KAUNAS UNIVERSITY OF TECHNOLOGY

FACULTY OF MECHANICAL ENGINEERING AND DESIGN

VENKATA NARAYANA RAO TIRUVEEDHULA

THE IVESTIGATION OF CUTTING FORCES IN MILLING, ACCORDING TO THE PROPERTIES OF STEEL

Final project for Master degree

Supervisor
Lecturer. Dr. Virginija Gylienė

KAUNAS, 2015

KAUNAS UNIVERSITY OF TECHNOLOGY

FACULTY OF MECHANICAL ENGINEERING AND DESIGN

THE IVESTIGATION OF CUTTING FORCES IN MILLING, ACCORDING TO THE PROPERTIES OF STEEL

Final project for Master degree

Mechanical Engineering (621H30001)

Supervisor
(signature) Lecturer. Dr. Virginija Gylienė
(date)

Reviewer
(signature) Assoc. Prof. Dr.Giedrius Janušas
(date)

Project made by Venkata Narayana Rao Tiruveedhula
(signature)
(date)

KAUNAS, 2015

KAUNAS UNIVERSITY OF TECHNOLOGY

Faculty of Mechanical Engineering And Design
(Faculty)

Venkata Narayana Rao Tiruveedhula
(Student's name, surname)

Mechanical Engineering,621H30001
(Title and code of study programme)

"THE IVESTIGATION OF CUTTING FORCES IN MILLING, ACCORDING TO THE PROPERTIES OF STEEL"

DECLARATION OF ACADEMIC HONESTY

04 June 2015
Kaunas

I confirm that a final project by me, Venkata Narayana Rao Tiruveedhula, on the subject "The Investigation of cutting forces in milling, according to the properties of steel" is written completely by myself; all provided data and research results are correct and obtained honestly. None of the parts of this thesis have been plagiarized from any printed or Internet sources, all direct and indirect quotations from other resources are indicated in literature references. No monetary amounts not provided for by law have been paid to anyone for this thesis.

I understand that in case of a resurfaced fact of dishonesty penalties will be applied to me according to the procedure effective at Kaunas University of Technology.

(name and surname filled in by hand) *(signature)*

KAUNAS UN IVERSITY OF TECHNOLOGY
FACULTY OF MECHANICAL ENGINEERING AND DESIGN

Approved:
Head of Mechanical Engineering Department

_______________ (Signature, date)

Vytautas Grigas
(Name, Surname)

MASTER STUDIES FINAL PROJECT TASK ASSIGNMENT
Study programme MECHANICAL ENGINERING

The final project of Master studies to gain the master qualification degree, is research or applied type project, for completion and defence of which 30 credits are assigned. The final project of the student must demonstrate the deepened and enlarged knowledge acquired in the main studies, also gained skills to formulate and solve an actual problem having limited and (or) contradictory information, independently conduct scientific or applied analysis and properly interpret data. By completing and defending the final project Master studies student must demonstrate the creativity, ability to apply fundamental knowledge, understanding of social and commercial environment, Legal Acts and financial possibilities, show the information search skills, ability to carry out the qualified analysis, use numerical methods, applied software, common information technologies and correct language, ability to formulate proper conclusions.

1. Title of the Project

THE INVESTIGATION OF CUTTING FORCES IN MILLING, ACCORDING TO THE PROPERTIES OF STEEL

Approved by the Dean 2015 y. May m.11d. _ Order No. ST17-F-11-2

2. Aim of the project

The determination of cutting forces in milling, according to the properties of steel C10-C60.

3. Structure of the project

Introduction of milling machines, classification of milling and terminology of milling, explanation of different types of milling machines. Investigation of milling cutting force methods such as analytical, numerical, experimental and hybrid. Chemical composition of carbon steel group C10-C60 and physical and mechanical characteristics of C10-C60, and selection of cutting conditions. Investigating analytical and 3D numerical milling methods to determine total cutting forces and results were compared.

4. Requirements and conditions

General Requirements for Master Thesis

5. This task assignment is an integral part of the final project
6. Project submission deadline: 2015 June 1st.
Given to the student

____

Task Assignment received Venkata Narayana Rao Tiruveedhula
(*Name, Surname of the Student*) (*Signature, date*)

Supervisor Lecturer. Dr.Virginija Gylienė
(*Position, Name, Surname*) (*Signature, date*)

Venkata Narayana Rao Tiruveedhula. Pjovimo jėgų tyrimas frezavimo proceso metu, priklausomai nuo plieno savybių. Final Master's degree project / supervisor Lecturer. Dr. Virginija Gylienė; Kaunas University of Technology, faculty of Mechanical Engineering and Design, Department of Mechanical Engineering

Kaunas, 2015. 54p.

SANTRAUKA

Šiame darbe aprašytas tyrimas pjovimo jėgų frezavimo atveju, pagal plieno grupės C10-C60 savybes. Pjovimo jėgos matavimas yra vienas iš dažniausiai naudojamų metodų apdirbimo procesų stebėsenai.
Analitinės išraiškos ir skaitinis modeliavimas yra naudojami nustatyti pjovimo jėgoms. Du tipai skaitinės analizės buvo realizuoti: skaitinio modelio adekvatumui patikrinti ir pjovimo jėgoms nustatyti, priklausomai nuo medžiagos, kai įrankiui užduota pastūma ir sukimasis. Dviem atvejais buvo atrinkti ty, kai priemonė juda suderinimas judėjimas ir sukamuoju judesiu. 3D skaitmeninis modeliavimas (FEM-SPH - *angl.)* atliekamas naudojant programinę įrangą LS – DynaV7. 3D baigtinių elementų modelis sukurtas atsižvelgiant į ruošinio matmenis ir pjovimo įrankį. Ruošinio medžiagos skerspjūvis tam tikros gyliu yra pašalinamas virtualaus modeliavimo metu. Po modeliavimo programa LS – Dyna, gautos pjovimo jėgos verteė. Skaitinės analizės rezultatai buvo palyginti su analitiniais metodais.

Venkata Narayana Rao Tiruveedhula, The Investigation of cutting forces in milling, according to the properties of steel, final Master's degree project / supervisor Assoc. Prof. Dr. Virginija Gyliene; Kaunas University of Technology, Faculty of Mechanical Engineering and design, Department of Mechanical Engineering.

Kaunas, 2015. 54 p.

SUMMARY

This paper describes the investigation of cutting forces in milling, according to the properties of steel group C10-C60. The measurement of cutting forces is one of the most frequently used techniques for the monitoring of machining processes. Analytical model and numerical models are used to determine the cutting forces. In analytical model and numerical model cutting tool moves in translational movement and rotational movement. Two types of numerical analysis was chosen: the numerical model a validity test and definition of cutting forces according to the steel material group C10-C60.

3D numerical FEM-SPH modelling is performed by using commercial software LS-DynaV7. A 3D finite element model is created by taking an account of workpiece dimensions and cutting tool. Workpiece material cross-section of given depth is removed during milling process. The inputs of the model consists of feed, cutting speed, depth of cut and physical and mechanical charecterisics of workpiece material. After running the simulation program in LS-dyna, cutting force values are obtained. The numerical results were compared with analytical results.

Table of Contents:

List of Figures:

List of tables:

1. **Introduction**:

Milling is the machining process in which rotary cutters are used to remove the workpiece material. Metal cutting process is common and an essential procedure for machining. Productivity in milling is usually reduced due to the process limitations such as high cutting forces and stability. The side and slot milling operation is one of the most broadly used for machining materials with relative high metal removal rates. In milling processes, prediction of cutting forces have great significance for machining free form surfaces. The determination of cutting forces helps to minimize tool deflections and vibrations in order to increases the tool life, to avoid tool breakage and to obtain a good surface finish.

In this research thesis four inserts of carbide cutting tools are used and different types of plain carbon steels from C10 to C60 are used as workpiece. Major contribution of this project is to determine the cutting forces in the case of side milling, by using composed 3D numerical FE-SPH model. Different kind of materials were selected to test the influence of material properties on cutting forces. The range of selected materials was as follows: C10, C20, C35, C40, C45, C50 and C60 according to EN 10020. These steels are classified as non-alloy steels and the other steel grades as non-alloy special steels. Numerical model was generated in numerical analysis and simulation is done by using LS-DYNA software 3.2 version package. The numerical results were compared with analytical formula.

Aim: The determination of cutting forces in milling, according to the properties of steel C10 - C60.

Objectives:

1. To investigate the cutting forces in analytical model for translational movement and rotational movement.
2. To investigate the cutting forces in numerical model (SPH-FE) test for translational movement: to study the numerical model validity.
3. The definition of cutting forces according to steel material group (C10-C60) in rotational movement.
4. The comparison between analytical and numerical models for translational and rotational movements should be done.

2. Literature Review:

2.1 Introduction of Milling Machine:

The Milling machines are most adaptable. Milling machines have lots of usage as they are usually used to machine flat surfaces, but can also produce uneven surfaces. They can also be used to drill, bore, cut gears, and produce slots [4]. Milling machine is a machine tool in which metal is removed by means of a revolving cutter with many teeth within, each tooth have a cutting edge which helps in removing the metal from a work piece [3]. As this machine yields high production of different varieties of jobs, in choice for production machines, it comes after the lathe.

2.1.1 Working Principle:

Working principle of a milling machine as shown in Fig.2.1. The Milling machine removes metal with fast rotating multi-tooth cutter, each tooth having a cutting edge which removes metal from the workpiece when the workpiece fixed on the machine table is fed to the cutter longitudinally, transversely, or vertically by operating the table feed accordingly. The multi-tooth cutter is known as milling cutter which has equally spaces peripheral teeth on it.

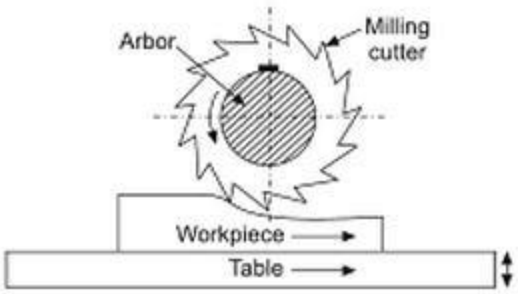


Figure 2.1: Working principle of a milling machine [3]

2.2 Classification of Milling:

Milling operations may be classified under three general heading as follows:

1. Slab Milling
2. Face Milling
3. End Milling

2.2.1 Slab Milling:

In slab milling, the axis of cutter rotation is parallel on the work piece surface to be machined .Cutter for slab milling may have straight or helical teeth resulting in respectively, orthogonal or oblique cutting action. The helical tooth on the cutter is preferred over straight teeth because the load on the tooth is lower. Slab mills are used either by themselves or in gang milling operations on manual horizontal or universal milling machines to machine large broad surfaces quickly [7].

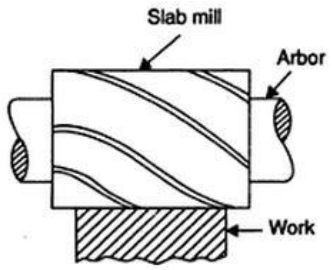


Figure 2.2: Slab Milling [4]

2.2.2 Face Milling:

In face mill machines the depth of face is typically small, may be machined in a single pass or can be machined by making multiple passes. In face milling operation workpiece can get smooth surface finish.

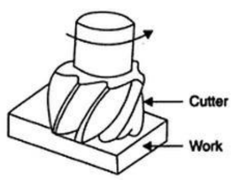


Figure 2.3: Face Milling [4]

2.2.3 End Milling:

An end mill makes either peripheral or slot cuts, determined by the step-over distance, across the work piece in order to machine a specified feature, such as a profile, slot, pocket, or even a complex surface contour. The depth of the feature may be machined in a single pass or may be reached by machining at a smaller axial depth of cut and making multiple passes [7].

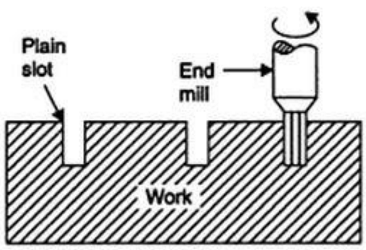


Figure 2.4: End Milling [4]

2.3 Mechanism of Milling:

Generally there are two types of milling processes, namely:

1. Up-milling or conventional milling process
2. Down milling or climb milling process.

2.3.1 Conventional Milling Process:

Conventional Milling is also called as Up Milling. In conventional milling, the workpiece material is removed by a rotating cutter in the form of small chips against the direction of travel to the workpiece. In this type of milling, the chip thickness is zero at the start of the cut and becomes maximum at the end of cut [6]. As a result the cutting force also varies from zero to the maximum value per tooth movement of the milling cutter. The major disadvantages of conventional-milling process is poor surface finish. But it is a commonly used method in milling [6].

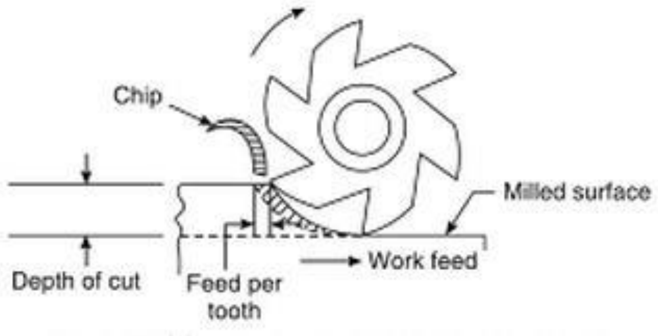


Figure 2.5: Conventional Milling [5]

2.3.2 Climb Milling Process:

Climb Milling is also known as Down Milling. In this method, the metal is removed by a cutter rotating in the same direction of feed of the work piece. The effect of this is that the teeth cut downward instead of upwards. Chip thickness is maximum at the start of the cut and becomes minimum in the end. In this method, it is claimed that there is less friction involved and consequently less heat is generated on the contact surface of the cutter and work piece [6]. Climb milling can be used advantageously on many kinds of work to increase the number of pieces per sharpening and to produce a better finish.

