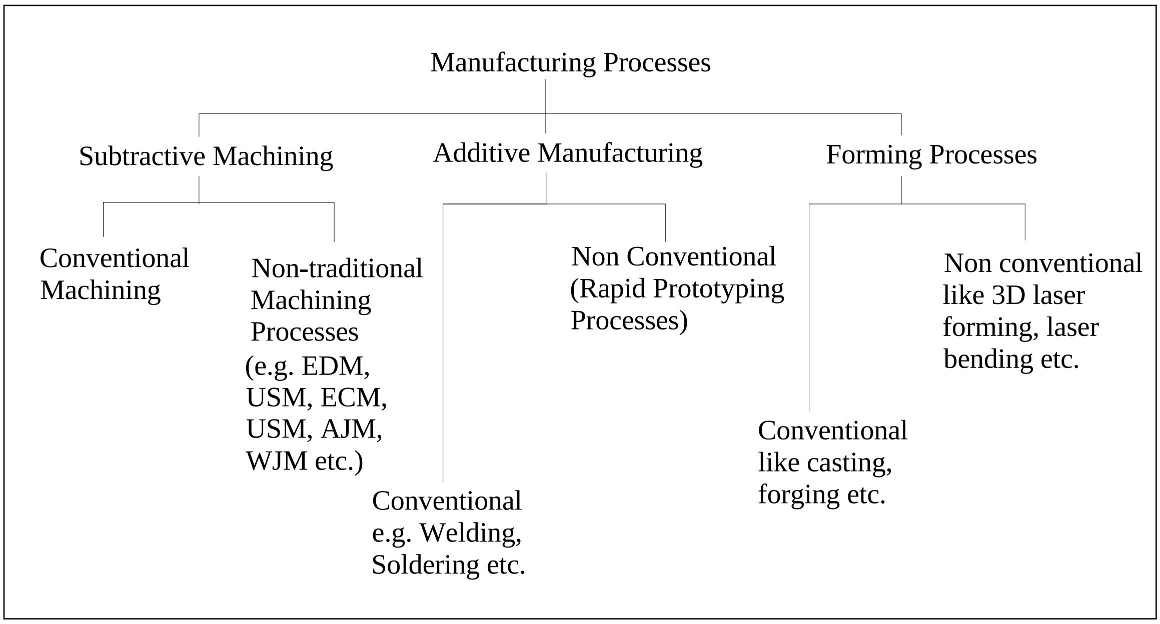


Figure 1.1: Classification of Manufacturing Processes

1.5 Metal Cutting

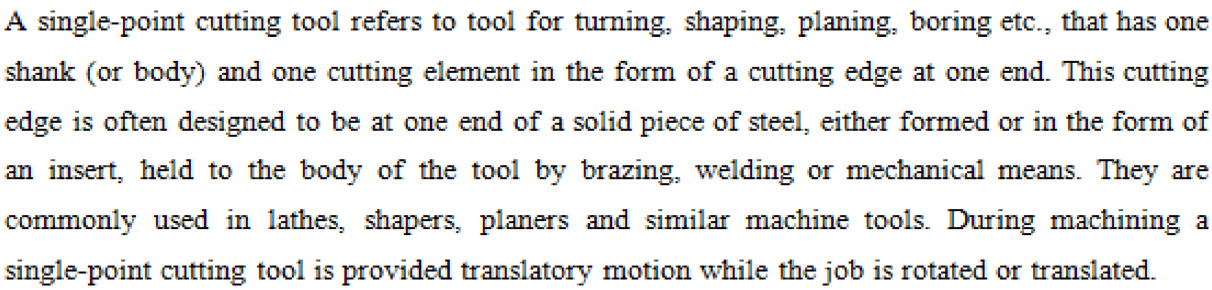
Basically, machining is a semi-finishing or finishing process where the excess material is removed in the form of chips from the preformed blanks in order to impart required dimensional and structural accuracy and surface finish. It provides a higher degree of geometric complexity to the work.

The cutting tool is an important elements to realize the full potential out of a machining operation. It includes relative movement of the cutting tool(s) with respect to the work surface(s) to produce the machined surface. The material is made to flow by pressing against the hard edge(s) of the cutting too. Shear deformation produced over the tool face removes excess material.

A cutting tool consists of two groups of functional parts. The first group contains surfaces and edges responsible for cutting operation. These are critical tool elements form teeth of the cutter. The second group consists of cylinder, hub, shank, disk etc. on which the cutting elements are established. These form cutter body and are non-critical and are meant for completion of the geometry.

Face(s) or rake surface(s), flanks, land, cutting edges and the corner(s) or nose constitute cutting tool geometry. Face is the tool surface along which chip flows out, while flanks are surfaces that face the workpiece. The land is part of the back of the tooth that is adjacent to cutting edge. It is relieved to provide good mating between the machining surface and tool. The cutting edge is intersection of the tooth face with the land leading edge. The basic cutting tools can be single-point or multi-point, based on the cutting element geometries.

1.5.1 Single-Point Cutting Tools



A single-point cutting tool refers to tool for turning, shaping, planing, boring etc., that has one shank (or body) and one cutting element in the form of a cutting edge at one end. This cutting edge is often designed to be at one end of a solid piece of steel, either formed or in the form of an insert, held to the body of the tool by brazing, welding or mechanical means. They are commonly used in lathes, shapers, planers and similar machine tools. During machining a single-point cutting tool is provided translatory motion while the job is rotated or translated.

1.5.2 Multi-Point Cutting Tools

A tool with a series of two or more cutting elements / edges (points) on a common body is known as multi-point cutting tool. These include double (two) point cutters: e.g., drills and multipoint (more than two) cutters: e.g., milling cutters, broaching tools, hobs, gear shaping cutters, etc. The majority of multi-point cutting tools are provided rotary motion for shape realization as shown in Table 1.1. A common machining operation associated with multi-point tools - milling - is introduced in the following section.

1.5.3 Milling and Micro Milling

Milling is a subtractive shape realization process that removes a predetermined amount of material from the work piece with a cutting tool rotating at a comparatively high speed. The cutting tool used for the purpose has multiple cutting teeth. The characteristic feature of the milling process is that each milling cutter tooth removes its share of the stock in the form of small individual chips during each revolution from the advancing work.

Table 1.1: Relative Motion of various Cutting Operations

Operation	**Motion of Cutting Tool**	**Motion of Workpiece**
Turning	Translation	Rotation
Shaping	Translation	Intermittent Translation
Planing	Intermittent Translation	Translation
Milling	Rotation	Translation
Drilling	Rotation and Translation	Fixed
Boring	Rotation	Forward Translation
Hobbing	Rotation and Translation	Rotation
Surface Grinding	Rotation	Translation

Micro milling is used to make miniaturized parts with feature sizes ranging typically from one micron to several millimetres. A wide variety of operations can be performed during micro milling since both the workpiece and the cutter can be moved relative to one another in combination or independently.

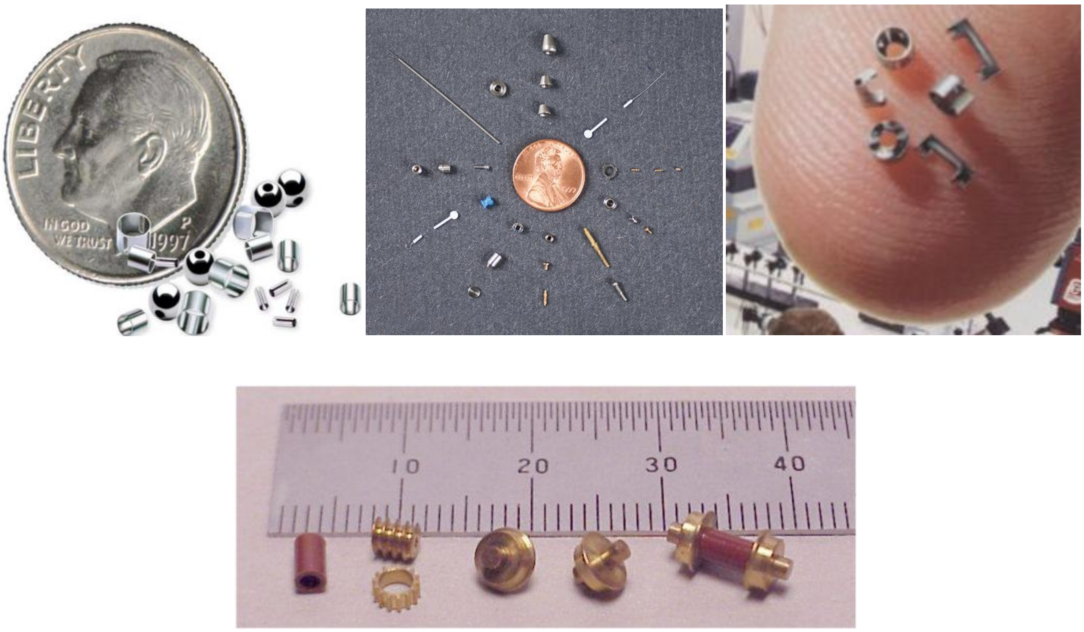


Figure 1.2: Various miniaturized components

Micro milling consists of two motions: cutter rotation about its axis and a feed motion. In some applications, the feed is given to the workpiece while in others workpiece is stationary and the cutter traverses across with a given feed rate. The motion of feed is along a straight line in milling flat and cylindrical surfaces, rotary in milling surfaces of revolution and helical in milling helicoidal surfaces.

