MANUFACTURING AN INVOLUTE SPLINE CUTTING TOOL ON WIRE EDM USING SOLIDWORKS AND ESPRIT

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Mechanical Engineering

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TABLE OF CONTENTS

SIGNATURE PAGE .................................................................................................................. ii

ACKNOWLEDGEMENT ........................................................................................................... iii

LIST OF TABLES ...................................................................................................................... vii

LIST OF FIGURES ................................................................................................................... viii

LIST OF ACRONYMS ........................................................................................................... xii

ABSTRACT .............................................................................................................................. xiii

1. INTRODUCTION .................................................................................................................. 1
   1.1. STATEMENT OF PROBLEM ..................................................................................... 1
   1.2. THESIS STATEMENT ............................................................................................... 1
   1.3. DELIMITATIONS ....................................................................................................... 1
   1.4. BACKGROUND RESEARCH .................................................................................... 2
       1.4.1. RESEARCH ON WIRE EDM ........................................................................... 3
       1.4.2. CNC MILLING ............................................................................................... 16
       1.4.3. BROACHING ................................................................................................. 20
       1.4.4. HOBBING ....................................................................................................... 21
       1.4.5. GEAR SHAPING ............................................................................................ 22
       1.4.6. SPLINE ROLLING .......................................................................................... 24
       1.4.7. APPLICATIONS OF SPLINES ........................................................................ 26

2. SPLINES .............................................................................................................................. 28
   2.1. INTRODUCTION TO SPLINES .............................................................................. 28
   2.2. TYPES OF SPLINES .............................................................................................. 29
       2.2.1. PARALLEL KEY SPLINES ........................................................................... 29
       2.2.2. INVOLUTE SPLINE ....................................................................................... 30
       2.2.3. CROWNED SPLINES .................................................................................... 30
5. MANUFACTURING PROCESS .................................................................67
   5.1. OVERVIEW OF MACHINING TECHNOLOGY .....................................67
   5.2. GENERATING AND SAVING NC CODES .............................................67
   5.3. EXPERIMENTAL SETUP OF WIRE EDM ..........................................68
       5.3.1. TECHNOLOGY NUMBER .........................................................70
   5.4. EXPERIMENTAL SETUP OF HAAS VF-2 MILLING MACHINE ...............72
   5.5. PROPERTIES OF 6061 ALUMINUM TEST SPECIMEN .........................73
   5.6. PROPERTIES OF 4340 STEEL SPECIMEN .......................................74
6. EXPERIMENTAL RESULTS ......................................................................76
   6.1. WIRE EDM MACHINED INSERTS .....................................................76
   6.2. TESTING ON 6061 ALUMINUM ......................................................77
   6.3. TESTING ON 4340 STEEL DRIVE SHAFT ........................................77
CONCLUSION AND RECOMMENDATIONS ..................................................82
REFERENCES .........................................................................................83
APPENDIX A: TABLES ...........................................................................86
APPENDIX B: DRAWINGS .......................................................................88
APPENDIX C: NC CODES .......................................................................91
LIST OF TABLES

Table 1: Classification of CNC machines.................................................................18

Table 2: American National Standard Involute Spline Symbols .............................36

Table 3: Formulas for Flat Root Major Diameter Fit with 30-deg Pressure Angle ........37

Table 4: Basic Dimensions of Involute Splines of 30-deg Pressure Angle ................38

Table 5: Input Parameters for Involute Spline ..........................................................40

Table 6: Basic Geometry parameters of Involute Splines .........................................40

Table 7: Pitch and Tooth Thickness values of Involute Spline ..................................40

Table 8: Spline Equation and its Parameters ............................................................41

Table 9: Design Table with Involute External Spline Parameters .............................47

Table 10: Brother HS-70A Wire EDM Machine Specifications .................................71

Table 11: Physical Properties of 6061 Aluminum ....................................................74

Table 12: Mechanical Properties of 6601 Aluminum .............................................74

Table 13: Mechanical Properties of 4340 Steel ......................................................75

Table 14: Physical properties of 4340 Steel ............................................................75

Table 15: VF-2 Milling Machine Inputs for 6061 Aluminum Testing .........................77

Table 16: Wire EDM Machine Technology Number ..................................................86

Table 17: Wire EDM Generator Settings ...................................................................87
LIST OF FIGURES