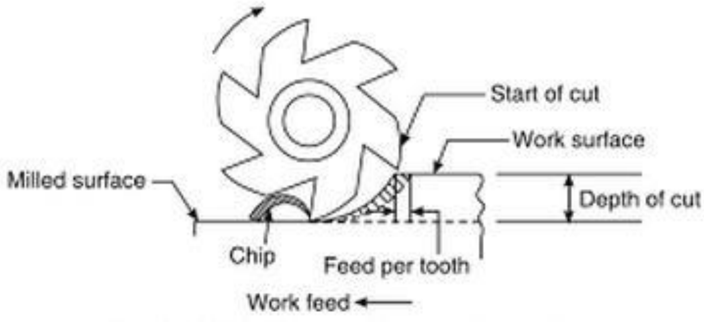


Figure 2.6: Climb Milling [5]

2.4 Types of milling machine

Milling Machines are available in various designs covering a wide range of work and capabilities. In present situation many of these machines and operations are now being replaced with computer controls and machining centres (CNC). Broad classification of milling machines according to their design features is as follows:

1. Column and knee type
2. Bed-type Milling Machines
3. Other Types of Milling Machines

2.4.1 Column and Knee type:

Column and knee type machines are used for general-purpose milling operations, these are the most common milling machines. The spindle on which the milling cutter is mounted may be horizontal Fig.2.7 for peripheral milling or vertical for face and end milling, boring, and drilling operations Fig.2.8. The basic components of these machines are as follows [7]:

i. **Worktable:** Workpiece is clamped using T-slots on the worktable. The table moves longitudinally relative to the saddle.
ii. **Saddle:** It supports the table and can move in the transverse direction.
iii. **Knee:** It supports the saddle and gives the table vertical movement so that the depth of cut can be adjusted and Workpieces with various heights can be accommodated.
iv. **Overarm:** used on horizontal machines; it is adjustable to accommodate different arbor lengths.
v. **Head:** contains the spindle and cutter holders. In vertical machines, the head may be fixed or can be adjusted vertically, and it can be swivelled in a vertical plane on the column for cutting tapered surfaces.

Plain milling machines have three axes of movement, with the motion usually imparted manually or by power. In universal column-and-knee milling machines, the table can be swivelled on a horizontal plane. In this way, complex shapes (such as helical grooves at various angles) can be machined to produce parts such as gears, drills, taps, and cutters [7].

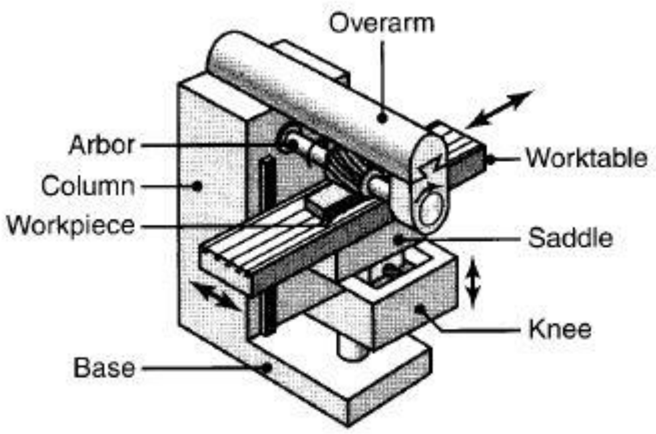


Figure 2.7: Horizontal-spindle column-and-knee-type milling machine [8]

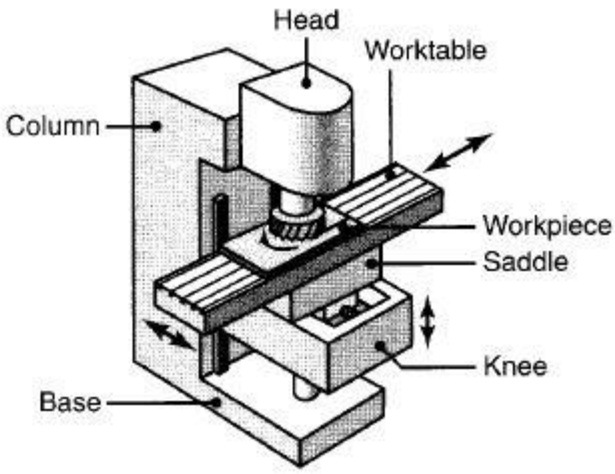


Figure 2.8: Vertical-spindle column-and-knee-type milling machine [8]

2.4.2 Bed-type Milling Machines:

In bed-type machines, the worktable is mounted directly on the bed, which replaces the knee and can move only longitudinally Fig 2.9. These machines are not as versatile as other types, but they have high stiffness and typically are used for high- production work. The spindles may be horizontal or vertical and of duplex or triplex types (with two or three spindles, respectively), for the simultaneous machining of two or three Workpiece surfaces [8].

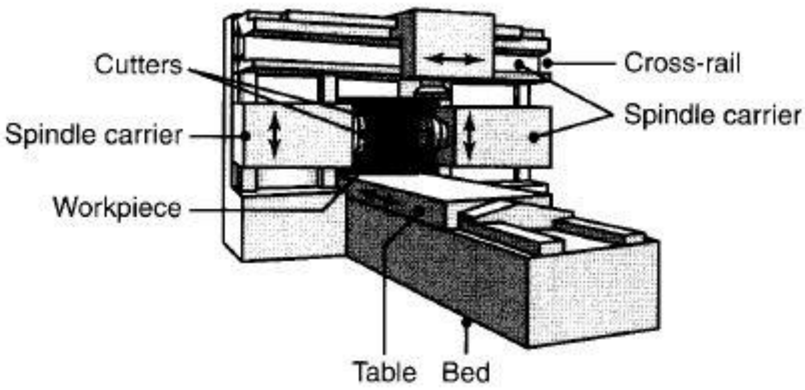


Figure 2.9: Bed-type milling machine [7]

2.4.3 Other Types of Milling Machines:

Several other types of milling machines are available such as Planer-type milling machines, which are similar to bed-type machines are equipped with several heads and cutters to mill different surfaces. They are used for heavy workpieces and are more efficient than simple planers when used for similar purposes. Rotary-table machines are similar to vertical milling machines and are equipped with one or more heads for face-milling operations [8]. Milling machines have been rapidly replaced by computer numerical-control (CNC) machines for all but the lowest production quantities. These machines are versatile and capable of milling, drilling, boring, and tapping with repetitive accuracy Fig. 2.10. Also available are profile milling machines, which have five axes of movement Fig. 2.11; note the three linear and two angular movements of the machine components [8].

Figure 2.10: CNC Milling Machine [6]

s**3. Theoretical Part:**

3.1 Cutting tool:

Many types of tool materials, ranging from high carbon steel to ceramics and diamonds, are used as cutting tools in today's metalworking industry. The cutting tool materials influence the machining operations essentially and it is very important to select the proper tool material for a particular task. Cutting tools are subjected to high localized stresses, high temperatures, chip sliding along the rake face, and tool flank sliding along the naturally cut surface which directly cause tool wear [17].

The cutting tool materials must possess a number of important properties to avoid excessive wear, fracture failure and high temperatures in cutting. Important characteristics of cutting tool are hardness, specifically hot hardness, toughness, wear resistance, and chemical stability or inertness with respect to the workpiece material [18]. By following these characteristics cutting tool can be able to produce a good quality part in an economic manner. Cutting tool materials are generally divided into various categories, such as- Carbon and medium-alloy steels, High-speed steels (HSS), Carbides, Coated Tools, Alumina-base ceramics, Cubic boron nitride (CBN), Silicon-nitride-base ceramics, Diamond, and Whisker-reinforced materials [17].

3.1.1 Carbon Steels:

It is the oldest of tool material. The carbon content is 0.6to1.5% with small quantities of silicon, chromium, manganese, and vanadium to refine grain size. Maximum hardness is about HRC 62. This material has low wear resistance and low hot hardness [19].

3.1.2 High-speed steel (HSS):

High-speed steels are highly alloyed with vanadium, cobalt, molybdenum, tungsten and chromium added to increase hot hardness and wear resistance [19]. Can be hardened to various depths by appropriate heat treating up to cold hardness in the range of HRC 63-65. With the high toughness and good wear resistance properties HSS can be suitable for all type of cutting tools with complex shapes for relatively low to medium cutting speeds [19]. Taps, drills, reamers, gear tools, end cutters, slitting, broaches are the most widely used tools.

Figure 3.1: Thread tap and die made of high-speed steel [19]

3.1.3 Cemented Carbides:

Cemented carbides are the most important tool materials today because of their high hot hardness and wear resistance. The main disadvantage of cemented carbides is their low toughness [19]. These materials are produced by powder metallurgy methods, sintering grains of tungsten carbide (WC) in a cobalt (Co) matrix (it provides toughness). There may be other carbides in the mixture, such as titanium carbide (TiC) and/or tantalum carbide (TaC) in addition to WC [19].

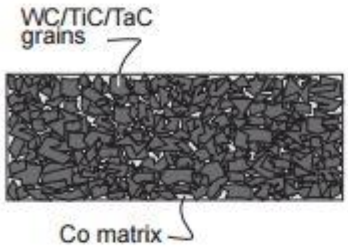


Figure 3.2: Microstructure of cemented carbides [19]

In spite of more traditional tool materials, cemented carbides are available as inserts produced by powder metallurgy process [19].

Figure 3.3: Different types of cemented carbide inserts for use by different cutting tools [19]

Inserts are available in various shapes, and are usually mechanically attached by means of clamps to the tool holder, or brazed to the tool holder.

Carbides (cemented or sintered carbides) are used for higher rates of production. Those are the most important, versatile and cost effective tool materials for a wide range of applications [17]. To compare the operating characteristics of uncoated and coated carbide tools, it can be noted that the uncoated carbide tools are high hardness over a wide ranges of temperatures, toughness, wear resistance, versatility and wide range of applications whereas the coated carbides have improved wear resistance over uncoated ones, and better frictional and thermal properties [17].

3.1.4 Ceramics:

Ceramic materials are composed primarily of fine-grained, high-purity aluminium oxide (Al_2O_3), pressed and sintered with no binder. Basically two types of ceramics are available [19]:

1. White, or cold-pressed ceramics, which consists of only Al_2O_3 cold pressed into inserts and sintered at high temperature.

2. Black, or hot-pressed ceramics, commonly known as cermet (from ceramics and metal). This material consists of 70% $Al_2O_3$and 30% TiC.

Both materials have very high wear resistance but low toughness, therefore they are suitable only for continuous operations such as finishing, turning of cast iron and steel at very high speeds.

3.1.5 Cubic boron nitride (CBN) and synthetic diamonds:

Diamond is the hardest substance ever known of all materials. It is used as a coating material in its polycrystalline form, or as a single-crystal diamond tool for special applications, such as mirror finishing of non-ferrous materials [19]. Next to diamond, CBN is the hardest tool material. CBN is used mainly as coating material because it is very brittle. In spite of diamond, CBN is suitable for cutting ferrous materials [19].

3.2 WorkPiece Material:

The metal cutting industry produces an extremely wide variety of components machined from many different materials. Each material has its own unique characteristics that are influenced by the alloying elements, heat treatment, hardness, etc [17]. The conditions and physical properties of the work material have a direct influence on the machinability of a workpiece material. There are some various conditions and characteristics described as "condition of work material" [18].

3.2.1 Condition of Work material:

The following eight factors ascertain the condition of work material: They are

1. **Microstructure:** The microstructure of any metal highlights the crystal or grain view of a structure for the surface that is prepared and polished as revealed by a magnification under a microscope. The machining behaviours and properties are originated to be same for the homogeneous microstructures of various metals. The main outlook regarding the microstructure can be the variations in similar work piece that will influence the ability of machine [18].
2. **Grain Size:** Grain size or particle size and structure of any metal performs a key role as a barometer that indicates the significant ability to ease machinability. Tiny undistorted grains of any metal subjects to be cut down and finish easily when compared to other metals. Those type of metals have the property of ductility and are 'gummy' [18] in nature. Intermediate size of a grain provides a conclusion that allows both finishing as well as cutting machinability. Hardness of a metal together with grain size is also an indicator of machinability which is so useful [18].

3. **Heat Treatment:** When the metal is in its solid state, the metal is undergone through the series of heating and cooling procedures for acquiring the desired properties of an ideal metal. A material of any kind is subjected to treatments in reduction of brittleness, removal of stress, to obtain the nature of toughness or ductility, to increase strength, to gain microstructure, to change hardness or to make various changes that turn machinability [18].
4. **Chemical Composition:** The significant factor in determining the machinability is chemical composition of a metal. Non-ferrous alloys that are made up of different compositions are permitted to certain type of generalizations, which are about chemical compositions of steel with respect to machinability [18]. The components that create an alloy metal work singly as well as collectively, this is the reason for the observed effects in compositions which aren't clear [18].
5. **Fabrication:** The qualities of any metal to be hot or cold rolled, cold drawn, cast or forged will place a great affect in the properties of mental being grain size, ductility, strength, hardness or its structure and even in its machinability [18].
6. **Hardness:** Hardness is the tendency of being hard for a material to resist deformation. Hardness is often measured using either the Brinell or Rockwell scale. Cutting speed is always selected based on the hardness which tends to higher speed and hence productivity is enhanced by less hardness of a material [18]. The tool life is reduced by the rise in temperatures for certain cutting speed with part hardness and cutting loads and is also affected by increasing hardness in work piece. In milling, increased material hardness produces higher impact loads as inserts enter the cut, which often leads to a premature breakdown of the cutting edge [18].
7. **Yield Strength:** The yield strength is the stress at which a material deform and is measured just before the process of permanent deformation [18]. The properties of tensile strength and yield strength are known by the test of conducting tensile. During the heat treatment the yield strength increases simultaneously with the hardness of material. When compared to moderate strengths, high yield strength materials are found relatively difficult for machine and leads to reduce the tool life [18].
8. **Tensile strength:** The tensile strength is the maximum stress the metal withstands and it increases with respect to yield strength as it is treated with heat with increased levels of hardness. This property of a material is also established using a tensile test [18].