Micro milling applications include the production of flat or contoured surfaces, recesses, slots, bodies of revolution, profile surfaces, threads, grooves and other configurations.

1.6 Review of Literature

In direction of micro cutting tools, researchers have approached few works related to modeling and analysis of micro drilling (Cheong [1999], Hinds [2000], Kudla [2001], Endo [2006], Nakagawa [2007], Chen [2007], Kim [2008], Fu [2010], Zhang [2011], Aziz [2012]). In the field of micro milling cutters, some work has been significantly explored. Bao et al. [2000] had presented a work discussing analytical modeling of micro end mill cutters and tool run out. Vogler [2004], Jun [2006], Liu [2007] has worked on dynamic modeling and analysis of machining performance for surface generation and prediction of cutting forces in micro milling. Three dimensional dynamic force model for micro end milling have been investigated by Kang [2007], Li [2007], Filiz [2011], Li [2011]. Recently, Jun [2012], Wu [2012] & Mustapha [2013] have done the work related to cutting force and finite element modeling of micro milling process.

Modeling and control of burr formation in both macro- and micro- machining processes assumes a lot of significance. Gillespie [1976], Ko [1996], Chu [2000], Satish [2003], Alrabii [2009], etc. have discussed the burr formation and minimization in macro level. Besides, Kim [2004], Lee [2005], Liang [2009], Chang [2010], Lekkala [2011], Saptaji [2012], Chen [2012], Aziz [2012], etc. have also discussed micro burr modeling, analysis and minimization.

The finite element method (FEM) features accurate predictions on a user friendly graphical interface and is employed widely for modeling, simulation and optimization of cutting processes. Thus, the cutting process potentially allows designers and engineers to reduce need for costly shop-floor trials, optimizes process conditions, improves cutting tool design, and shortens the lead time. The analysis of stresses in micro-drills using the finite element method was presented by Hinds et al. [2000], who discussed correlation between the stresses and life of the drill bit tool. Park et al. [2000] have presented finite element model of orthogonal metal cutting including burr formation. Thrust force analysis of the drilling burr formation using finite element model have been discussed by Min et al. [2001]. Laia et al. [2008] have discussed the FE model and analytical model of micro-milling considering size effect, micro cutter edge radius and minimum chip thickness. Liang et al. [2011] developed a three-dimensional finite element model to analyze micro burr formation in micro end-milling process and predicted effects of tool-tip breakage and various tool edge radius on burr formation. The micro burr formation is dynamically simulated. Afazov et al. [2010] presented a new approach for predicting micro-milling cutting forces using the finite element method. Finite element modeling of a micro-drill bit and experiments on high speed ultrasonically assisted micro-drilling was conducted by Zhang et al. [2011].

Recently, Chen et al. [2012] and Lekkala et al. [2011] have worked on the characterisation and modeling of burr formation in micro end milling. Chen et al. observed the effects of axial depth of cut, spindle speed and feed per tooth on size of top burr and concluded that, among the three factors, axial depth is most significant. Lekkala et al. deduced that the depth of cut and the tool diameter are the main parameters, which influence the burr height and thickness significantly whereas the speed and the feed rate have small to negligible effect on the burr thickness and height. Zhang et al. [2013] has analysed the influence of size effect on burr formation in micro cutting. They examined the effect of the ratio of uncut chip thickness to cutting edge radius on the height of Poisson burr. The work related to minimization of micro-burr through process control has been elaborately discussed by K. Lee [2005].

1.7 Scope of the Present Work

The outcome of the research will be a static finite element analysis of micro burrs formed during micro-milling which can help in determining tool life and detailed dynamic analysis of micro burrs formed during micro-milling operation in Al6061T6 which can benefit the aerospace industry, which utilises this alloy for fabrication of a large number of components. The results obtained during the analysis may be used for further research for burr minimization through tool optimization and process control.

1.8 Flow of Work

The approach adopted to accomplish the present work is by:

(i) Generating CAD models of two flute and four flute micro end milling cutters as well as of the workpiece.

(ii) Performing detailed FEA on each of the tool and by varying tool parameters in each case.

(iii) Performing simulation of the burr formed during the process.

(iv) Results in the form of Von Mises Stress and deformation of selected micro cutters.

1.8.1 Proposed Method for Analysis

Various outputs and characteristics of the metal cutting processes such as cutting forces, stresses, temperatures, chip shape, etc. can be predicted by using FEM without doing any experiment.

1.8.1.1 Lagrangian method

Lagrangian formulation is used mainly in problems on solid mechanics. In this, the mesh moves and distorts with the material being modeled as a result of forces from neighboring elements. It is highly preffered when flow of material involved is unconstrained. Boundaries and chip shape need not be known beforehand. Simulation of discontinuous chips or material fracture can be done by using chip separation criteria in metal cutting models based on Lagrangian formulation. However, metal being suffers severe plastic deformation and distortion occurs. Mesh regeneration is therefore needed. Chip separation criteria also must be provided.

1.8.1.2 Eulerian method

In Eulerian formulation, the FE mesh is fixed spatially, which allows materials to flow from one element to the next. Besides, fewer elements are required for the analysis, which reduces the computation time. However, determination of the boundaries and the chip shape needs to be done prior to the simulation. Also during the analysis, the tool-chip contact length, the contact conditions between tool-chip and the chip thickness, have to be kept constant.

1.8.1.3 Arbitrary Lagrangian-Eulerian (ALE) method

Arbitrary Lagrangian-Eulerian (ALE) combines the best features of Eulerian and Lagrangian formulations. In ALE formulation, the material flow is followed and Langrangian step is used to solve displacement problems, while the mesh is repositioned and Eulerian step is used to solve velocity problems. Eulerian approach is used for modeling the tool tip area where cutting process occurs. Hence, without using remeshing, severe element distortion is avoided. Lagrangian approach is used for the unconstrained material flow at free boundaries.

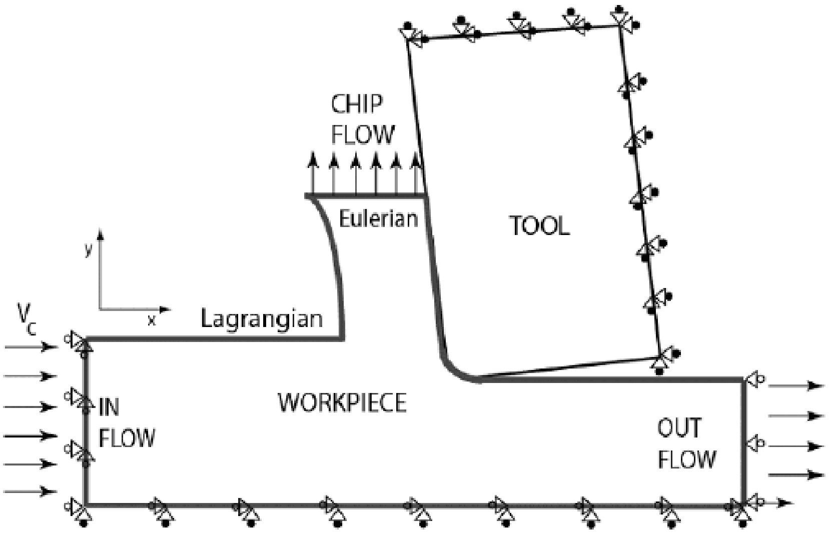


Figure 1.3: Eulerian and Lagrangian boundary conditions in ALE simulation

1.9 The Layout of the Thesis

A brief overview of the work carried out in the thesis and organization of the same are summarized below.

Chapter 1 presents the background, motivation and problem definition of the thesis work. Here, brief information is given for the manufacturing processes, cutting tools available and a brief description of milling and micro milling operations. It is followed with a brief review of the relevant literature. This chapter concludes with the scope of the work along with the methodology adopted to accomplish the work.

Analytical modeling of a micro end mill is presented in Chapter 2. The chapter describes force models obtained during micro milling operations and micro burr formation.

Chapter 3 gives a detailed description of burrs formed during micro milling. It includes types of burrs, mechanism of burr formation and various cutting parameters that affect the characteristics of the burrs formed.

Chapter 4 deals with three dimensional CAD modeling of different two flute and four flute micro flat end mills by using different rake and relief angles. The virtual tool models are developed using CATIA V6 environment. The chapter further presents details of the finite element static analysis performed on the tool. It includes material properties of the tool and the workpiece as well as the machining parameters and the tool parameters chosen to carry out the analysis.