Figure 1: Schematic Diagram of Basic principle of Wire EDM ........................................5

Figure 2: Brother HS-70A Wire EDM Machine ..................................................................9

Figure 3: Wire EDM Cut with Spark Gap .................................................................11

Figure 4: Orientation of Different Axes on a Typical CNC Machine ..........................18

Figure 5: Rotary Broaching Machine Setup ..............................................................21

Figure 6: Shape of a Hob .........................................................................................22

Figure 7: Barber Coleman Hobbing machine ............................................................23

Figure 8: Gear Shaping Machine ..............................................................................24

Figure 9: Spline Rolling Process ...............................................................................25

Figure 10: Applications of Internal and External Splines in Industrial Braking System ..27

Figure 11: Internal and External Spline ......................................................................28

Figure 12: Parallel Key Splines with 4, 6 and 8 tooth ...............................................29

Figure 13: External and Internal Involute Splines.......................................................30

Figure 14: Crowned Splines ....................................................................................31

Figure 15: Serrations .................................................................................................31

Figure 16: Helical Cut Splines ..................................................................................32

Figure 17: Generation of Involute Spline Curve ......................................................33

Figure 18: Equations of Involute Splines as per ANSI ...........................................38

Figure 19: SolidWorks Interface ...............................................................................43
Figure 20: SolidWorks Sketch showing Spline Profile .............................................45
Figure 21: 3-Dimensional Spline Tooth Profile .......................................................45
Figure 22: External Involute Spline with 27 Teeth ..................................................46
Figure 23: 2-D SolidWorks Assembly Drawing showing formation of Cutting Insert with a Detail View .................................................................................48
Figure 24: SolidWorks model of Machine Insert with Involute Spline Profile ............49
Figure 25: ESPRIT Graphical User Interface .............................................................52
Figure 26: ESPRIT’s New File Template ..................................................................53
Figure 27: ESPRIT’s Open Native File Template ......................................................54
Figure 28: ESPRIT’s Open File with Options Command ............................................55
Figure 29: SolidWire Part Setup ..............................................................................56
Figure 30: Part-Setup and SolidWire Contour of Insert ............................................57
Figure 31: SolidWire Contour Operation with General Tab .....................................58
Figure 32: SolidWire Contour Operation with Cut Data Tab .....................................58
Figure 33: SolidWire Contour with Approaches Data ..............................................59
Figure 34: SolidWire Contour with Advanced Tab ...................................................60
Figure 35: CNC Cutting Tool Assembly ..................................................................61
Figure 36: Custom Milling Tool Operation Window ..................................................61
Figure 37: SolidMill Traditional Contouring-General tab .........................................62
Figure 38: SolidMill Traditional Contouring-Strategy Tab .......................................63
Figure 39: SolidMill Traditional Contouring-Advanced Tab

Figure 40: Tool Path with Blend Radius and with No-Blend Radius

Figure 41: SolidMill Traditional Contouring-Links Tab

Figure 42: List of contour operations around the external involute spline (left) and simulation of the external involute spline cutting in ESPRIT (right)

Figure 43: Experimental Setup of the Wire EDM Machine

Figure 44: Wire EDM Corner Finding Technique

Figure 45: Machine Insert Before (left) and after (right) Wire Cutting

Figure 46: Haas VF-2 Machine Equipped with a 7500 RPM, 40 taper, and 20HP (14.9 kW) Vector Drive Spindle

Figure 47: Tool fixture to the VF-2 Milling Machine Shank

Figure 48: Involute profile cut on Insert #1 (left) and Insert #2 (right)

Figure 49: 6061 Aluminum Test Specimens

Figure 50: Insert #2 with Damage at its Tip

Figure 51: Insert #3 fixed to Tool Holder with Involute Cut on Corners

Figure 52: VF-2 spline manufacturing process in Left View (top) and Front View (bottom)