In this research paper, workpiece material is taken as carbon steel group from C10 to C60.

3.3 Physical and Mechanical Characteristics of C10 – C60:

The term steel is used for many different alloys of iron. These alloys vary both in the way they are made and in the proportions of the materials added to the iron. All steels, however, contain small amounts of carbon and manganese. In this research paper we are talking about the plain carbon steel from C10 to C60.

3.3.1 Plain carbon steels:

Carbon steels are widely used kind of steel of which maximum carbon content is 1.5% along with small percentages of silica, sulphur, phosphorus and manganese. Most carbon steel has a carbon content of less than 1% and the properties of carbon steel are depend on the content of carbon. Plain carbon steels are numbered in a four digit code according to the AISI or SAE system (i.e. 10XX). The last two digits of the code indicate the carbon content of the material in hundredths of a percentage point. For example, AISI 1030 steel has a 0.30% carbon content [18].

Generally plain carbon steel are categorized into four types.

1. **Low carbon steel or mild steel:** Low carbon steels of which having carbon content up to 0.25%. It is a low-cost material that is easy to shape. While not as hard as higher-carbon steels, carburizing can increase its surface hardness.
2. **Medium Carbon Steel:** In medium carbon steel, carbon composition ranging from 0.25 to 0.45%. Medium carbon steel is ductile and strong, with long-wearing properties.
3. **High Carbon Steel:** In high carbon steel, carbon composition ranges from 0.45 to 0.75% carbon. It is very strong and holds shape memory well, making it ideal for springs and wire.
4. **Very High Carbon Steel:** With up to 1.50% carbon content, very high-carbon steels are used for hard steel products such as metal cutting tools and truck springs. Like high-carbon steels, they require heat treating before, during, and after welding to maintain their mechanical properties.

3.3.2 Physical Properties of Work Materials:

Physical properties will conclude those characteristics included in the individual material groups, such as the modulus of elasticity, thermal conductivity, thermal expansion and work hardening [19].

1. **Modulus of elasticity:** The modulus of elasticity is the ratio of stress to the strain that can be determined during the tensile test as stress in not directly measurable. The modulus of elasticity is determined material property which is fixed and is unaffected by the heat treatment unlike hardness, yield or tensile strength [19].
2. **Thermal conductivity:** Thermal conductivity is the degree to which a specified material conducts and is a measure of heat transferred accurately as well as efficiently. The material that has lower level of thermal conductivity is referred as an inductor whereas the one with relatively higher conductivity is considered as conductor [19].

3. **Thermal expansion:** Thermal expansion is the tendency of matter to change in volume in response to change in temperature with respect to heat transfer. The rate at which metals expand varies in accordance with the alloy of material which is considered and can be determined using materials expansion coefficient [19]. If the value of this expansion coefficient is high then the material will expand to a temperature rise or contracts when subjected to temperature reduction.
4. **Work hardening:** Work hardening is also known as strain hardening in which heat plays an efficient role to increment the material hardness. Work hardening is also referred as cold working in which some metals produce high hardness. Cold working involves the changes in shapes of a metal by deforming, bending, rolling and shaping. Internal stress among develops as metal is shaped and acts to harden the part [19]. When materials exhibit work hardening or cold working they are subjected to increase temperature and produce the high hardness to the work piece [19].

3.3.3 Applications:

Plain Carbon Steel C10:

C10 carbon steel is used in Automobile components, including auto bodies, fenders, pans, washers, rivets, and brushings [25].

Plain Carbon Steel C20:

C20 steel is used in case hardened condition. The applications of C20 steel are: It is used for simple structural application such as cold headed bolts. C20 steel is also used in shafts, camshafts, ratchets, spindles, gudgon pins [26].

Plain Carbon Steel C35:

C35 grade of steel is used for manufacture of links and couplings, gears, forges shafts and axles. It is also used for the production by open die forging [25].

Plain Carbon Steel C40:

This grade of steel is used for forged parts where the strength and toughness of the material. C40 can be used for the manufacture of forged crankshafts and couplings, along with range of parts where the properties of heat treated C40 are suited to the application [25].

Plain Carbon Steel C45:

C45 is widely used for all industrial applications requiring more wear resistance and strength. Typical applications of C45 are gears, shafts, axles, studs, connecting rods, pins, spindles, torsion bars [26].

Plain Carbon Steel C55:

Applications of C55 include battering tools, hot upset forging dies, ring-rolling tools, wear-resistant parts, hand tools, and parts for agricultural implements which require high strength at low cost. When heat treated, this steel C55 yields a high surface hardness, combines with good toughness [27].

Plain Carbon Steel C60:

Applications of C60 is almost same for C55 which includes battering tools, hot upset forging dies, ring-rolling tools wear-resistant parts, hand tools [27].

4. Investigation of milling cutting force methods:

As the prominence of product quality, cost management and productivity in manufacturing many methods have been developed to maintain the above standards. So to maintain these standards cutting force plays an important role in cutting process. Many models have been developed to model and predict cutting forces in machining operations. During machining operations cutting forces should be reduced to increase the productivity and quality of the product. Here in this research project we are discussing few methods in cutting processes.

4.1 Analytical method:

Analytical methods have anticipated the occurrence of new bifurcation phenomena in interrupted cutting processes. Many empirical, analytical or finite element models have been developed in orthogonal cutting, in oblique cutting or more recently in 3D turning and 3D milling [9]. Merchant has proposed the first basic analytical model in orthogonal cutting taking into account only shearing effects in a specific plane orthogonal to the cutting edge [9]. The useful of this LS-Dyna is to simulate the cutting forces and chip formation during the cutting process. With analytical model, the material behaviour is described with a Johnson and Cook constitutive law (Johnson and Cook, 1983) [9] and a modified Merchant law.

The Johnson–Cook model is well-accepted, numerically robust and heavily utilized in modelling and simulation studies [9]. This model describes flow stress as a product of strain, strain-rate and temperature dependent terms

$$R = [A + B\varepsilon^n]\left[1 + Cln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon_0}}\right)\right][1 - (\frac{T - T_0}{T_f - T_0})]$$

Where *A* corresponds to yield strength, *B* and *n* corresponds to the hardening coefficients, *C* defined the strain rate sensitivity, and *m* defined the temperature dependency coefficient. T_f And T_0 are respectively the melting temperature and the ambient temperature.

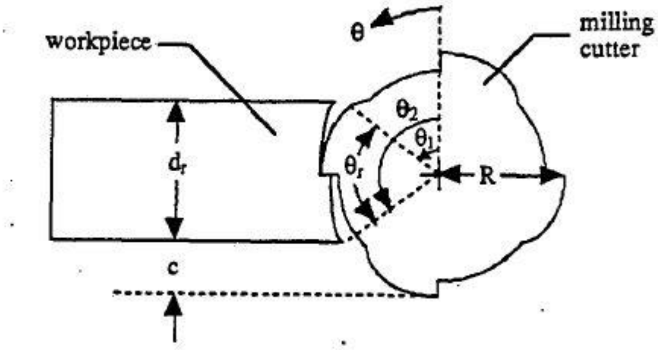


Figure 4.1: 2Dimentional view of 4tooth milling cutter [10]

However, the cutting force analytical model the specific cutting force equation is represented as

$$K_C = \frac{1-0.01\times\gamma_0}{h_m^{mc}} \times k_{c\,1.1}$$

Where, K_c is the Cutting force parameter, $\gamma_0$is the effective rake angle, $k_{c\,1.1}$is the cutting force for 1mm chip thickness.

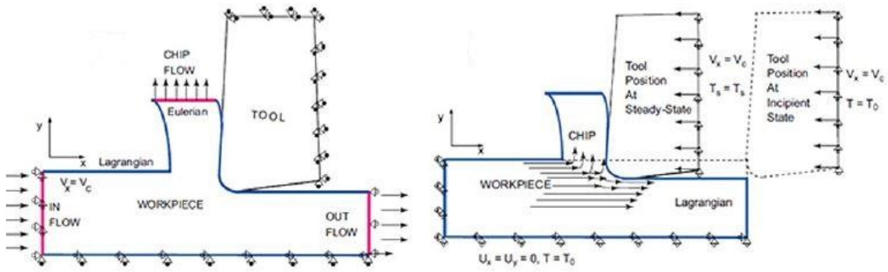
$$h_m = \frac{360\times f_z \times a_e}{\pi\times D_c \times\omega_e}\times \; sin_{\;k}$$

Where, h_m is the average chip thickness (mm), f_z is the feed per tooth (mm/tooth), D_c is the cutter diameter (mm), ω_e is the engagement angle, k is the cutting edge angle [10].

4.2 Numerical methods:

During last year's many numerical models using finite element method have been developed for material forming simulations. Industries and research laboratories have focused on these developments to try to understand, analyse the physical phenomena in the metal cutting process [12]. In the field of machining, these models are complementary to the analytical models, more efficient for considering industrial operations but limited in output data. The FE models are used particularly to provide more information on strain, stress contours and temperature field in the machined material zones or in the tool.

Numerical models are essentially based on three possible descriptions: Lagrangian, Eulerian and Arbitrary Lagrangian Eulerian (ALE) [12]. A Lagrangian mesh deforms in time with the material. An Eulerian mesh is fixed in space (control volume). In both analyses, either implicit or explicit time integration techniques can be utilized. A major drawback of the Eulerian formulation is the assumption of a steady-state mesh configuration [12]. The ALE method combines the both features of Lagrangian and Eulerian methods, and selects explicit model for fast convergence.



(a) (b)

Figure 4.2: FEM models for ALE formulation with (a) Eulerian and Lagrangian boundary Conditions, and (b) pure Lagrangian boundary conditions [12]

New methodologies based on meshless techniques have been produced. However, they are not generally utilized as a part of the machining field. In machining operations, the improvement approach requires to choose suitable tool, tool paths and cutting conditions (particularly cutting speed and feed). During machining process thermal factor has a great impact on material behaviour. So in the developed simulation program thermal properties are considered. Finally the heat equation is represented as [12]:

$$\rho c \frac{dT}{dt} = \beta \bar{\sigma} \dot{\bar{\epsilon}}$$

Where β is the Taylor–Quinney coefficient corresponding to heat fraction dissipated by deformation process, $\bar{\sigma}$ is the equivalent stress and $\dot{\bar{\epsilon}}$ is the strain rate. Therefore, a FE numerical modelling of milling is proposed in order to obtain numerical cutting forces.

The numerical results are finally compared to cutting forces calculated by analytical method and also it can be compared with other models.

4.3 Experimental Method:

Experimental method is a cost-effective technology used in machining process. In order to measure the apparent coefficient of friction on the rake face, we conducted orthogonal tube cutting tests on a conventional lathe. In Fig 4.3 shows the experimental setup involves dynamometer and DAQ setup to collect the cutting force data. Dynamometer is used to measure the normal and friction forces. A fine slider in order to make the initial contact between tool and workpiece smoother, and a DAQ setup in order to collect the data [23]. In this experimental process uncoated carbide is used as tool material with 5˚ rake angle and carbon C10 to C60 is used as workpiece material. . The cutting speed range was 130m/min and the feed rate range was 1mm/min.

After each experiment the chip cut thickness is measured by two methods. In the first measurement method, the cut chip thickness is simply measured by a micrometre. In the second method the average thickness of the cut chip is determined from weight measurements and the mean value of the chip cut thickness is used for shear angle calculations [23]. The apparent friction coefficient on the rake face between the tool and the workpiece is calculated as follows [23]:

$$\mu = \tan(\text{rake} + \text{atan}\,(^{F_f}/_{F_t}))$$

Where, F_f and F_t are the measured feed and tangential forces respectively. It is common to observe higher cutting forces with higher workpiece hardness. However, it is also observed that different thermal properties of the tool material may result in lower cutting forces [13]. Therefore, in order to understand the process better and improve the performance of cutting tools, the use of deformation theory and advanced numerical techniques is recommended.

Figure 4.3: Experimental test setup [23]

4.4 Hybrid method:

Today a very interesting challenge derives from the combining of different classes on analysis called hybrid-models. Combining of some analytical, numerical, empirical or Artificial Intelligence (AI)-based methods may result hybrid method. The main purpose of this hybrid model is to propose the easy implementing approach for the complex tool geometry and cutting force predictions [16]. In recent studies, Artificial Intelligence (AI) based methods such as neural networks, genetic algorithms, Gene-Expression Programming (GEP) model, which is an extension to genetic programming, and other machine learning methods are being utilized to expand the capabilities of empirical models [15].

The aim of this approach is to predict 3D cutting forces from 2D numerical simulations. This can be achieved with the use of the chip flow angle (CFA) from which an equivalent uncut chip thickness was deduced. Number of analyses have been conducted in the field of chip flow direction and cutting force predictions. Gene Expression Programming (GEP) is suitable to model complex physical phenomenon with explicit expression, which provides a promising way to predict cutting force in face milling. GEP does not require a precise formulation of physical relationships, however, it can find the precise expression for cutting force [28].

Basic framework of GEP:

GEP proposed by Candida Ferreira in 2001 (Ferreira, 2001) is a means of developing functions through the evolutionary process of natural selection. GEP combines the advantages of Genetic Algorithm (GA) and Genetic Programming (GP) [28]. It is a genotype/ phenotype genetic algorithm that evolves computer programs with different sizes and shapes encoded in linear chromosomes of fixed length. The chromosomes are composed of multiple genes, each gene encoding a smaller subprogram [28].