Chapter 5 deals with the dynamic finite element analysis performed on the tool and work piece. It also shows the simulation of micro burrs formed during the micro milling process.

Chapter 6 summarizes the significant findings of the work performed and provides some recommendations for future work that would be further helpful in the minimization of micro burrs during micro milling operation.

Micro Milling Burrs

2.1 Introduction

Burrs structured in processing and also micro-processing operations are points of far reaching examination in light of the fact that these operations discover requisitions in passes on and molds utilized as a part of the injection molding of micro fluidic gadgets, prototyping and assembling of energy components (micro channels), generation of tubular parts in fluid filtration. A few requisitions in the fields of optics, gadgets, pharmaceutical, biomedical gadgets, correspondences and flying oblige without burr parts. Hence, demonstrating and control of burr arrangement in the micromachining methods that produce micro parts accept a considerable measure of centrality. On the other hand, it is noted that the all the micro and in addition macro machining courses of action leave burrs on the machined parts. In the micro-machining methodology, be that as it may, the burr is generally extremely troublesome to evacuate and, all the more vitally, burr evacuation can genuinely harm the workpiece. Accepted deburring operations can't be effectively connected to micro-burrs because of the little size of parts. Likewise, deburring may present dimensional blunders and lingering burdens in the part. These issues are exceedingly subject to burr size and sort. Consequently, the best result is to avoid burr arrangement in any case. In the event that this is not plausible, a second approach is to minimize burr creation. For the usage of this methodology, it is discriminating to comprehend the essential systems included in burr development and the relationship between the cutting parameters, device geometry and burr phenomena.

2.2 Mechanism of micro burr formation

According to Min and Dornfeld [2004], burr formation has eight basic stages. The process starts with the **continuous cutting** stage in which burr formation is unaffected by the deformation and stress distribution, as long as the workpiece edge does not affect it. In the **pre-initiation** stage, the workpiece edge bends due to elastic deformation and a plastic deformation zone is formed around the primary shear zone. This is followed by **burr**

initiation in which the plastic deformation zone and the primary shear zone both extend. A pivoting point appears on the workpiece edge in the **pivoting** stage, and cutting forces decrease, leading to a large deformation. As the burr develops, it enters the **negative shear zone development stage** in which the large deformation in the pivoting point expands and connects with the primary shear zone. The burr size increases as the tool approaches the work piece edge. Following this stage, there are three more stages – **crack initiation**, **crack growth** and **positive** (in case of ductile materials) **or negative** (in case of brittle materials) **burr formation**. These final three stages are characterised by the ductile or brittle nature exhibited by the material.

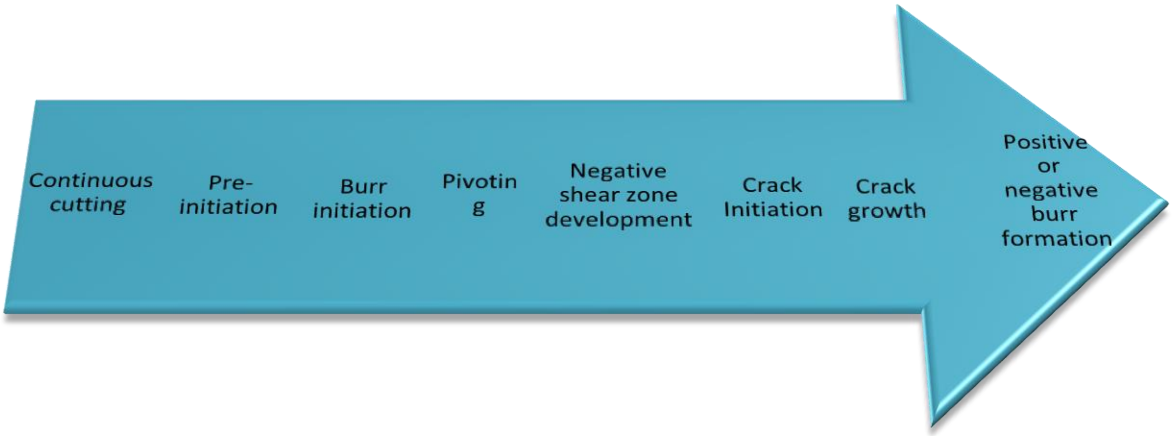


Figure 2.1: Schematic of the burr formation process

2.3 Types of burrs

Figure 2.2 contains a flowchart classifying different types of burrs.

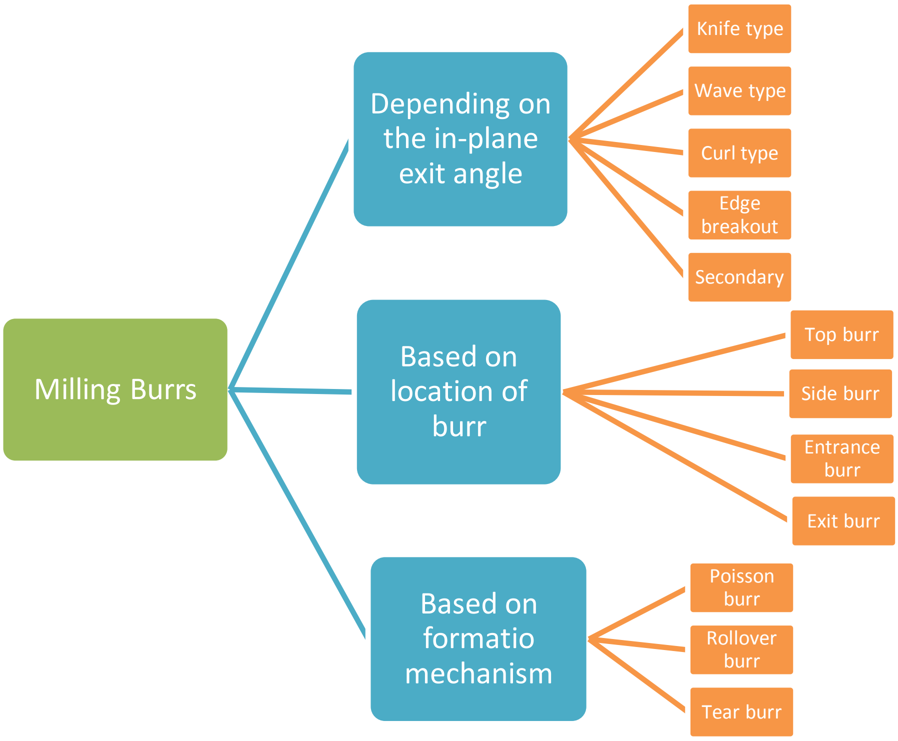


Figure 2.2: Flowchart showing different types of burrs formed in milling

Chern [1993] found that burrs formed in milling are dependent on the in-plane exit angle and classified burrs formed into five categories - the knife-type burr, the wave type burr, the curl-type burr, the edge breakout, and the secondary burr.

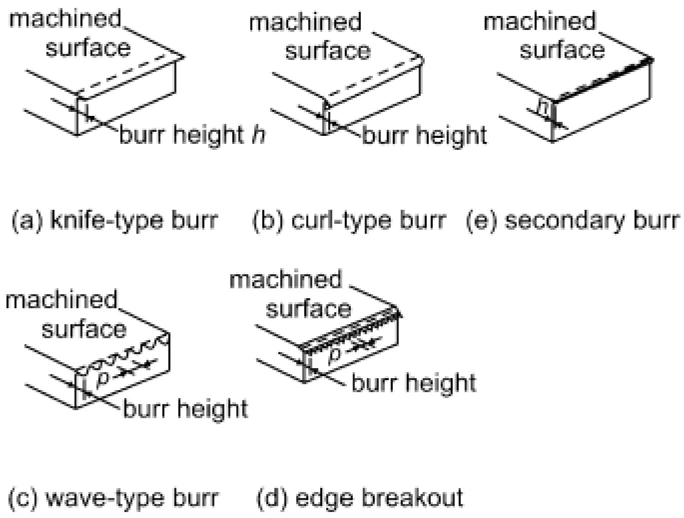


Figure 2.3: Types of burrs based on dependency on in-plane exit angle

Hashimura [1999] classifies burrs formed in milling according to burr locations as top burrs, side burrs, entrance burrs and exit burrs.

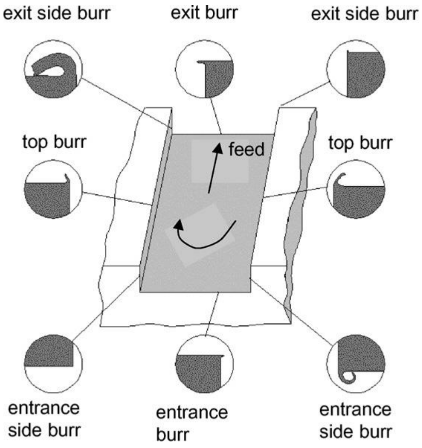


Figure 2.4: Types of burrs based on burr location

Gillespie [1976] classified four types of burrs based on formation mechanism - Tear, Rollover, Poisson and Cut-off burrs. A tear burr is the consequence of material tearing detached from the workpiece as opposed to shearing. The rollover burr is basically a chip that is bowed as opposed to sheared, bringing about a nearly bigger burr. This kind of burr is otherwise called a passageway burr in light of the fact that it is typically framed at the end of a cut in face-processing. The Poisson burr is an aftereffect of a material's tendency to lump at the sides when it is compacted until perpetual plastic deformation happens. It is like the burr shaped in punching operations. The cut-off burr is the consequence of workpiece partition from the crude material before the detachment cut is done.