Figure 53: Drive Shaft before and after Cutting the External Involute Splines

Figure 54: Drive Shaft and Drive Hub Assembly showing External Involute Splines

Figure 55: SolidWorks Drawing of Drive Hub with Internal Involute Splines

Figure 56: SolidWorks Design of Drive Shaft with External Involute Splines
Figure 57: Tool Holder, Tool Insert and Spline Assembly showing Aake Angle Projection
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>CAD</td>
<td>Computer-Aided Design</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer-Aided Manufacturing</td>
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<tr>
<td>CNC</td>
<td>Computer Numerical Control</td>
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<tr>
<td>RPM</td>
<td>Revolution per Minute</td>
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<tr>
<td>NC</td>
<td>Numerical Code</td>
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<tr>
<td>GUI</td>
<td>Graphical User Interface</td>
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<tr>
<td>EDM</td>
<td>Electrical Discharge Machine</td>
</tr>
<tr>
<td>MRR</td>
<td>Material Removal Rate</td>
</tr>
<tr>
<td>CW</td>
<td>Clock Wise</td>
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<tr>
<td>CCW</td>
<td>Counter Clock Wise</td>
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<tr>
<td>RPT</td>
<td>Rise per Tooth</td>
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<tr>
<td>SFPM</td>
<td>Surface Feet per Minute</td>
</tr>
<tr>
<td>ANSI</td>
<td>American National Standard Institute</td>
</tr>
<tr>
<td>FSAE</td>
<td>Formula Society of Automotive Engineers</td>
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<td>USD</td>
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ABSTRACT

MANUFACTURING AN INVOLUTE SPLINE CUTTING TOOL ON WIRE EDM USING SOLIDWORKS AND ESPRIT

BY

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Master of Science in Mechanical Engineering

Today’s Mechanical Engineering field is growing rapidly in designing techniques to manufacture Splines and Gears. Over the decades, numerous methods and manufacturing processes have been used in making the various kinds of Splines based on various criteria, including applications, reliability, life time, processing time and manufacturing cost. This thesis is also carried out with the same notion of experimenting to manufacture an External Involute Spline cutting tool using state-of-art CAD/CAM package and current trend CNC machines like Brother HS-70A Wire Electrical Discharge Machine and HAAS VF-2 Vertical Milling Machine. This thesis is divided into two distinct phases: (1) analysis phase and (2) manufacturing phase. The analysis phase is dedicated to the study and simulation of involute splines, while the manufacturing phase covers the actual manufacturing process.

This thesis starts with the extensive study of splines and the two different kinds of splines; a) Internal Involute splines and b) External Involute splines. The primary objective is to design the internal involute spline in Dassault Systems’ SolidWorks®. This entire design process is to be automated with embedding Microsoft EXCEL Spreadsheet with SolidWorks. Using this EXCEL spreadsheet, spline design parameters iterations are carried out in SolidWorks with the help of design tables. Based on the calculations made in EXCEL Spreadsheets and CAD design in SolidWorks, CNC machining parameters are defined in DP Technology’s CAM package ESPRIT and the machining process as well as tool/insert design is simulated.
The main objective is to manufacture a spline cutting tool using Wire EDM machining process. For this Solid Carbide Machine Inserts are chosen as a cutting tool which cuts the external splines. Once the machine insert was manufactured, it was tested on 6061 Aluminum test specimen and successfully cut on 4340 Steel Drive shaft on the CNC Milling machine. These external splines are the inverse of the Involute splines on the drive shaft hub of the FSAE Formula one car. It can be concluded that, the involute spline cutting tool was successfully manufactured and tested by cutting external involute splines on drive shaft which match with internal splines on drive hub.
1. INTRODUCTION

1.1. STATEMENT OF PROBLEM

Internal and External Involute splines are the most efficient and most widely used splines for many applications. Because of their wide range of applications increasing day by day, manufacturing of these splines is also very important. Though gears and splines have similar kind of design manufacturing techniques, it is important to have different kinds of spline manufacturing techniques. The purpose of this project is to study splines and automate the design process of involute spline cutter using CAD/CAM packages and manufacture a cutting tool with the help of CNC machine.

1.2. THESIS STATEMENT

The purpose of this study is to manufacture an involute spline cutting tool using CAD package Solid Works and CAM software ESPRIT. To interface Microsoft EXCEL spreadsheet and SolidWorks to automate the design process of the external and internal involute splines for the drive train shaft and hub. SolidWorks Design Tables embedded with Microsoft EXCEL spreadsheets are used to automate the designing process.

Designing the manufactured spline cutting tool and using it is the key issue of this study. This study has manufactured the tool, tested on Aluminum test specimen and successfully cut the corresponding external involute splines on the drive shaft to the internal splines of the drive train hub (see Appendix B for illustrations).