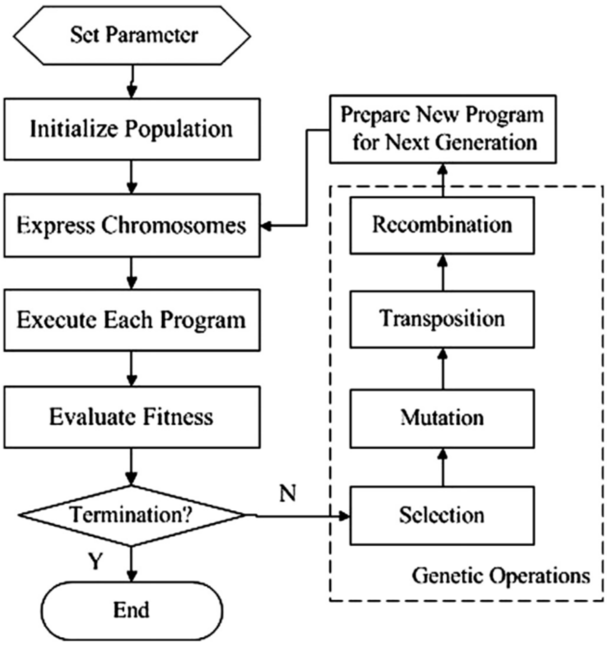


Figure 4.4: Flow chart of GEP [28]

However, this paper is concerned with mostly based on analytical and numerical modelling approaches.

5. Research part:

5.1 Milling case study:

The aim of this research paper is to determine the cutting forces for plain carbon steel group C10 to C60. Side milling cutters can handle long, deep, open slots in a more efficient manner, and gives the best stability and productivity for this type of milling. Side milling operation in which two or more milling cutters are mounted on the same arbor and used to machine more than one surface in the same plane in the meantime. To keep the chip thickness at same value, it is necessary to increase the feed rate and it is also possible to increase the cutting tool speed to keep the same tool life [11]. Fig. 5.1 shows the schematic diagram of side milling. In side milling the cutting tool cuts the workpiece material in translational movement. The main cutting force F_x is the tangential cutting force and F_y is the normal cutting force.

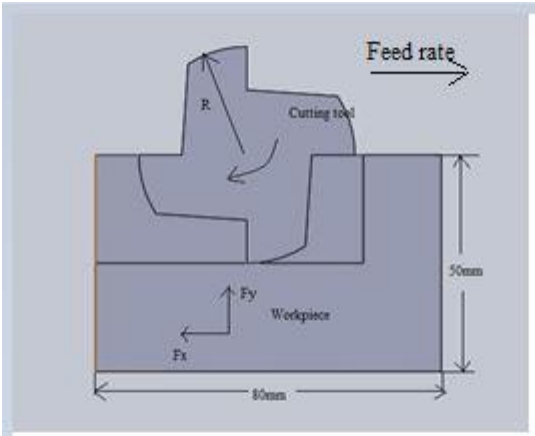


Figure 5.1: Schematic diagram of side milling

Fig. 5.2 shows the schematic diagram of slot milling. In this slot milling the cutting tool rotates and cuts the workpiece material. The main force F_y is the tangential cutting force and F_x is the normal cutting force. Slot milling can produce flat and complex shapes with the use of multi-tooth cutting tool.

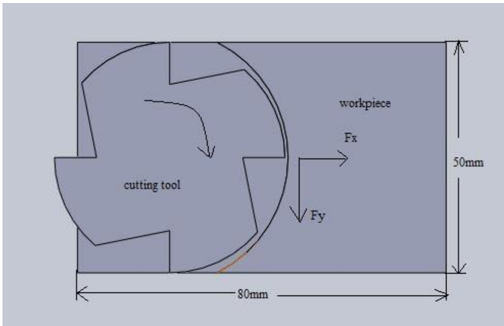


Figure 5.2: Schematic view of 2D slot milling

By using side milling process cutting forces of carbon steel group (C10-C60) are determined in analytical and numerical analysis.

5.2 Chemical composition of C10-C60:

Variations in steel compositions are responsible for a great variety of steel grades and steel properties. The table 1 shows the chemical composition of C10 (Mild steel) to C60 (Hard steel)

Table 1: Chemical composition of steel from C10 to C60 [25, 26]

Material Type	Carbon (C) %	Manganese (Mn) %	Phosphorus(P) %	Sulphr (S) %	Silicon (Si) %	Chromium (Cr) %	Nickle (Ni) %	Molybdenum (Mo) %
C10	0.10	0.30-0.60	Max 0.045	Max 0.045	Max 0.40	-----	-----	-----
C20	0.20	0.80	0.06	0.06	0.10	-----	-----	-----
C35	0.32-0.39	0.50-0.80	Max 0.045	Max 0.045	Max 0.40	Max 0.40	Max 0.40	Max 0.10
C40	0.37-0.44	0.6-0.9	0-0.04	0-0.05	-----	-----	-----	-----
C45	0.43-0.50	0.50-0.80	Max 0.045	Max 0.045	Max 0.40	Max 0.40	-----	Max 0.10
C55	052-0.60	0.60-0.90	Max 0.045	Max 0.045	Max 0.40	Max 0.40	Max 0.40	Max 0.10
C60	0.57-0.65	0.60-0.90	0.025	0.025	-----	0.20-0.40	-----	-----

5.3 Physical and Mechanical properties of C10-C60:

Steel derives its mechanical properties from a combination of chemical composition, heat treatment and manufacturing processes. There are also other properties of plain carbon steel that needs to be considered. Table 2 shows the material properties of the workpieces from C10 to C60. It is essential for successfully simulating, the cutting process to use a proper material-constitutive model for the workpiece. By using these properties Tangent modulus is solved.

The formula for finding Tangent modulus is

$$\text{etan} = \frac{\sigma_s - \sigma_y}{e - e_y}$$

Where, σ_s is the Tensile strength, σ_y is the Yield strength, e is the elongation in percentage value, δ_y is the Deformation at the yield point. Recommended deformation at the Yield point is considered as 0.002mm. Physical and mechanical characteristics of carbon steel C10-C60 are used in

FE model. Variations in Tangent modulus is responsible for increase and decrease of cutting forces in numerical analysis. To define each material these properties are used in SPH-FE numerical model.

Table 2: Physical and Mechanical carbon steel Characteristics of C10 to C60 [25, 26]

Carbon Steel	**Modulus of elasticity [MPa]**	**Density [g/c m^3]**	**Elongation [%]**	**Yield Strength [MPa]**	**Poisson index**	**Tensile strength [MPa]**	**Tangent Modulus [MPa]**
C10	210	7.85	15	450	0.30	750	2027
C20	190	7.85	25	245	0.28	410	827
C35	200	7.85	17	430	0.29	630	1190
C40	200	7.70	15	450	0.29	750	2027
C45	205	7.85	16	370	0.29	700	2089
C55	200	7.85	16	450	0.28	760	1962
C60	210	7.85	14	490	0.30	750	1884

5.4 Selection of cutting conditions:

To perform Milling operation high cutting speed and feed rate is required. While performing milling operation it is necessary to check weather power required to cut the workpiece is within the capacity. More power is required when cemented carbide cutters are using. For more metal removal rate it requires high horsepower.

The selection of cutting conditions involves 3 phases [24]. Selection of depth of cut will be initial phase. Maximum depth of cut can be given to the workpiece and it has the least impact upon the tool life.

The second phase is selection of feed. The available power must be sufficient to make the required depth of cut at the selected feed. The maximum feed possible that will produce an acceptable surface finish should be selected [24].

The third phase is selection of cutting speed. Machinery guide books provide the recommended cutting speeds for different types of materials. Those recommended cutting speeds are already machined to adjust for particular job [24]. However, in general the sequence of selecting cutting conditions are as follows: Depth of cut should be selected first, followed by the feed, and last the cutting speed.

The formula for calculating the table feed rate, when the feed in inches per tooth is known, is as follows:

$$\boldsymbol{v_f} = f_t \ n_t \ N$$

Where v_f is the milling machine table feed rate in mm per minute, $f_t$is the feed in mm per tooth, n_t is the number of teeth in the milling cutter, N is the spindle speed of the milling machine in revolutions per minute (rpm).

The recommended cutting speed and feed rate conditions of different types of carbon steel group C10-C60 are listed in table3. The depth of cut, and feed rate will affect the cutting speed conditions. These three Variables i.e, depth of cut, feed rate and cutting speed are known as cutting conditions. Machinability is the comparing of materials on their ability to be machined. From machinability ratings we can derive recommended cutting speeds.

Table 3: Cutting speeds and feed rates of C10 to C60 [21, 22]

Plain Carbon Steel AISI	**Brinell Hardness (HB)**	**Cutting Speed v_c(m/min)**	**Feed Rate, f_t (Feed per tooth, mm)**
1010	105	182	0.304
1020	121	137	0.304
1035	183	152	0.28
1040	201	183	0.254
1045	163	183	0.254
1055	197	122	0.304
1060	183	122	0.304

The milling machine speed must be set so that the milling cutter will be operating at the correct cutting speed. To set the proper speed it is necessary to calculate the proper RPM to rad/sec setting. The cutting speed or surface speed would change with the size of the cutter. So to keep the surface speed the same for each size cutter formula must be used that includes the size of the cutter to calculate the proper RPM to maintain the proper surface footage.

To calculate RPM for all these plain carbon steel material AISI1010 or C10 to AISI1060 or C60 following formulae is being used.

$$N = \frac{v_c \times 1000}{\pi \times D_c}$$

Where, v_c is the cutting speed (m/min), D_c is Cutter diameter (mm), N is RPM. The suggested cutting speed value is taken as 130m/min because the cutting speed for AISI 1010 is 182m/min and for AISI 1060 is 122m/min. So to satisfy the cutting conditions for all Plain carbon materials from AISI 1010 to AISI 1060 the recommended cutting speed rate is taken as 130m/min and the cutter diameter for this experiment is 50mm. The width of cut is 25mm. From the below table 4 speed factor can be chosen according to width of cut and feed rate. The suggested cutting edge angle for the side milling operation is considered as 90°.

Table 4: Milling cutters with cutting edge angle 90° [11]

a_e mm	Feed per tooth, mm/tooth									Speed factor
	0.03	0.06	0.10	0.20	0.30	0.40	0.50	0.80	1.00	
	Average chip thickness, mm									
25	0.015	0.03	0.045	0.09	0.15	0.19	0.24	---	--	1.35

Where a_e is the width of cut, from the table 4 speed factor for 25mm width of cut is considered as 1.35. The calculated RPM value for the plain carbon steel from AISI 1010 to AISI 1060 is 828 RPM or 86.7 rad/sec.

N = 828 RPM or 86.7 rad/sec

The feed rate in mm per tooth must be converted into feed rate in mm per minute (mm/min) before you can make the feed rate setting on the machine. The formula for converting feed rate in mm per tooth into millimetre per minute is as follows:

$$\mathbf{v_f} = f_t \times n_t \times N$$

The average value of feed rate for all plain carbon steel material from C10 to C60 is assumed as 1mm/min because while doing the analysis in LS-dyna the space distribution between the particles is less, and to increase the performance of sensitivity the feed rate value is changed to 1mm and also to know the cutting forces for each material how they are reacting by increasing the feed rate for all materials. The number of tooth in milling cutter is 4. The table 4 shows the average feed and speed rates maintained throughout the milling cutting process for all materials from C10 to C60.

$$v_f = 828 \times 4 \times 1 = 3312\text{mm/min or } 55.2\text{mm/sec}$$

Table 5: shows the average speed and feed rates

Plain Carbon steel material	**Feed rate v_f (mm/sec)**	**RPM n(rad/sec)**
C10 – C60	55.2	86.7

5.5 Analysis of Cutting Forces:

The first step to examine the behaviour of a cutting tool is to determine the forces model in order to estimate the magnitude and direction of the cutting forces in the milling operation.

Cutting force is one of the main variable that can give more data in the examination of tool wear, cutter breakage. By examining the relationship between these process factors and the cutting force, it will be useful for future cutting operations. It can be able to reduce the cutting forces and improves the production rate and efficiency.

In this research paper force modelling techniques include two methods, they are analytical and numerical models. These are the most commonly known modelling procedures in practical applications. By using these models the cutting forces are calculated on different plain carbon steel alloy from C10 to C60.

5.5.1 Analytical Analysis of milling Cutting Forces:

Basically, analytical models for cutting force evaluation were developed for a single cutting insert. The precision of the models were improved by considering the specific cutting pressure that was determined experimentally. Chip cross-section varies throughout the milling process therefore the models allow to estimate cutting forces by selecting the assumption of average chip thickness [29].

Two case studies were taken to determine the cutting forces of steel material group (C10 to C60) in analytical model. In case 1 the cutting tool movement is in translational movement and in case 2 cutting tool is in rotational movement.

Let us discuss about the case 1: The below schematic diagram Fig. 5.3 shows the Analytical modelling of 3D side milling process. The dimensions of workpiece is 80mm×50mm×25mm. Cutting tool is taken as carbide material of four inserts of cutter diameter 50mm as shown in the Fig. 5.3. The depth of cut is given as 1mm and width of cut is 25mm. work piece is made up of plain carbon steel from C10 to C60. The cutting edge angle in this paper is 90˚.

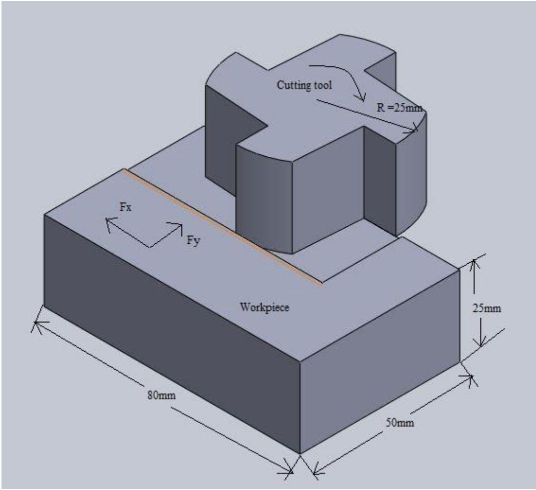


Figure 5.3: Schematic view of side milling process in translational movement

To determine specific pressure during the cutting the Koenigsberger and Sabberwal model is used

$$K_t = F_t(\theta) / S(\theta)$$

$$K_n = F_n(\theta) / S(\theta)$$

Where, K_t and K_n are Specific pressure in tangential and normal direction respectively, $F_t(\theta)$, $F_n(\theta)$ are tangential and normal forces (N), $S(\theta)$ is the Chip section, assuming cutting tool rotation angle (°)

Kronenberg 1966, Ehmann et al 1997 and waldorf et al. 1998 proposed a direct relation between cutting forces and chip cross sectional area [29]. The total cutting force corresponding to specific pressure is determined by

$$F_s = k_s \times S$$

Where, k_s is the Specific cutting pressure, S is the Cutting cross-section.