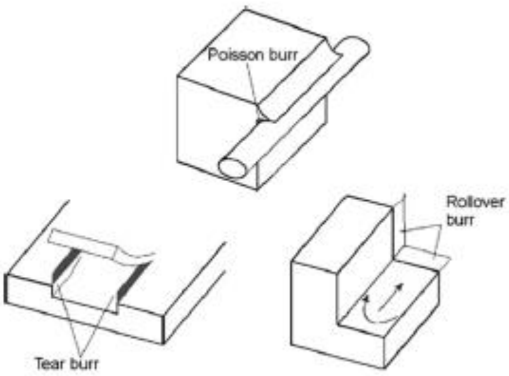


Figure 2.5: Types of burrs based on formation mechanisms

A combination of the Poisson and tear burr can end up as a so-called top burr or entrance burr along the top edge of a machined slot, or along the periphery of a hole when a tool enters it (Lee [2005]). In traditional courses of action, these top or entrance type burrs are generously more diminutive than exit type burrs, and typically no deburring procedure is important. Then again, micro-top or entrance type burrs are large comparatively in light of the fact that the cutting edge radius is substantially large as compared to the feed per tooth.

2.4 Cutting parameters affecting micro burrs

The important characteristics of the burr are burr height, burr thickness and burr width. Major cutting parameters that influence these characteristics of burrs are tool diameter, depth of cut, feed rate, number of flutes in the milling tool and cutting speed.

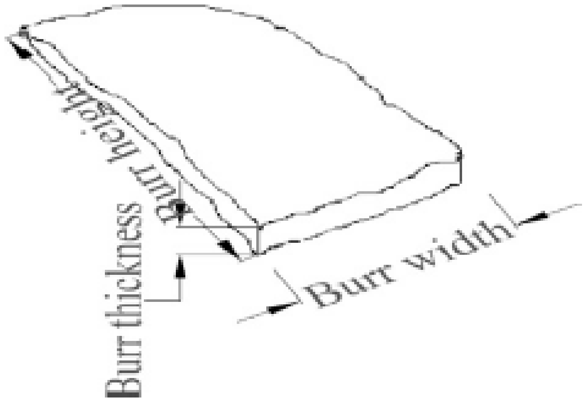


Figure 2.6: Indicators of burr size

In research work effectively done in this field, it has been seen that the depth of cut and the tool diameter are the principle parameters, which impact the burr height and thickness essentially. On the other hand, the velocity and the feed rate have little to immaterial impact on the burr thickness and height. Additionally, it has been seen that expanding the no. of flutes reduces the burr height in up and down milling. The proportion of uncut chip thickness to cutting edge radius was additionally seen to influence the height of Poisson burr.

CHAPTER 3

Analytical Modeling of Micro End Mill

3.1 Introduction

The investigation of the progress of cutting forces in any machining methodology is profoundly key for fitting, arranging and control of machining process and for the enhancement of the cutting conditions to minimize production expenses and times. Cutting force analysis assumes an imperative part in study of the different qualities of a machining process, viz. the dynamic stability, situating precision of the instrument as for the work piece, harshness of the machined surface and structure mistakes of the machined component, and so on.

In most micro-end-processing operations, the micro cutting device measurement differs from 0.1 mm to 1 mm, and anxiety variety on the modest shaft of the micro cutting apparatus is much higher than that on an expected scale instrument, which definitely abbreviates the instrument's life (Li et al. [2007]). The tools can even break if the cutting conditions are not chosen likewise. Subsequently, an exact estimation of the cutting powers of micro-end-milling assumes an essential part in controlling the determination of cutting conditions with a specific end goal to monetarily acquire high machining quality and guarantee as long an tool life as could be expected under the circumstances. At micro level, we can't accept that edge radius has unimportant impacts on cutting powers. Weule et al [2001] discovered that the roundness of a forefront is more critical at micro scale machining. As the span of an instrument decreases, the sharpness of the gadget can't be upgraded moderately due to stipulations in the mechanical assembly creation strategies and reduction in the structural nature of the instrument. Along these lines, the feed per tooth in micro-processing may be for all intents and purpose indistinguishable to or even short of what the cutting edge span because of the obliged reach of approach parameters for a stable machining scale with the method. Yuan et al. [1996] worked on ultraprecision machining to determine minimum chip thickness. Kim et al [2004] tentatively confirmed that when the feed per tooth is practically identical with the edge radius of the apparatus, as is frequently the case in micro-milling courses of action, the chip shaping methodology gets discontinuous and the accepted comprehension that a chip is framed with each tooth pass is no more legitimate. As indicated by their model, the base chip thickness of different consolidations of devices and work piece materials may be evaluated focused around effortlessly achievable cutting force information.

3.2 Force Modeling

The Coordinate system of model in end-milling operations is shown in figure 2.1.

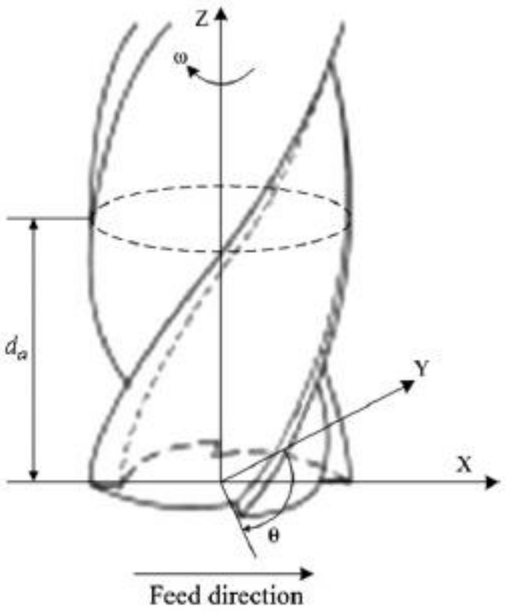


Figure 3.1: Coordinate system of model in end-milling operations

Cutting forces can be modeled according to two different milling regimes.

(i) At the point when the genuine uncut chip thickness $h_a(t, k)$ is littler than the base chip thickness, the work piece flexibly and plastically misshapes under the connection with the processing cutter, and no material is thought to be uprooted from the work piece. For describing the relationships of forces and actual engagement, the tangential force F_t, radial force F_r and axial force F_a are modeled as power functions (Kim *et al. [2004])* described by,

$$dF_t(t, k, z) = A_t h_a(t, k, z)^{B_t}\, dz$$

$$\mathrm{d}F_r(t, k, z) = A_r h_a(t, k, z)^{B_r}\ \mathrm{d}z$$

$$\mathrm{d}F_a(t, k, z) = A_a h_a(t, k, z)^{B_a}\ \mathrm{d}z$$

where, A_t and B_t are tangential force coefficients, A_r and B_r are radial force coefficients and A_a and B_a are axial force coefficients. These six coefficients are steady for the specified cutter and work piece material, and could be procured by curve fitting the force data measured into the energy model using the least-squares strategy.

(ii) At the point when the actual uncut chip thickness $h_a(t, k)$ is bigger than the base chip thickness, shearing strengths rule the communication powers of the cutter with the work piece. All material as thick as the real engagement is thought to be evacuated as a chip. The tangential cutting force F_t, radial cutting force F_r and axial cutting force F_a are modeled as (Wang *et al* [2002])

$$\mathrm{d}F_t = A_{ts} h_a(t, k, z)\ \mathrm{d}z + B_{tp}\ \mathrm{d}z$$

$$\mathrm{d}F_r = A_{rs} h_a(t, k, z)\ \mathrm{d}z + B_{rp}\ \mathrm{d}z$$

$$\mathrm{d}F_a = A_{as} h_a(t, k, z)\ \mathrm{d}z + B_{ap}\ \mathrm{d}z$$

where, A_{ts} and B_{tp} are tangential shearing and ploughing force coefficients; A_{rs} and B_{rp} are radial shearing and ploughing force coefficients and A_{as} and B_{ap} are axial shearing and ploughing force coefficients, respectively. These six coefficients can also be acquired by curve fitting the measured force data into the force model using the least-squares method.