1.3. DELIMITATIONS

The focus of this thesis is to automate the involute spline design and manufacture it on wire EDM machine and test it by cutting on by using 4th axis machining on HAAS VF2 CNC Milling machine. 

The following is a list of delimitations for this thesis.

- Calculating the involute profile parameters based on the inputs including number of teeth, pressure angle and diametral pitch.
• Creating a spreadsheet of the above calculations to make the changes whenever it is needed as per the design.

• Creating a SolidWorks design of the external involute spline and automate the parameter dimensioning using Design Tables.

• Creating the SolidWorks parts of the tool holder and machine insert for the corresponding involute external spline using SolidWorks Assembly and “Convert Entities” Command in it.

• Converting the SolidWorks parts to “Parasolid” in order to match the co-ordinates of the both the interfaces of SolidWorks and ESPRIT.

• Importing the SolidWorks part of the tool insert into ESPRIT and creating a “Custom Milling Tool” using the involute spline profile on it and save it with (*.ect) file extension.

• Parasolid part of the insert and define the “SolidWire” contour operations to cut the insert on Wire EDM machine and simulate the machining process.

• Opening the SolidWorks part of the external involute spline and define the Milling operation with importing the custom milling tool profile on splines’ tooth. Automate the whole 4-th axis milling process and look for the precision.

• Generating NC codes for Machining on Wire EDM and Milling machines.

1.4. BACKGROUND RESEARCH

This thesis is based on the manufacturing of a tool which cuts involute splines. Both gears and splines are manufactured with similar manufacturing processes and techniques. Though the Splines are manufactured in different ways, based on the criteria of machinery availability, time and money we chose to manufacture spline cutting tool on the Brother HS-70A wire EDM machine and test it by cutting the external splines on a drive shaft of Formula one car built by California State University, Northridge. This manufacturing is done on HAAS VF2 CNC machine. Therefore, this thesis is based on the background research on the different spline manufacturing techniques like Broaching, Hobbing, milling and Wire Electrical Discharge Machine.
1.4.1. RESEARCH ON WIRE EDM

Wire EDM is a manufacturing process whereby a desired precise shape is obtained using electrical discharges called “sparks”. It is considered as a unique adoption of the conventional EDM processes, which uses an electrode to initialize the sparking process. Wire EDM technology has grown tremendously since it was first applied more than 30 years ago. In 1974, D.H. Dulebohn applied the optical-line follower system to automatically control the shape of the components to be machined by the Wire EDM process [5]. By 1975, its popularity rapidly increased, as the process and its capabilities were better understood by the industry. It was only towards end of the 1970s, when Computer Numerical Control (CNC) system was initiated into Wire EDM, which brought about a major evolution of the machining process.

Electrical Discharge Machining (EDM) is a non-traditional concept of machining which has been widely used to produce dies and molds. The EDM process was invented by two Russian scientists, Dr. B.R. Lazarenko and Dr. N.I. Lazarenko in 1943. The first numerically controlled EDM was invented by Makino in Japan. It is also used for finishing parts for aerospace and automotive industry and surgical components. This technique has been developed in the late 1940s where the process is based on removing material from a part by means of a series of repeated electrical discharges between tool called the electrode and the work piece until the gap is small enough so that the impressed voltage is great enough to ionize the dielectric. Short duration discharges are generated in a liquid dielectric gap, which separates tool and work piece. The material is removed with the erosive effect of the electrical discharges from tool and work piece. EDM does not make direct contact between the electrode and the work piece where it can eliminate mechanical stresses chatter and vibration problems during machining [23].

The basic EDM system consists of an electrode and the work piece connected to a DC power supply and placed in a di-electric fluid. The functions of the dielectric fluids are to:

1. Act as insulator until the potential is sufficiently high.
2. Provide cooling medium.
3. Act as a flushing medium and carry away the debris in the gap.

The most common dielectric fluids are mineral oils, kerosene and distilled and de-ionized water. Clear, low viscosity fluids are also available although they are more expansive. However, these fluids make cleaning easier. The machines usually are equipped with a pump and filtering system for dielectric fluid. When the potential is difference between the tool and the work piece is sufficiently high, the dielectric breaks down and a transient spark discharge through the fluid, removing a very small amount of metal from the work piece surface.