This equation came from observations that there seems to be an approximate linear relation between force and area in some experimental data, mainly from turning. In general, the specific cutting pressure shows significant variations as per feed rate, cutting speed, width of cut and also depth of cut. Low values of feed rate indicate that the shear model could not fit satisfactorily the chip formation process. Since the material is subjected to lower strain rates. In this way the values of the specific cutting pressure tends to increase [30]. The variation of k_s with the cutting speed is not strong, but it seems to be related to the cutting temperature, since both have a direct relationship [30]. The Specific cutting pressure for plain carbon steel C10 was determined by:

k_S Value with Zero degree effective cutting rake angle is 1350. For other rake angles, reduce the k_S value by 1% for every degree increase in the cutting rake angle [11]. In my research project axial rake angle equal to 6.5˚, edge inclination angle equal to 0˚ and clearance angle equal to 0˚ [35]. So we need to decrease 6% of original k_S value to calculate k_S value for C10. Cutting cross-section of the workpiece is 25mm^2 . k_S Value 6% of 1350 is 1269 N/mm^2

$$F_S = 31.7 \text{ kN}$$

The total cutting force value in translational movement for plain carbon steel C10 is calculated as 31.7 kN. The range of cutting forces for translational movement using analytical model for plain carbon steel group C20 to C60 are discussed in results.

Let discuss about the case 2: In this case milling cutter moves in rotational movement. The same dimensions are used as workpiece and four inserts of cutting tool is used in this case as shown in Fig 5.4. The terminology of cutting tool is different. The first cutting tooth finishes to cut the workpiece material and next tooth start to cut. In the similar manner all four cutting tooth cuts the workpiece material until the given depth of cut is finished.

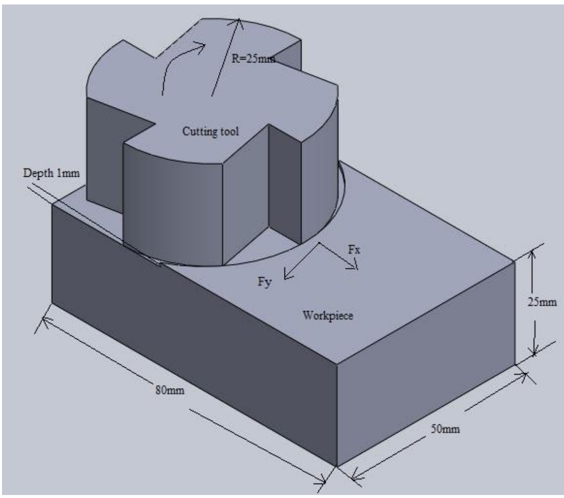


Figure 5.4: Schematic of solt milling process

The total cutting force in rotational milling is determined by [36]:

$$F_c = 1.2 \times A \times K_c \times C$$

Where, A is the tooth processed cross-sectional area, K_c is the specific cutting force, C is the correction coefficient. Suggested correction coefficient is taken as 1.0 and for C10 material recommended specific cutting force is taken as 2262 [36]. Tooth processed cross-sectional area is $1mm^2$. The total cutting force for carbon steel C10 is calculated as:

$$F_c = 2.64 \text{ kN}$$

The cutting forces for rotational movement using analytical model for plain carbon steel from C20 to C60 are discussed in results.

5.5.2 Numerical Analysis in 3D milling Cutting Forces:

After the introduction of the different assumptions used to perform cutting force simulations, the numerical milling model is presented in two configurations. The aim consists in simulating the process in cutting conditions that are reachable analytically. The two configurations are as follows:

1) The numerical model (SPH- FE) validity test in translational movement
2) The definition of cutting forces according to the steel material group (C10 to C60) in rotational movement.

In the system of LS-dyna Fig 5.5 shows the cutting tool movement is in only translational movement. The cutting tool cuts the workpiece material of 1mm depth and 25mm width of cut in X-direction. The resultant cutting forces are high in X-direction, because Fx is the main cutting force in translational movement, Fy is the normal force.

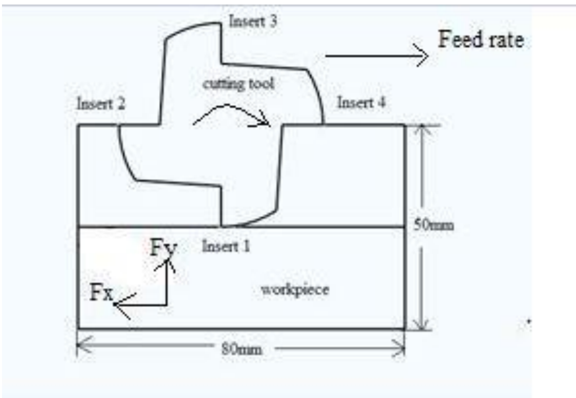


Figure 5.5: Schematic view of translational movement of cutting tool

To conduct Numerical analysis first we need to create numerical SPH-FE model. That FE model should estimate workpiece and cutting tool interaction during cutting process. After creating FE model LS-DYNA package prepost 3.2 version is used for simulation process.

The FE model was composed according to the cut cross-section, and cutting speed and feed rate and depth were mentioned in the program. Modelling dynamics of cutting tool, Keywords used in LS-dyna are [32]:

1) DEFINE_CURVE
2) BOUNDARY_PRESCRIBED_MOTION_RIGID

Keywords used for workpiece material properties are defined by:

1) MAT_RIGID
2) SECTION_SPH
3) MAT_PLASTIC_KINEMATIC_TITLE

Keywords used for creating Elements and nodes for workpiece and cutting tool are:

1) ELEMENT_SOLID
2) ELEMENT_SPH
3) SET_NODE_LIST
4) CONTACT_AUTOMATIC_NODES_TO_SURFACE_ID
5) NODE

Keywords used for terminating the simulation and particular time setup for simulation are:

1) CONTROL_TERMINATION
2) CONTROL_TIMESTEP

Here we will discuss some important key words which significantly used to create the FE model in LS-dyna.

SECTION_SPH

SPH is an advanced particle has been added to LS-dyna. SPH is often known as Smoothed Particle Hydrodynamics. It is a meshless Lagrangian numerical technique used to simulate fluid equations of motion. At first this method was used to simulate astrophysical phenomenon, but recently it has been utilized to determine other physics problems in crash simulations, brittle and ductile fracture in solids [34]. Due to the absence of a grid, this method allows solving many problems that are hardly reproducible. In other classical methods discarding the problem of large mesh deformations or tangling this kind of method offers ease. Another point of interest in SPH technique is that due to absence of a mesh, problems with irregular geometry can be rectified [34].

This variable is for memory allocation of arrays during the initialization phase, it can be positive or negative. If this value is positive, memory allocation is dynamic. During the calculation, some particles can request more neighbors and LS-DYNA will automatically adapt the size of that variable [33]. Default value should apply for most applications. If this value is negative, memory allocation is given as static. During the calculation only the closest SPH particles will be considered as neighbors. Using this option can avoid memory allocation problems [33].

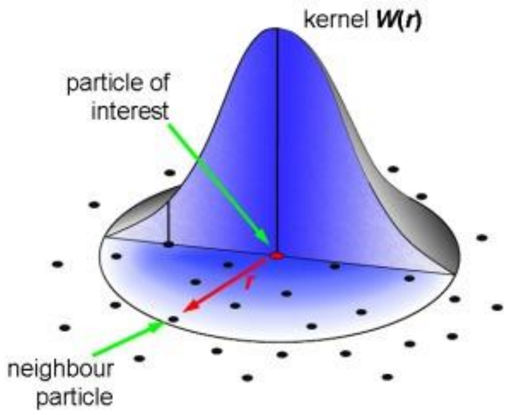


Figure 5.6: Neighbouring particle geometry [34]

The SPH processor in LS-DYNA uses a variable smoothing length. LS-DYNA computes the initial smoothing length h_0, for each SPH part by taking the maximum of the minimum distance between every particle. Every particle has its own smoothing length which varies in time according to the following equation [32]:

$$\frac{d}{dt}\left(h(t)\right) = h(t)div(v)$$

$h(t)$is the smoothing length, $div(v)$ is the divergence of the flow. The smoothing length increases when particles separate from each other and reduces when the concentration of particles is important. It varies to keep the same number of particles in the neighbourhood [32]. The smoothing length varies between the minimum and maximum values.

MAT_PLASTIC_KINEMATIC_TITLE:

This is type 3 Material. This model is suited to model isotropic and kinematic hardening plasticity with the option of including rate effects. It is a very cost effective model and is available for beam (Hughes-Liu and Truss), shell, and solid elements. Strain rate is accounted for using the Cowper and Symonds model which scales the yield stress with the factor [32].

$$1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{1/p}$$

$\dot{\varepsilon}$ is the strain rate. A fully viscoplastic formulation is optional which incorporates the Cowper and Symonds formulation within the yield surface. An additional cost is incurred but the improvement allows for dramatic results. To ignore strain rate effects set both SRC and SRP to zero. Kinematic, isotropic, or a combination of kinematic and isotropic hardening may be specified by varying β' between 0 and 1 [32]. *MAT_ISOTROPIC_ELASTIC_PLASTIC, requires less storage and is more efficient.

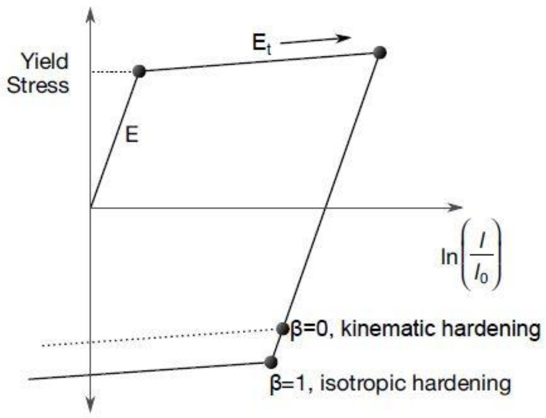


Figure 5.7: Elastic-plastic behaviour with kinematic and isotropic hardening [32]

Fig.5.7 shows the Elastic-plastic behaviour with kinematic and isotropic hardening where $l_0$and l are un-deformed and deformed lengths of uniaxial tension specimen. E_t is the slope of the bilinear stress strain curve [32].

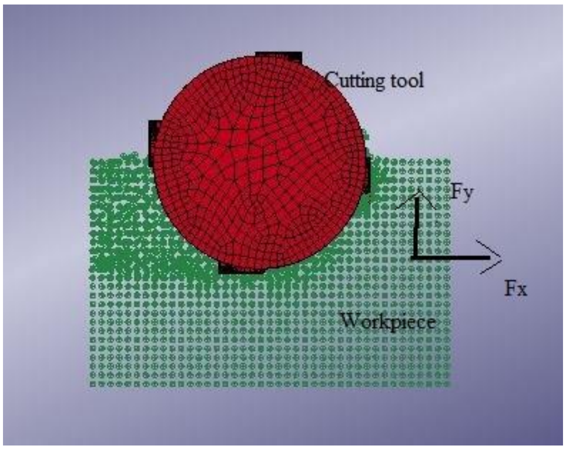


Figure 5.8: Translational motion of milling FE model

Regarding to cut cross-section assumption, the FE model was composed for translational movement as it is shown in Fig 5.8. After running the simulation program in LS-dyna prepost manager 3.2 version the Resultant cutting force value is obtained. The Fig.5.9 shows the resultant force for C10 carbon steel in translational movement. The cutting forces are calculated with respective to time. This is because the removal of material increases with increase in time and therefore cutting force increases. By studying the below Fig. 5.9, a force is obtained at which graph becomes uniformed compared to fluctuations and that steady point is determined as Resultant cutting force.

The resultant cutting force is for plain carbon steel C10 is observed as F_s = 36.2 kN.

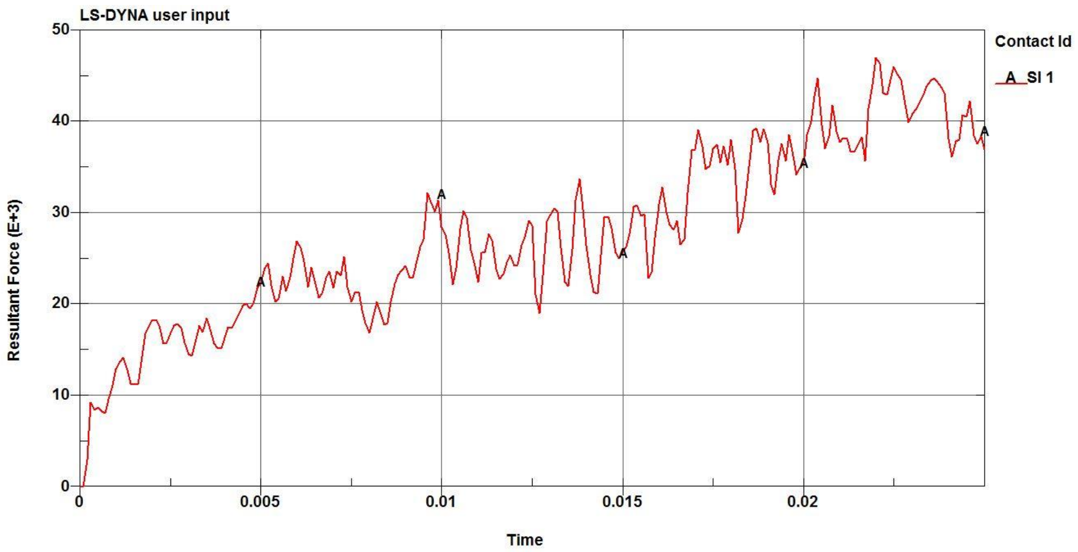


Figure 5.9: Resultant cutting force for C10

In the system of LS-dyna as shown in the Fig 5.10 the cutting tool is in rotational movement, so the main cutting force is tangential cutting force i.e, in Y-direction and Fx is the normal cutting force. Regarding to cut cross-section assumption, the FE model was composed as it is shown in Fig 5.11. Each run type of analysis takes about 20minutes. The cutting forces are calculated at the same time i.e, 0.025sec.