The three-dimensional cutting forces, F_x , F_y and F_z, can be expressed as,

$$\begin{bmatrix} \mathrm{d}F_x \\ \mathrm{d}F_y \\ \mathrm{d}F_z \end{bmatrix} = \begin{bmatrix} -\cos\theta & -\sin\theta & 0 \\ \sin\theta & -\cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \mathrm{d}F_t \\ \mathrm{d}F_r \\ \mathrm{d}F_a \end{bmatrix}$$

Considering the geometric conditions,

$$\frac{r d\theta}{dz} = \tan\beta$$

and integrating, the cutting force expressions obtained are,

$$
\begin{aligned}
F_x(t) &= \frac{r}{\tan\beta}\sum_{k=0}^{K-1}\int_{\theta_{en}}^{\theta_{ex}}[-A_t h_a(\theta,k)^{B_t}\cos\theta \\
&\quad - A_r h_a(\theta,k)^{B_r}\sin\theta]\,\mathrm{d}\theta \\
F_y(t) &= \frac{r}{\tan\beta}\sum_{k=0}^{K-1}\int_{\theta_{en}}^{\theta_{ex}}[A_t h_a(\theta,k)^{B_t}\sin\theta \\
&\quad - A_r h_a(\theta,k)^{B_r}\cos\theta]\,\mathrm{d}\theta \\
F_z(t) &= \frac{r}{\tan\beta}\sum_{k=0}^{K-1}\int_{\theta_{en}}^{\theta_{ex}} A_a h_a(\theta,k)^{B_a}\,\mathrm{d}\theta
\end{aligned}
$$

when $h_a(\theta,k) < h_{min}$

$$
\begin{aligned}
F_x(t) &= \frac{r}{\tan\beta}\sum_{k=0}^{K-1}\int_{\theta_{en}}^{\theta_{ex}}\{-[A_{ts}h_a(\theta,k)+B_{tp}]\cos\theta \\
&\quad - [A_{rs}h_a(\theta,k)+B_{rp}]\sin\theta\}\,\mathrm{d}\theta \\
F_y(t) &= \frac{r}{\tan\beta}\sum_{k=0}^{K-1}\int_{\theta_{en}}^{\theta_{ex}}\{[A_{ts}h_a(\theta,k)+B_{tp}]\sin\theta \\
&\quad - [A_{rs}h_a(\theta,k)+B_{rp}]\cos\theta\}\,\mathrm{d}\theta \\
F_z(t) &= \frac{r}{\tan\beta}\sum_{k=0}^{K-1}\int_{\theta_{en}}^{\theta_{ex}}[A_{as}h_a(\theta,k)+B_{ap}]\,\mathrm{d}\theta
\end{aligned}
$$

when $h_a(\theta, k) >= h$min

CHAPTER 4

Micro End Mill

4.1 Introduction

Different machines and different types of cutters are used to perform micro milling operations. Micro milling cutters rotate about their axes and have surfaces containing equally spaced cutting. Micro milling operation does not depend on work piece materials, dimensions and shapes. However, micro mill cutters are very thin and cutter deflection and vibration may cause degradation of tool failure and accuracy. The calculations and formulae for determining speeds and feeds that work reasonably well for conventional mills require changes for use in the case of micro milling cutters.

Flat and ball end milling cutters are the most common types of micro milling cutters used for various operations. End mills have cutting teeth at one end as well as on the sides. These can be broadly categorized as being one of two types: Flat end mill cutters (Flat bottomed cutters) or Ball nose end mill cutters (Hemispherical-ended cutters).

They are usually made from HSS (High Speed Steel) or cemented carbide and can have one or more flutes.

Figure 4.1: Micro end mills

4.2 Development of Three Dimensional CAD model of micro flat end mill

The micro end mill cutters used in this work are a two flute and a four flute flat micro end mill cutter. Method involved in the design of a micro end mill cutter includes:

- Creation of cross-sectional profile of the tool and helix generation
- Flute creation using slot operation
- Creation of back surface of the tool
- Cutting edge generation

Parameters involved in generating the cross sectional profile are:

- Rake angle of the tool
- Relief angle of the tool
- Tool diameter
- Number of flutes

Parameters involved in modeling the helix are:

- Height of the tool
- Diameter of the tool
- Pitch of the helix
- Helix angle of the tool

The three dimensional CAD models of both the flat end mills was produced by performing solid modeling in CATIA V6 environment.

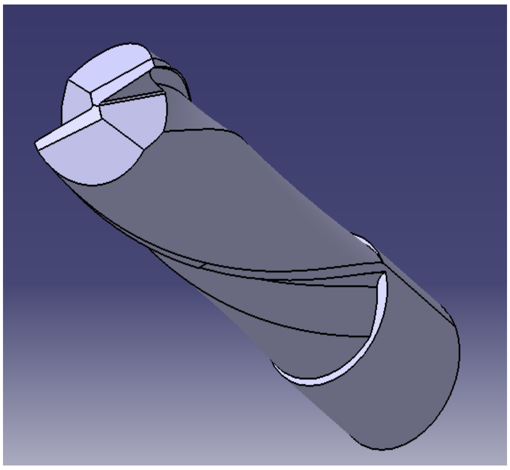


Figure 4.2: CATIA model of two flute micro end mill

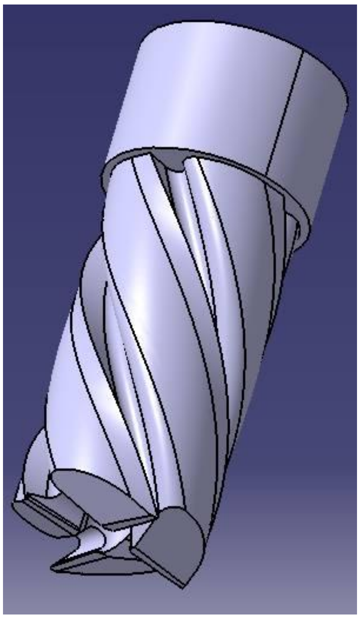


Figure 4.3: CATIA model of four flute micro end mill

CHAPTER 5

Analysis and Simulation

Once a three dimensional CAD model of micro end mill cutter is developed, a no. of downstream applications can be performed, one of which is detailed finite element analysis and simulation of micro end mill during micro machining. Here, the static analysis of the micro end mill and simulation of burr formation process in micro milling has been carried out. In this work, tool material used is Tungsten Carbide (WC). Cemented carbides (WC-Co) are recently being used instead of tungsten carbides. Cemented carbide is a composite material containing a binder like cobalt (Co) which provides increased tool hardness.

The workpiece is a cuboidal block of aluminium alloy Al6061-T6 which is used in many aerospace applications. Al6061-T6 is a T6 tempered aluminium alloy containing magnesium and silicon as its major alloying elements.

Table 5.1: Alloy composition of Al6061-T6

Elements	**Minimum (% by weight)**	**Maximum (% by weight)**
Silicon	0.4	0.8
Iron	0	0.7
Copper	0.15	0.4
Manganese	0	0.15
Magnesium	0.8	1.2

Chromium	0.04	0.35
Zinc	0	0.25
Titanium	0	0.15
Others	0.05	0.15
Aluminium	95.85	98.56

Table 5.2: Properties of Tungsten Carbide and Al6061-T6

Properties	**Tungsten carbide (Tool)**	**Al6061-T6 (Work piece)**	**Units**
Density	15.63	2.703	g/cm^3
Poisson’s Ratio	0.2	-	-
Young’s Modulus of Elasticity	550	69	GPa
Ultimate tensile strength (UTS)	344.8	310	MPa
Tensile Yield Strength	-	276	MPa
Specific Heat	184	885	J/kgK

In research work done, it has been observed that, in case of micro milling, the depth of cut and the tool diameter are the main parameters, which influence the burr height and thickness significantly. The speed and the feed rate have been seen to have small to negligible effect on the burr thickness and height.

In the proposed method, different sets of machining parameters have been used for static and dynamic analysis as show in Table 5.3. These parameters have been kept constant during each analysis.

Table 5.3: Machining parameters

Properties	**Static analysis**	**Dynamic analysis**
Cutting speed	10,000 rpm	20,000 rpm
Feed rate	150 mm/min	500mm/sec
Depth of cut	0.2 mm	0.1 mm

Five different sets of relief and rake angles each have been used in the case of two flute and four flute micro end mill as input as listed in Table 5.4.

Table 5.4: Micro mill cutter parameters

Properties	**Two flute flat end micro mill cutter**					**Four flute flat end micro mill cutter**				
Relief angle (degrees)	0	2	3	5	5	0	2	3	5	5
Rake angle (degrees)	10	6	8	5	6	10	6	8	5	6
Cutter diameter (mm)	0.30					0.38				

5.1 Meshing

Meshing can be done by using tetrahedral or hexahedral elements. More the no. of nodes in the element type, the greater is the accuracy of the results obtained.