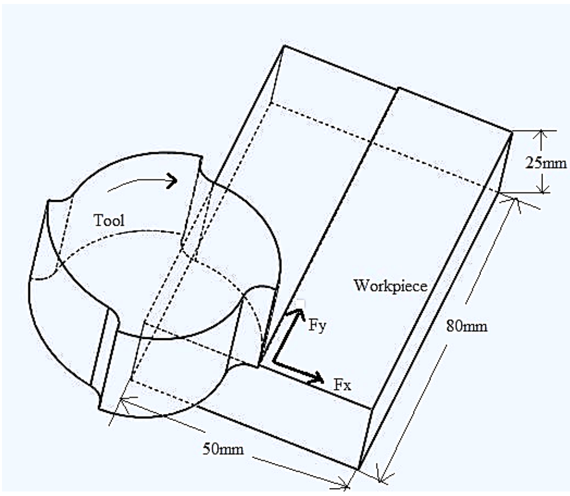


Figure 5.10: 3D schematic view of rotational movement of cutting tool

In Fig. 5.10 schematic diagram shows that the direction of cutting tool is in rotational motion. The models simulate four tooth paths. The first path initialise the mill position in the model, and it is not considered in this discussion. The next three tooth paths, we can notice a very good repeatability and a good similarity in the tool engagement on the cutting forces curves. In fourth cutting tooth the forces are high compared to the other cutting tooth. This phenomenon is mainly due to second tooth path just begins to cut the workpiece and corresponds to the initial force projection at the tool entrance. While in the fourth tooth path, cutting tool cuts the more workpiece material so the forces are higher. The table

6 shows the number of elements and nodes are defined in LS-dyna FE model to interact workpiece and cutting tool. The workpiece was constrained in all 6 Degree of freedom.

Table 6: shows the elements and nodes used to create the FE model

	Elements	**Nodes**
Workpiece	74753	74813
Cutting tool	13857	47097

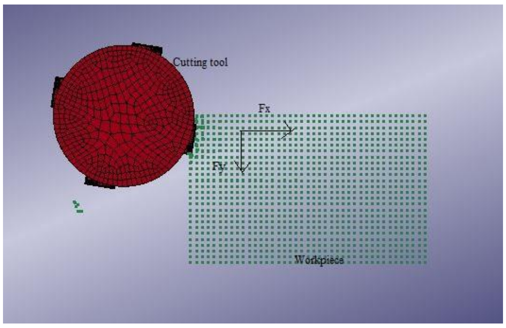


Figure 5.11: Rotational motion of milling FE model

After running the simulation program in LS-dyna prepost manager 3.2 version the Resultant cutting force value is obtained. The Fig.5.12 shows the resultant force for C10 carbon steel in rotational movement. The cutting forces are increasing with corresponding to time. This is because the removal of material increases with increase in time and therefore cutting force increases. By studying the Fig. 5.12, the average resultant force is calculated as the total cutting force value. The total cutting force value is for plain carbon steel C10 is calculated as $F_S = 2.8$ kN.

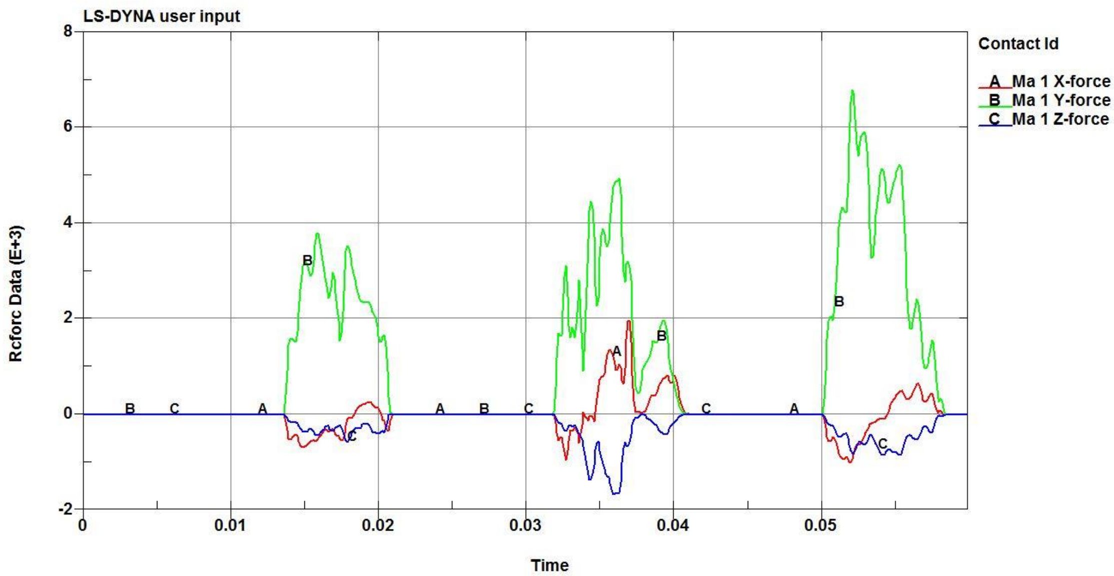


Figure 5.12: Cutting force distribution for C10

6. Results and Conclusions:

The two analysis i.e, analytical and numerical models were carried out in order to examine the influence of cutting forces. In this section we will discuss about resultant cutting forces for carbon steel material group (C10-C60).

6.1 Comparison of Resultant Cutting Forces:

By using Analytical model formulae for translational movement and rotational movement the cutting forces are calculated according to each carbon steel material (C10-C60). Fig 6.1 shows the calculated cutting force values for translational movement. The total cutting force corresponding to specific pressure is determined by [29]:

$$F_S = k_S \times S$$

Where, k_S is the Specific cutting pressure, and S is the cutting cross-section.

Cutting force values are same for C10, C20 and C35, because the recommended specific cutting pressure values are equal in data book for low carbon steel materials. The calculated percentage difference between C45 and C10 is about 10.6%, and for C60 to C45 specific cutting pressure differs 12% and cutting force difference is about 12.5%.

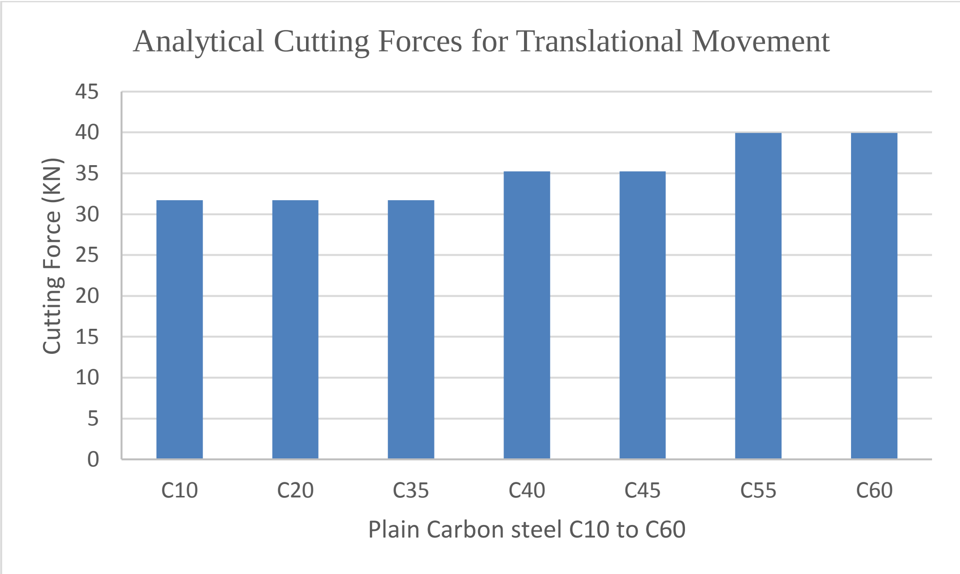


Figure 6.1: Analytical cutting forces for translational movement in carbon steel C10 to C60

Fig 6.2 shows the calculated analytical cutting force values for rotational movement. The total cutting force in rotational milling is determined by [36]:

$$F_c = 1.2 \times A \times K_c \times C$$

Where, A is the tooth processed cross-sectional area, K_c is the specific cutting force, C is the correction coefficient. The suggested cutting speed is considered as 130m/min, if the cutting speed range 80-400m/min, then Correction coefficient factor is assumed as 1. Standard specific cutting force values are taken from data book [36]. Resultant cutting force values were obtained by using standard specific cutting force for each carbon steel material. For C20 and C35 materials standard specific cutting force value is 13% lower compared to C10. So the cutting force difference between C10 and C35 is nearly 9.6%.

The percentage difference of standard specific cutting force for C35 to C45 is 10%, calculated total cutting force difference is 10.4% for C35 to C45, and the specific cutting force difference for C60 to C45 is 23%, the cutting force for C60 is increased almost 23% while compared to C45. The phenomenon for increasing the cutting forces is increase in standard specific cutting force.

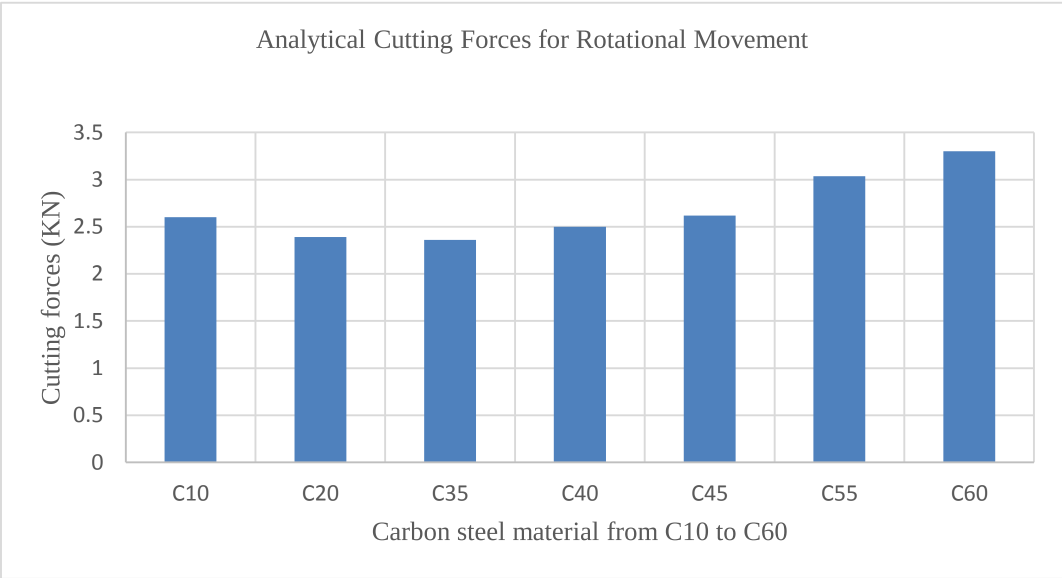


Figure 6.2: Analytical cutting forces for rotational movement in carbon steel C10 to C60

In numerical analysis SPH-FE model is created. In previous basis we already discussed bout the two cases which are carried in LS-dyna to determine the cutting forces. The LS-DYNA 3.2 version package is used to perform simulation results. The computation time is about 2days for steel material group (C10-C60) with ACER Intel i3core 2.40GHz processor with 8 GB ram. The different results obtained by simulation are discussed in this section. First we will discuss results when the cutting tool is in translational movement.

For each combination of cutting parameters, the cutting forces were recorded when the milling cutter arrive at the position where the depth of cut 1mm was reached. By running the program in LS-DYNA pre post-processor for each carbon steel material AISI 1010 or C10 to AISI 1060 or C60 values are obtained from the graph as shown in the Fig 6.3. The cutting forces are increases gradually when mill tooth starts to cut the workpiece material. As the workpiece material is hard the cutting forces are high. Finally the tool finishes its motion and comes to rest position. The negative force values indicates the change in direction of cutting tool.

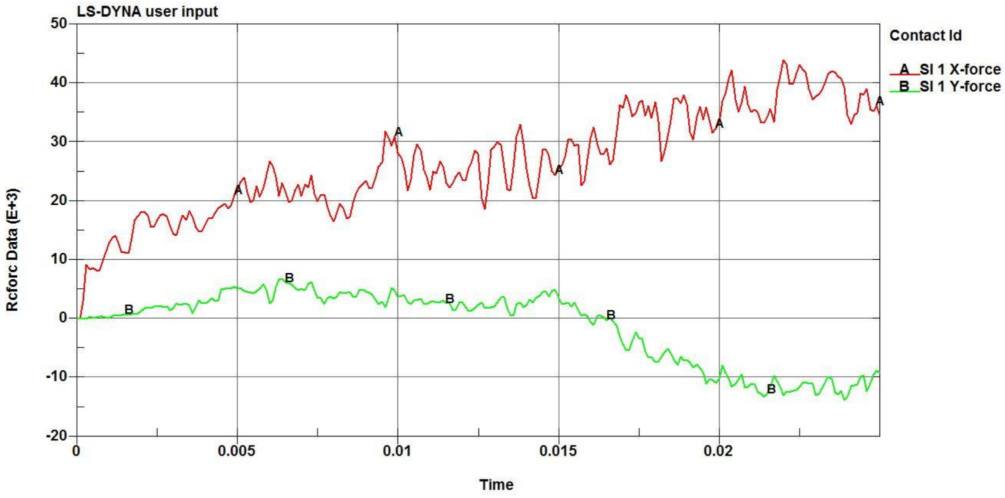


Figure 6.3: Cutting force distribution with time for C60

Fig.6.4 represents the average resultant cutting forces for different materials that are obtained from LS-dyna simulation process. These resultant forces Fx and Fy values were taken at the same time i.e, 0.025sec during simulation in LS DYNA pre-post processor. The force values in X-direction has a huge impact while compared to Y-direction. This is because during translational movement the cutting tool moves in X-direction, so that axis direction is tangential cutting force. The cutting force for C20 differs 25.5% while compared to C10, this is because influence of tangent modulus and yield strength is more for C10. The cutting force for C35 increased almost 22% while compared to C10. For C40 material the calculated cutting force difference for C40 to C60 is 15%.

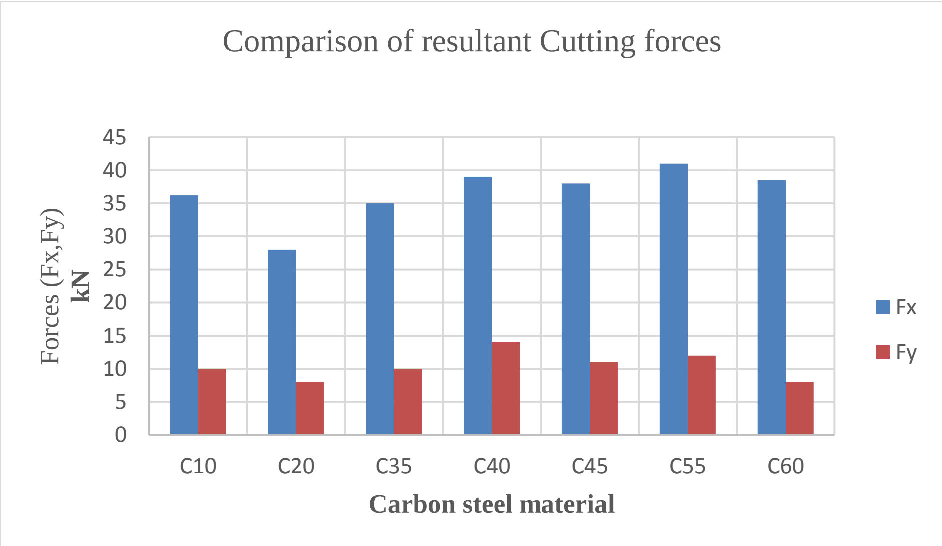


Figure 6.4: Comparison of Cutting forces in translational movement for numerical analysis

6.2 Comparison of Analytical and Numerical Model:

In this section both analytical and numerical analysis in both cases is presented. The cutting force output in translational movement from the analytical model and from numerical model were compared.

The comparisons between the analytical and numerical model is very important to validate in milling process. To predict the cutting forces of carbon steel group C10-C60 are varying in both models. The Fig.6.5 shows the comparison of Resultant cutting forces in translational movement for all plain carbon steel from C10 to C60 in analytical and numerical methods.

When compared the models of analytical and numerical it has been noticed that for C10 material, numerical cutting force is 13.25% more than analytical model and for C20 material numerical cutting force decreased to 12.4% over analytical model. The phenomena behind the decrement is due to the poor physical and mechanical properties of C20 in numerical model. In C35 material cutting force value increased almost 9.8% over analytical and the increment become saturated for C40 almost 10.1% more than analytical model. For C55 material the numerical cutting force value increased to 4.3% over analytical and in C60 material numerical cutting force value decreased to 2% over analytical model.

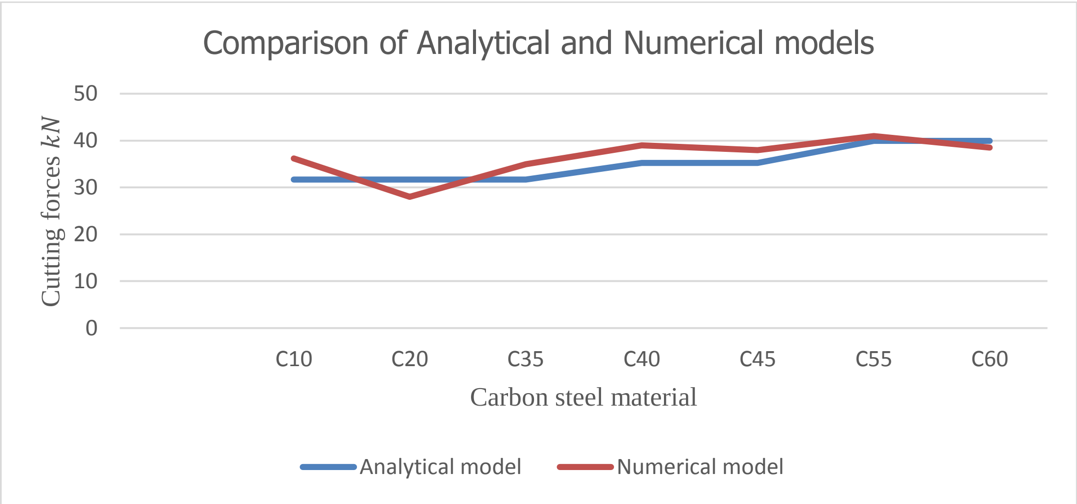


Figure 6.5: Comparison of Analytical and Numerical models in translational movement

Whereas in rotational movement the variation of 7.4% for numerical analysis over analytical analysis has been calculated in C10 material. Whereas it has been decreased to 36% in the case of C20 and for C35 it became saturated to 16%. In C20 and in C35 tangent modulus and yield strength differs nearly half to the C10 and C40. So, the total cutting forces in numerical model is low for C20 and C35 as compared to analytical model. Due to the standard specific cutting force value in C40, the increment 18% has been calculated. For C45 numerical value is observed as 16% over analytical. By observing C55 material the comparison of numerical model is 3.6% higher than analytical and in C60 analytical model increased to 6.2% over numerical model.

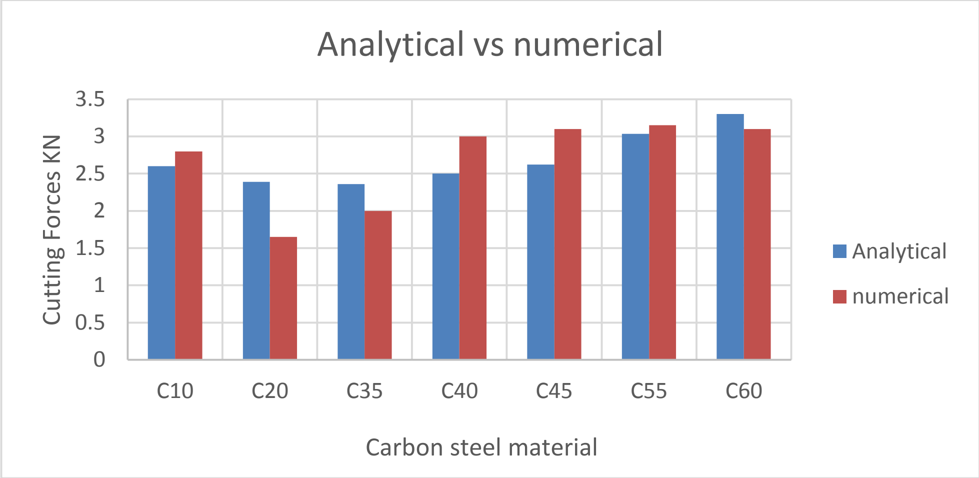


Figure 6.6: Comparison of Analytical and Numerical models in rotational movement

The fig 6.7 to 6.13 shows the comparison of analytical and numerical cutting forces in rotational moment. The three deflection lines are shown in the below figures are the cutting force values in X, Y, and Z directions. The yellow line corresponds to the analytical force value in rotational moment. The negative force values indicate the change in direction of cutting tool. Due to the tool rotation and vibrations on the tool axis, F_x and F_z cutting forces are very small and those forces are neglected. In X and Z directions the cutting forces are smaller and more sensitive than in Y direction. Moreover, the main cutting force in rotational moment is tangential force i.e, F_y. The constant line corresponds to a configuration where there is no contact of tooth with the workpiece.

The total cutting force (F_c) in rotational milling is determined by [36]:

$$F_c = 1.2 \times A \times K_c \times C$$

For C10 the analytical cutting force value is calculated as 2.6 kN. The relative difference of numerical model is calculated as 7.4% over analytical model.

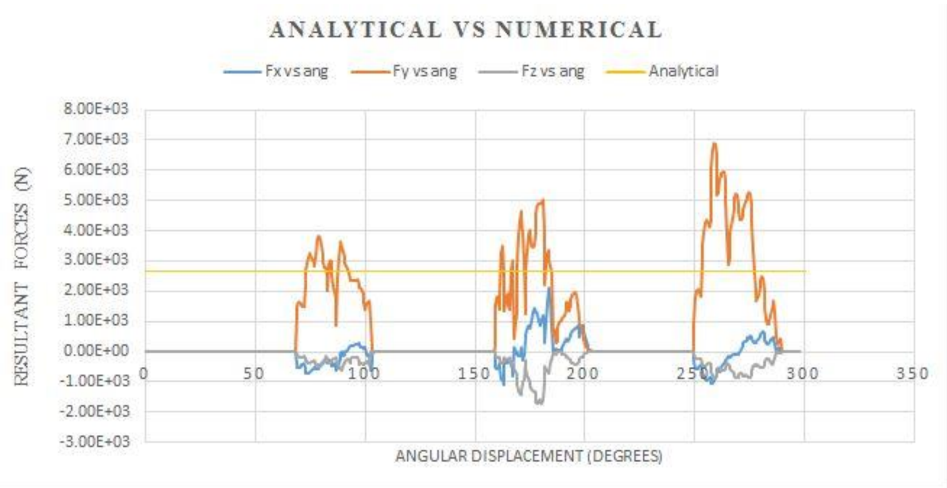


Figure 6.7: Numerical vs Analytical resultant forces for C10

The analytical cutting force value is calculated as 2.39 kN. The relative difference between analytical is calculated as 36% over numerical for C20 in rotational moment. The phenomena behind this difference is tangent modulus and yield strength is low for C20 material. Therefore, numerical value is decreases to 36% over analytical analysis.

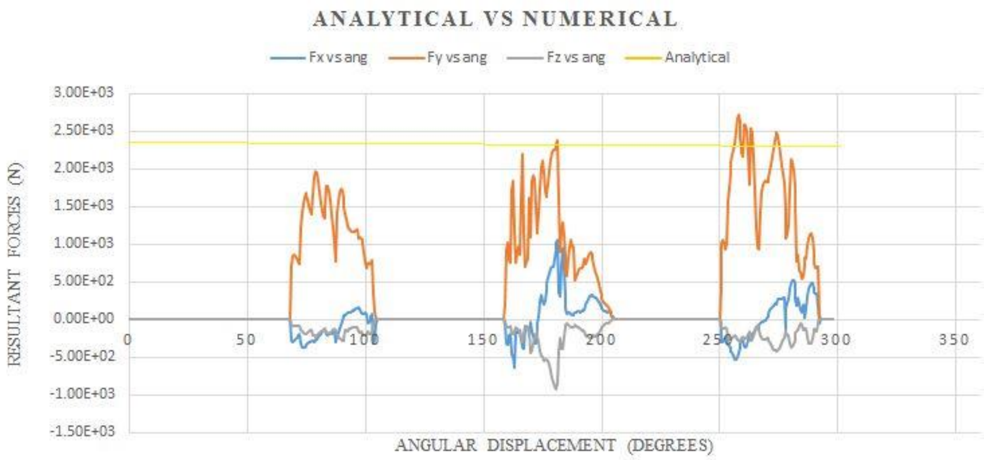


Figure 6.8: Numerical vs Analytical resultant forces for C20

For C35 material the analytical cutting force is calculated as 2.36 kN. The relative difference between numerical and analytical, numerical value is 16.5% over analytical model.

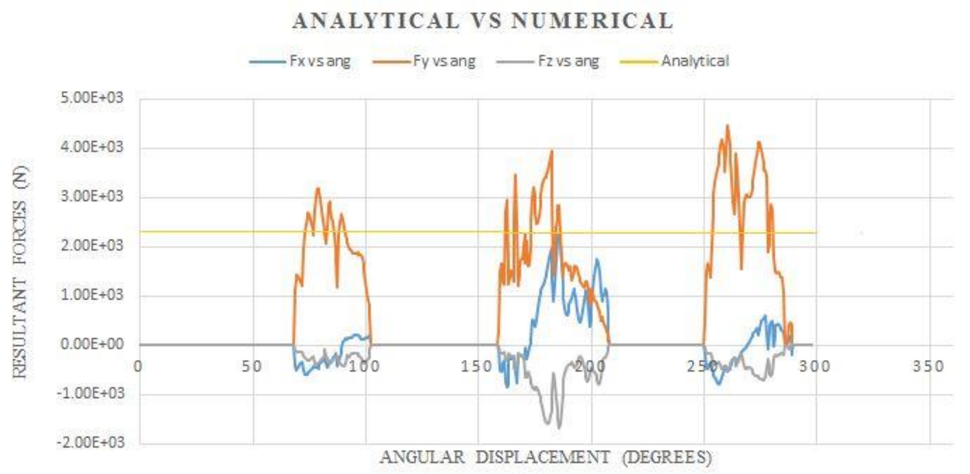


Figure 6.9: Numerical vs Analytical resultant forces for C35

The analytical cutting force for C40 is calculated as 2.5 kN. The relative difference between analytical and numerical model is calculated as 18%.