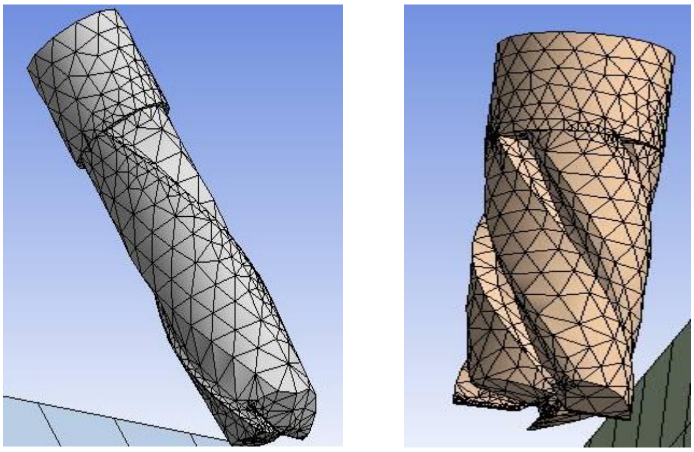
Tetrahedral meshing is a robust meshing routine and is easier way of meshing. However, linear tetrahedral elements perform poorly in problems with plasticity, nearly incompressible materials, and acute bending. Also, tetrahedral elements consider a lot of approximations, even more so in complicated structures.

Hexahedral elements, on the other hand, give more accurate results than tetrahedral elements, in case of complex structures. They also consider lesser amount of approximations. However, hexahedral elements face difficulties at corners of parts/elements. Also, automatic mesh generation is often not feasible for building many three dimensional hexahedral meshes.

Meshing and analysis of the micro milling machining operation has been carried out using ANSYS 13.0 software. The mesh generated for the end mill cutters in this work is a tetrahedral mesh, the properties of which are given in Table 5.5 and Table 5.6.

Table 5.5: Meshing Information for micro end mill cutter

Parameters	**Two flute micro cutter**	**Four flute micro cutter**
Nodes	5257	7190
Elements	2920	4039



(a) (b)

Figure 5.1: Meshing performed on (a) two flute and (b) four flute micro end mill

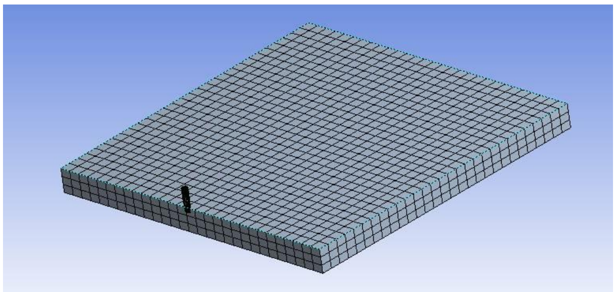


Figure 5.2: Meshing performed on the work piece

5.2 Static finite element analysis

5.2.1 Analysis

For static analysis at any particular instantaneous time, forces are considered on a single flute in feed direction (F_x), normal direction (F_y), and axial direction (F_z) for an axial depth of 0.2mm. The input forces for this analysis are obtained from the work done by Zaman et al. [2005] in which the analytical cutting force expressions developed in were simulated for a set of cutting conditions and were found to be comparable to experimental results..

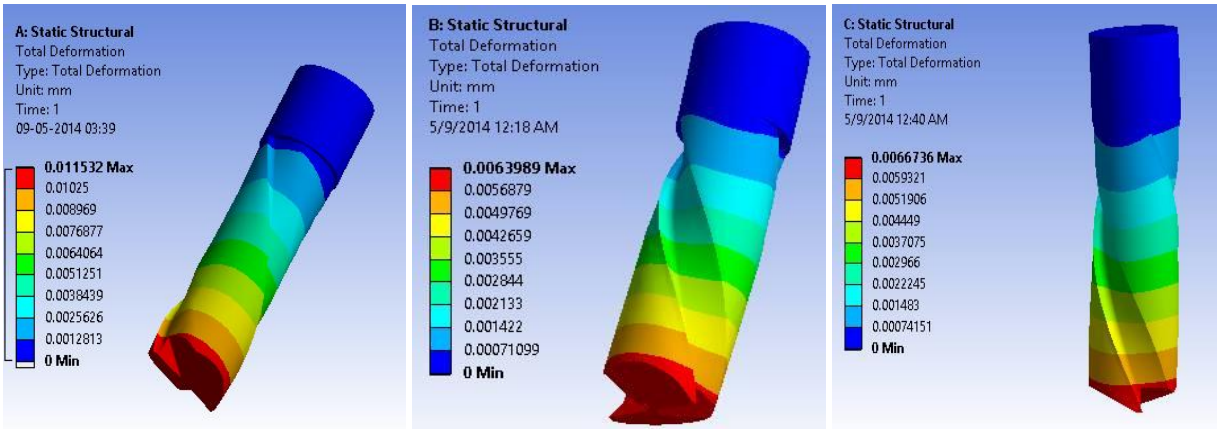
The applied forces in feed, normal and axial directions are F_x = 3.82 N, F_y = 4.01 N and Fz = -0.34 N.

Table 5.6: Cutting forces used as input

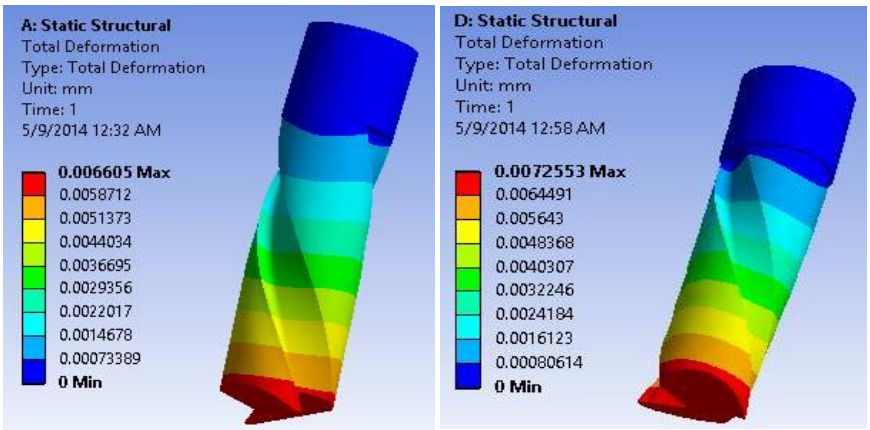
Force in feed direction (F_x)	3.82 N
Force in normal direction (F_y)	4.01 N
Force in axial direction (F_z)	-0.34 N
Cutting force applied (F_c)	5.548 N

5.2.2 Results

Figures 5.3 and 5.4 show the result for static analysis with deformed mesh and Von Mises stress respectively for the applied load for two flute flat end mill of diameter 0.3 mm.

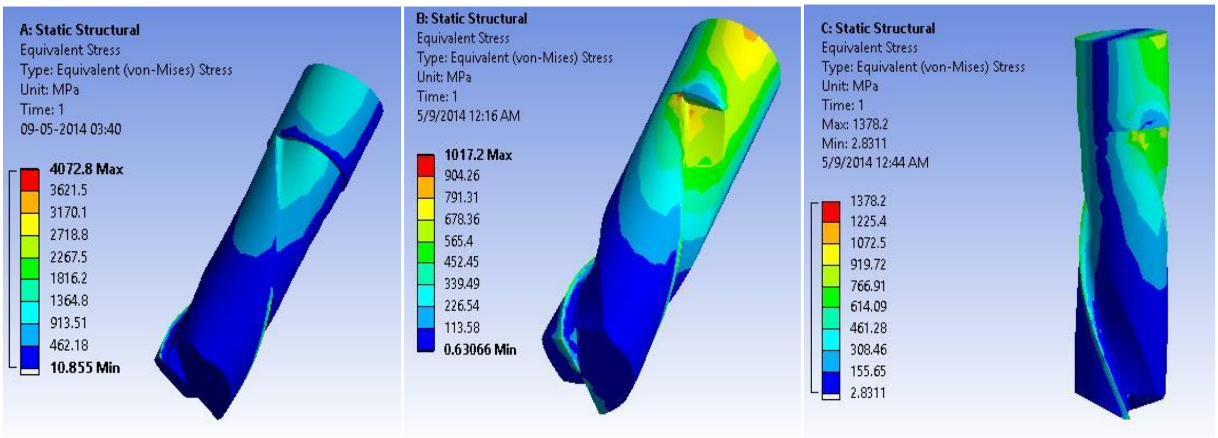


(a) Rake angle = 0°, Relief angle = 10° (b) Rake angle = -2°, Relief angle = 6° (c) Rake angle = 3°, Relief angle =8°

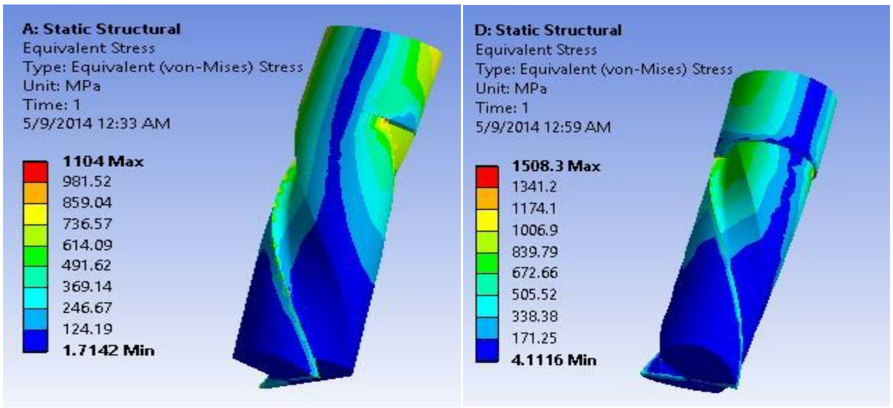


(d) Rake angle = 5°, Relief angle = 5° (e) Rake angle = 5°, Relief angle = 6°

Figure 5.3: Total deformation in the case of two flute micro end mills



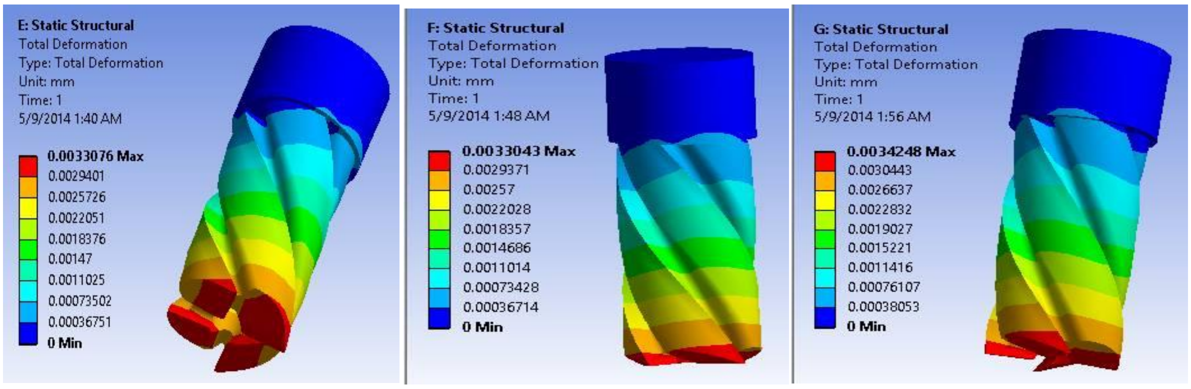
(a) Rake angle = 0°, Relief angle = 10° (b) Rake angle = -2°, Relief angle = 6° (c) Rake angle = 3°, Relief angle =8°



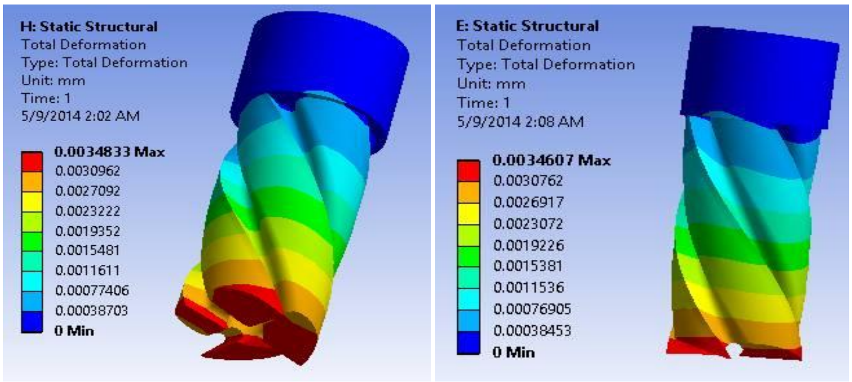
(d) Rake angle = 5º, Relief angle = 5º (e) Rake angle = 5º, Relief angle = 6º

Figure 5.4: Von Mises stress in the case of two flute micro end mills

Figures 5.5 and 5.6 show the result for static analysis with deformed mesh and Von Mises stress respectively for the applied load for four flute flat end mill of diameter 0.3 mm.

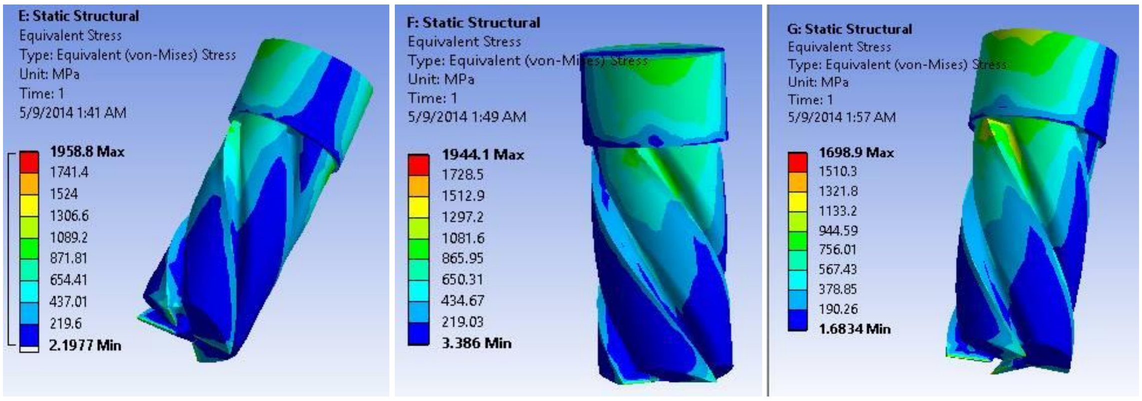


(a) Rake angle = 0º, Relief angle = 10º (b) Rake angle = -2º, Relief angle = 6º (c) Rake angle = 3º, Relief angle =8º

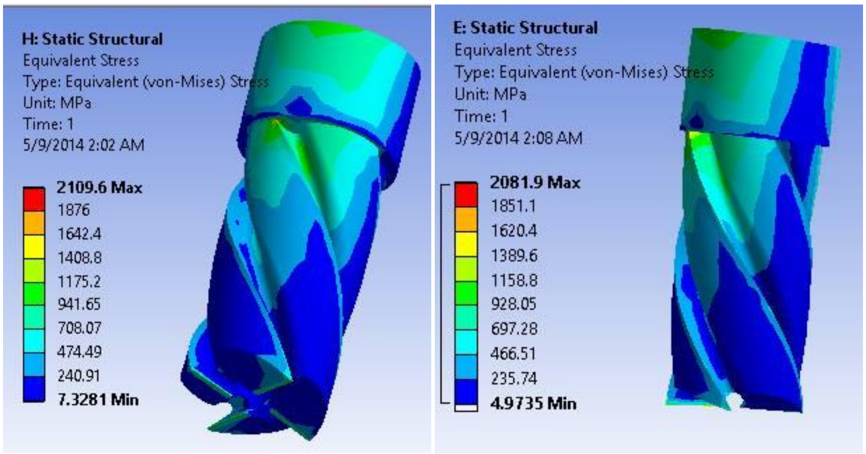


(d) Rake angle = 5º, Relief angle = 5º (e) Rake angle = 5º, Relief angle = 6º

Figure 5.5: Total deformation in the case of four flute micro end mills



(a) Rake angle = 0º, Relief angle = 10º (b) Rake angle = -2º, Relief angle = 6º (c) Rake angle = 3º, Relief angle =8º



(d) Rake angle = 5º, Relief angle = 5º (e) Rake angle = 5º, Relief angle = 6º

Figure 5.6: Von Mises stress in the case of four flute micro end mills

The results obtained are presented in Table 5.7.

Table 5.7: Results of static finite element analysis of micro end mills

No. of flutes	Rake angle (degrees)	Relief angle (degrees)	Maximum total deformation (mm)	Maximum Von Mesis stress (MPa)
2	**0**	**10**	**0.011532**	**1364.8**
	-2	**6**	**0.063989**	**339.49**
	3	**8**	**0.006736**	**461.28**
	5	**5**	**0.006605**	**369.14**
	5	**6**	**0.0072553**	**505.52**
4	**0**	**10**	**0.0033076**	**654.41**
	-2	**6**	**0.0033043**	**650.31**
	3	**8**	**0.0034248**	**567.43**
	5	**5**	**0.0034833**	**708.07**
	5	**6**	**0.0034607**	**697.28**

From Table 5.6 it can be seen that a two flute micro end mill cutter with rake angle -2° and relief angle 6° takes the least amount of Von Mises equivalent stress. In case of four flute micro end mills, the least amount of Von Mises stress is taken by tool with rake angle 3° and relief angle 8°.

The deformation values shown in the above figures actually occur momentarily due to vibration of the cutter which is not taken into account during the analysis.