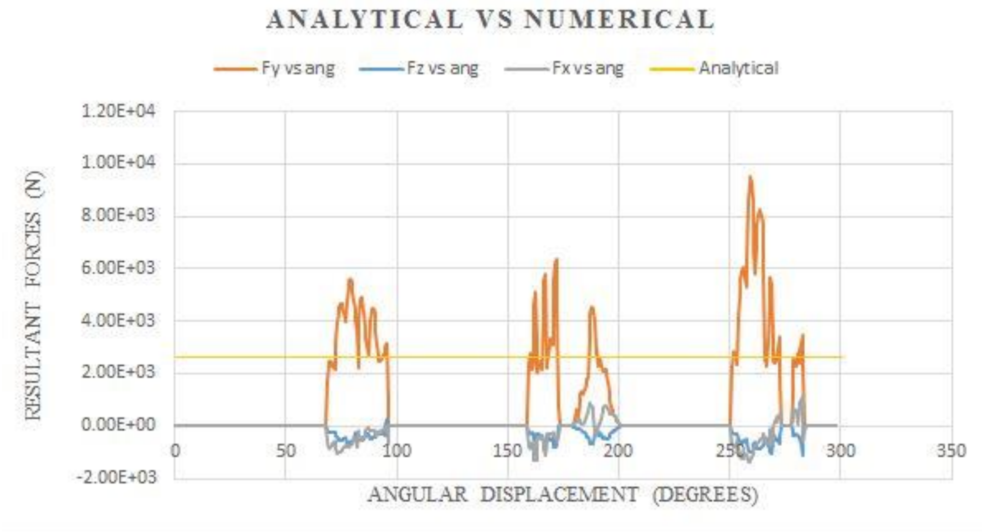


Figure 6.10: Numerical vs Analytical resultant forces for C40

For C45 material the analytical cutting force value is calculated as 2.62 kN. The relative difference of numerical model is measured as 13.5% over analytical model.

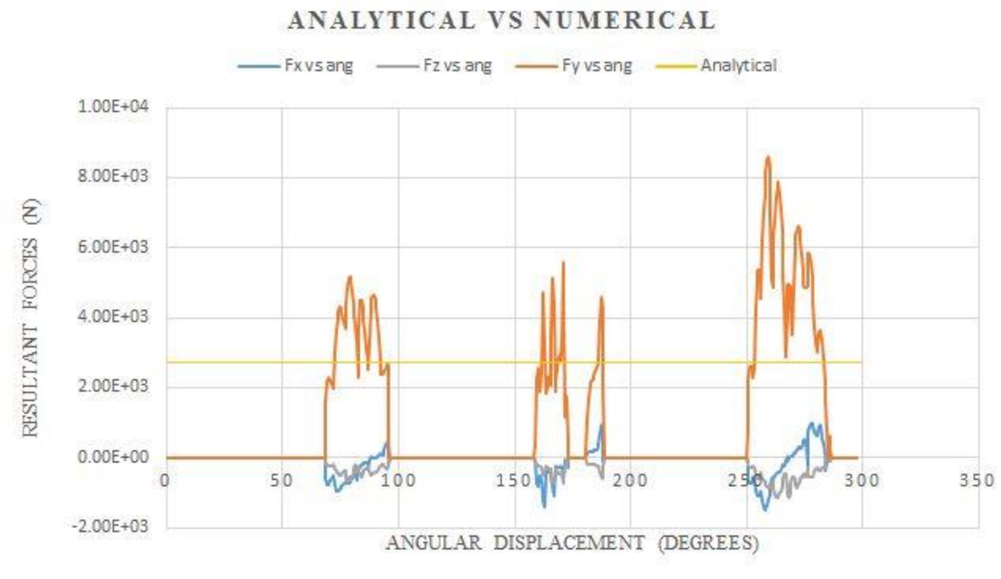


Figure 6.11: Numerical vs Analytical resultant forces for C45

For C55 the analytical cutting force value is calculated as 3.036 kN. The relative difference of numerical model is calculated as 5.5% over analytical model.

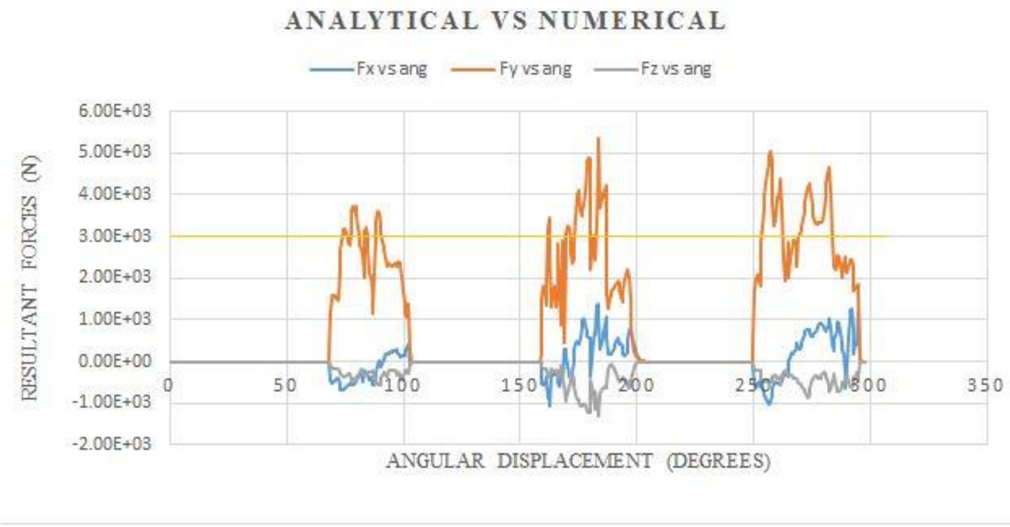


Figure 6.12: Numerical vs Analytical resultant forces for C55

The analytical cutting force value for C60 material is calculated as 3.3 kN. The relative difference of analytical model is calculated as 6.2% over numerical model.

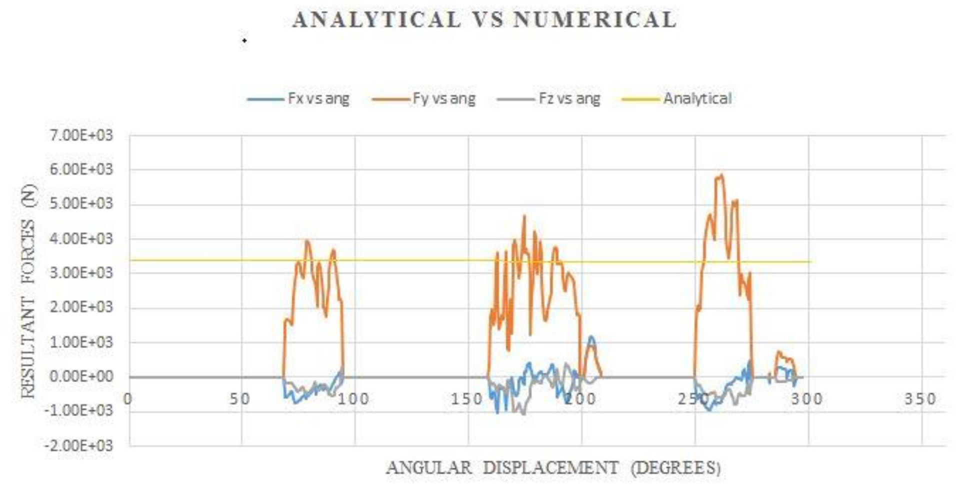


Figure 6.13: Numerical vs Analytical resultant forces for C60

Conclusions:

1. The total cutting forces in analytical model for translational and rotational movement were calculated.
2. The 3D numerical model of milling is very important step in modelling of machining, it helps to improve the cutting forces of different materials for industrial purpose.
3. In 3D numerical modelling (SPH-FE) validity test was performed. It was found the model adequacy, according to the analytical estimation 4.8% for C10.
4. The comparison between analytical and numerical models were performed. For both models it was found that it differs 6.1% difference in translational movement between C10 over C60, and in rotational movement it differs 10% between C10 and C60.

References:

1. “Analytical models for high performance milling. Part I: Cutting forces, structural deformations and tolerance integrity” by E. Budak INT J MACH TOOL MANU 2006; 46: 1478-1488
2. “Estimation of the specific cutting pressures for mechanistic cutting force models” by S.jayaram, S.G Kapoor, R.E. Devor Int J of Machine tools and Manufacture Urbana, IL 61801, USA
3. Mechanical Engineering tools/tutorial/mills.
4. A text book of Manufacturing Technology: Manufacturing processes by R. K. Rajput pp 506,507 published on 2007
5. “A text book of Manufacturing Processes/second edition” by J.P. Kaushush pp 425 published on August 2010.
6. “Introduction to Basic Manufacturing processes and Workshop Technology” Rajender Singh, pp 461 published on 2006.
7. “A text book of Manufacturing Processes for Engineering Materials” by Serope Kalpakjian, Steven R. Schmid published on 2007.
8. “A text book of Fundamentals of machining and machine tools” by G. Boothroyd published on 1989.
9. “Experimental investigations from conventional to high speed milling on a 304-L stainless steel” by A. Maurel-Pantel & M. Fontaine & G. Michel & S. Thibaud & J. C. Gelin Int J Adv Manufacturing Technology 2013 volume 69, Issue 9-12, pp2191-2213.
10. Johnson GR, Cook JR (1983) Constitutive model and data for metals subjected to large strains, high strain rates, and high temperatures. Proceedings of 7th Symposium on Ballistics, Netherlands.
11. “ Milling 1 catalogue and technical guide published on 2005 by SECO tools pp 377,379”
12. “3D FEM simulations of shoulder milling operations on a 304L stainless steel” by A. Maurel-Pantel , M. Fontaine, S. Thibaud, J.C. Gelin Simulation Modelling Practice and Theory, Volume 22, March 2012, pages 13-27.
13. P.J. Arrazola, T. O¨ zel, D. Umbrello, M. Davies, I.S. Jawahir, “Recent advances in modelling of metal machining processes” CIRO Annals- Manufacturing Technology Volume 62, Issue 2, 2013, pages 695-718.
14. “High-speed machining of cast iron and alloy steels for die and mold manufacturing” by P. FallboÈhmer, C.A. RodrõÂguez, T. OÈ zel, T. Altan Journal of materials processing technology Volume 98, Issue 1, 15 January 2000, pages104-115.

15. Grzesik W (2006) Determination of the Temperature Distribution in the Cutting Zone Using Hybrid Analytical-FEM Technique. International Journal of Machining Tools & Manufacture 46(6):651–658.
16. “A predictive hybrid force modeling in turning: application to stainless steel dry machining with a coated groove tool” by Christophe Czarnota, Fousseny Kone, Badis Haddag , Mohammed Nouari The international journal of Advanced Manufacturing Technology volume 79, Issue 1-4, pp65-79.
17. Study on carbide cutting tool life using various cutting speeds for α-β Ti-alloy machining by K.B. Ahsan, A.M. Mazid, R.E. Clegg, G.K.H. Pang JAMME volume 55 Issue 2 December 2012
18. Cutting tool applications by George Schneider, Jr. Cmfge Published on 2002
19. Machinability of metals/ cutting tools/ chapter 3/ American Machinist
20. “Machinery's Handbook 29th Edition -Full Book” by Erik Oberg Released on 2011
21. Machining cutting speed conditions are taken from this site foxvalleytech.com/MachShop3/speedCalc/SpeedRPM.htm
22. Machining cutting feed rate conditions are taken from this site foxvalleytech.com/MachShop3/speedCalc/feedratecalc.htm
23. “Experimental Analysis and Modeling of Orthogonal Cutting Using Material and Friction Models” by E. Ozlu, E. Budak Faculty of Engineering and Natural Sciences, Sabanci University, Istanbul, Turkey
24. A text book of “Manufacturing processes for metal products” by Valery Marinov published on Jul 22, 2008
25. Applications, chemical composition and Mechanical properties are taken from this site www.Steelforge.com/aisi-1010/aisi1035/aisi1040
26. Applications, chemical composition and Mechanical properties are taken from this site www.Azom.com/article.aspx?ArticleID=6114/6130
27. Applications are taken from this site matweb.com/search/datasheettext.aspx?matguid=c40f8cc77d5e46e1af49f7173abf34f9/bassnum=M1060F
28. “A new approach for predicting and collaborative evaluating the cutting force in face milling based on gene expression programming” by Yang Yang, Xinyu Li, Liang Gao, Xinyu Shao Journal of Network and Computer Applications Volume 36 Issue 6, November, 2013 Pages 1540-1550

29. "Analytical models for high performance milling. Part I: Cutting forces, structural deformations and tolerance integrity" E. Budak INT J MACH TOOL MANU 2006; 46: 1478-1488.
30. "Milling process study, assuming estimation of cutting force" V. Gyliene, V. Ostasevicius Assembly and manufacturing (ISAM), 2011 IEEE International symposium May 2011.
31. "Experimental Evaluation of Cutting Force Parameters Applying Mechanistic Model in Orthogonal Milling" by R. T. Coelho, A. Braghini Jr., C. M. O. Valente and G. C. Medalha 13.566-590, Brazil.
32. J. O. Hallquist, "LS-DYNA theoretical manual. 1998," Livermore Software Technology Corporation.
33. Smooth Particle Hydrodynamics for Bird-Strike Analysis Using LS-DYNA by Vijay K. Goyal, carlos A. Huertas, Thomas J. Vasko American Transactions on Engineering & Applied sciences: volume 2 No. 2 ISSN 2229-1652 eISSN 2229-1660
34. Smooth Particle Hydrodynamics: A new feature in LS-DYNA by Jean Luc Lacome
35. "The definition of cutting forces in square shoulder milling by 3D model smooth particles hydrodynamics methodology" by V. Gyliene, V. Eidukynas, G. Fehr, Mechanika ISSN 1392-207 (in Press)
36. "Mechanikos inzinieriaus zinynas" by Andrius Vilkauskas, Kazimieras juzenas, Marius Rimasaukas, Povilas Krasauskas 3rd edition published on 2012.
37. "Inzinerinu medziagu zymejimo sistemos" by rasa kandrotaite janutiene published on Technologija Kaunas 2013