5.3 Dynamic finite element analysis and simulation of burr formation of two flute micro end mill

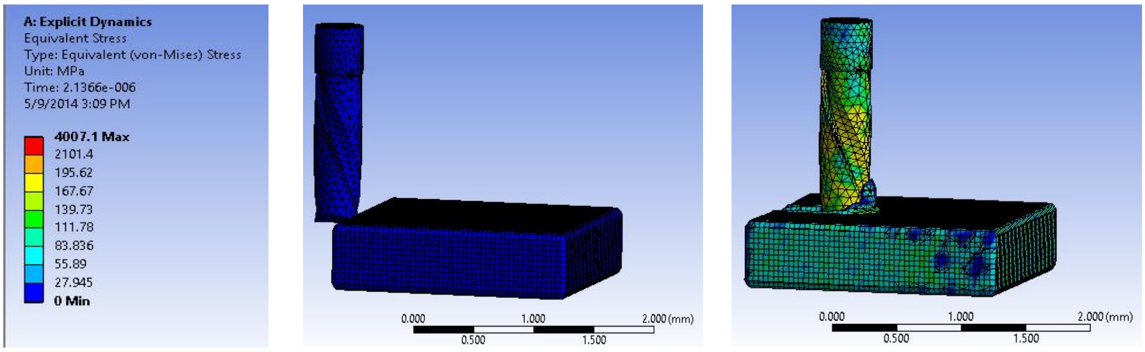
5.3.1 Analysis

In order to observe burr formation and chip flow mechanism in a virtual environment, an explicit analysis has to be done on the tool and work piece interaction. In this paper, we have achieved the same using ANSYS software. Two different two flute micro end mills have been used for dynamic finite element analysis. ALE has been used for carrying out the analysis. Reference frame for the tool is chosen to be Langrangian and that for the workpiece is chosen to be Eulerian.

In order to get required interaction between the two bodies, the required body interaction constraints among them must be defined properly. Since the desired result is the simulation of machining operation, the contact between the tool and the work piece has to be frictional in nature. When the tool runs over the work piece, the friction generates heat energy. The chip carries the heat from the work piece and releases it in the environment. So a frictional contact is defined between the tool and the work piece. The static coefficient of friction is kept to be 0.39 and the dynamic coefficient of friction is kept to be 0.32 (Raczy et al.).

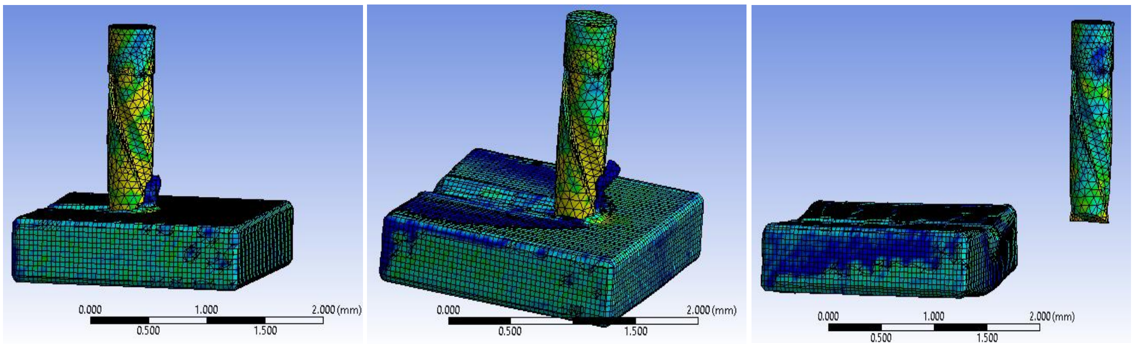
The work piece is fixed from three faces. The two side faces are given zero degree of freedom as they are constrained using mechanical fixtures while machining. The lower surface is given zero degree of freedom as they are held using vacuum fixtures. The tool is provided with an angular velocity of 20,000 rpm (Campos et al. [2013]). In the input variables, tool is provided with a linear velocity, which represents the feed rate of our machining operation. The feed rate in our setup is fixed to be 500 mm/sec (Campos et al. [2013]). The end time specifies the no. of iterations to be performed by the solver and informs the solver when to stop the process. Since the work piece is 20 mm in length, and the feed rate is 500 mm/sec, an end time of 0.05 seconds was chosen so that the entire tool length can be covered in the simulation. The total time taken in order to solve is 120 hours.

5.3.2 *Results*



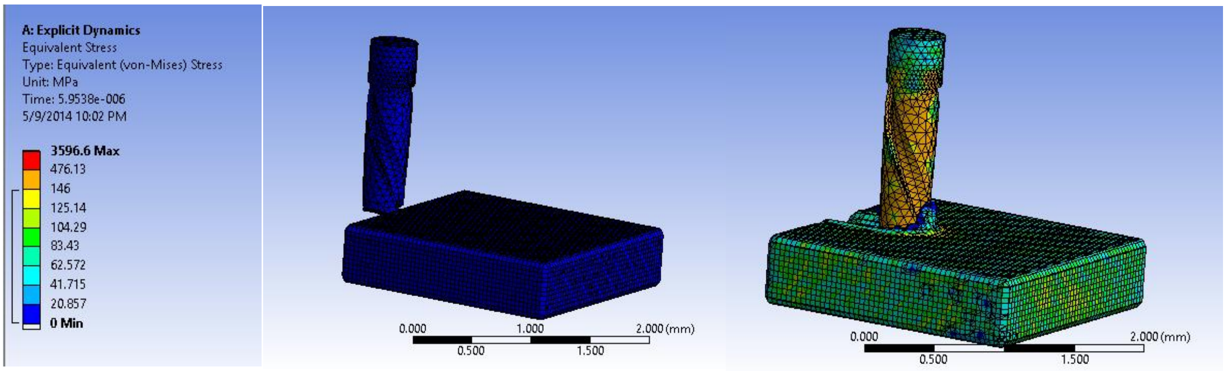
(a) Entry of tool into the workpiece

(b) Chip formation initiation

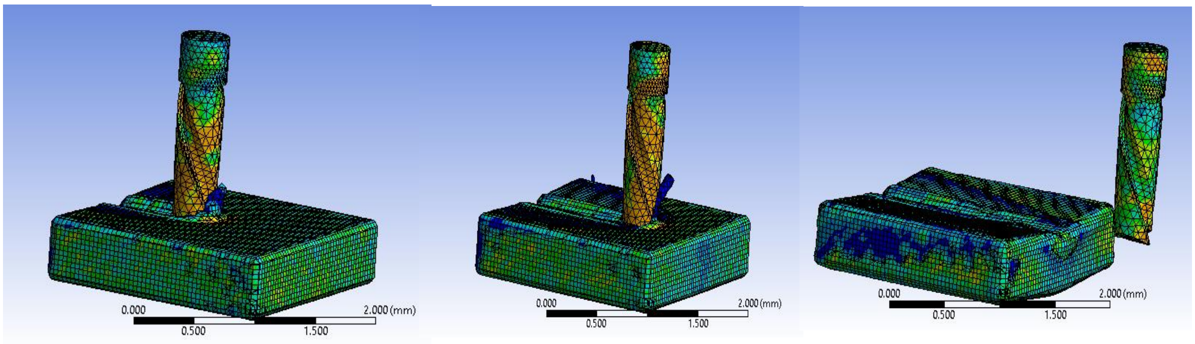


(c) Chip flow (d) Chip separation (e) Exit of tool from workpiece

Figure 5.7: Simulation of micro burr formation using tool with rake angle 3° and relief angle 8°



(a) Entry of tool into the workpiece (b) Chip formation initiation



(c) Chip flow (d) Chip separation (e) Exit of tool from workpiece

Figure 5.8: Simulation of micro burr formation using tool with rake angle 5° and relief angle 6°

CHAPTER 6

Conclusions and Future Directions

This chapter concludes the technical sum-up of the thesis work on three-dimensional geometric modeling and analysis of micro end milling cutters and simulation of micro burrs formed during micro milling of Al6061-T6 alloy by using a tungsten carbide two flute micro end mill cutter. This is followed by directions for future work.

6.1 Concluding remarks

Burr formation is a major hindrance to good surface finish in case of both macro and micro milling. However, burr formation in case of micro milling is of greater importance than in case of conventional milling as burrs formed in the former case are of sub-micrometer size and deburring processes are expensive, and sometimes impossible. Hence, burr minimization is the only way of obtaining good surface finish in microstructures.

To minimize formation of burrs in case of micro milling, either the cutting conditions or the tool geometry can be optimized. In this work, tool geometry optimization has been tried to be achieved by performing FE analysis on tools with different sets of rake and relief angles, for both two flute and four flute micro end mills. The results of the static finite element analysis of the tungsten carbide flat end micro milling tools offer the conclusion that in the given cutting conditions, the least amount of Von Mises stress generated in case of a two flute flat end micro mill cutter is for a cutter having rake angle -2^o and relief angles of 6^o and that in the case of four flute end micro mill cutter is for a cutter having rake angle 3^o and relief angle 8^o.

FE dynamic analysis of the tool-chip interaction in the micro milling process as performed and micro burr formation process was simulated using ANSYS 13.0 software.

6.2 Future scope

The results obtained from static FE analysis of micro end mills can be used in future to predict tool life and to choose the correct cutter geometry from available options for performing various micro milling operations.

The results obtained from dynamic analysis of micro burrs formed during micro-milling operation in Al6061T6 can benefit the aerospace industry, which utilises this alloy for fabrication of a large number of components.

The results obtained during the analysis may also be used for further research for burr minimization through tool optimization and process control.

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