Wire EDM provides the best alternative for machining conductive, exotic, high strength, temperature resistive engineering ceramics with the scope of generating intricate shapes and profiles. Due to the tremendous potential of Wire EDM its applicability in the present day metal cutting industry is for achieving a considerable dimensional accuracy, surface finish and contour generation with very fine design feature. Wire EDM is the most widely and successfully used method for machining difficult to machine materials such as super alloys. Also the cost of wire contributes only 10% of the operating cost of Wire EDM, since complex design tool is replaced by moving conductive wire and relative movement of the wire guides [5].

1.4.1.1. PRINCIPLE OF WIRE EDM

The principle of wire electrical discharge machine is Spark Theory. In wire EDM, the conductive materials are machined with a series of electrical discharges (sparks) that are produced between an accurately positioned moving wire (the electrode) and the work piece. High frequency pulses of alternating or direct current is discharged from the wire to the work piece with a very small spark gap through an insulated dielectric fluid (water) [24].

Huge number of sparks can be observed at one time. This is because actual discharges occurs more than one hundred times per second, with discharge sparks lasting in the range of 1/1,000,000 of a second or less than that. The amount of the metal removed during this small period of spark discharge depends on the desired cutting speed and the surface finish required.
The heat of each electrical spark which is estimated at around 15,000° to 21,000° F, erodes a small amount of material that is vaporized and melted from the work piece. Along with the material some of the wire material is also eroded away. These chips are flushed away from the cutting zone with the stream of de-ionized water through the top and bottom flushing nozzles and the water also prevents heat build-up in the work piece. Without the cooling thermal expansion of the part, would affect size and position accuracy. The ON and OFF time of the spark that is repeated over and over that removes material, not just the flow of electric current [24].

1.4.1.2. COMPONENTS OF WIRE EDM

Typically, a wire EDM machine can be divided into four major components based on its working.

COMPUTERIZED NUMERICAL CONTROL (CNC)

Today’s numerical control is produced with the needs of the operator in mind. Programs, machine coordinates, cutting speeds, graphics and relevant information is displayed on a color monitor, with easy to use menus.

The control unit displays menus that are designed to give top priority to operability. Characters and commands are input using keyboard. The system is very easy
to use, allowing the operator to quickly become familiar with it, resulting in his/her learning curve being drastically reduced [24].

Along with executing NC data for positioning movement of the axes, the control amends these movements when using offsets, tapering, scaling, rotation, mirror images or axis exchange. To ensure high accuracy positioning, the control also compensates for any pitch error compensation or backlash error in the axes drives. The machine has different coordinate systems, and work specimens can be programmed in absolute or incremental modes saving valuable programming time. Like, multiple work specimens can be set-up on the worktable, while storing the separate reference points or locations of these jobs in specific coordinate registers.

The Numerical Controls offers the capabilities of rotation, imaging, scaling, mirror, axis exchange and assist programs. This enables user to produce an entire set of parts from a single program without editing the program. For left and right handed parts, mirror imaging is the best option. When working with shrink factors for plastic cavities or extrusion dies scaling is a very handy option. Assist programs finds the edge of parts, vertically align the wire and perform centering processes that are very useful to the operator when setting up jobs. Others options include technology to aid in the prevention of wire breaks, background editing and graphic display of programs while the machine is running. Programs are generated and written for the center of the wire to follow the outline of the part [24].

POWER SUPPLY

When wire EDM machines were introduced for the first time, they were equipped with power supplies that could achieve less than one square inch per hour. Now a days, most machines are rated to cut over twenty square inches per hour and faster. Fast and slow speeds can be obtained depending on the part thickness, work piece material, and wire diameter, type of wire, nozzle position, flushing condition and part accuracy.

Another feature is the anti-electrolysis circuitry that prevents the risk of electrolysis while cutting work piece that are in the machine for extended periods. This
AC circuit also eliminates the blue discoloration that appears when cutting titanium alloys with DC circuits and is a beneficial feature when cutting aluminum [24].

MECHANICAL SECTION

With precision lead screws with recirculating ball bearings on all axes that are driven by AC motors, machine movement is accomplished. Before delivering, the position of the machine is checked and any errors or backlash are corrected by pitch error compensation that is permanently stored in the computer’s memory.

WIRE PATH

When wire EDM was introduced for the first time, copper wire was used on the machines since it is best in conducting electricity. As the speed increases, its drawbacks are discovered later. Since, the low tensile strength of copper wire, it is subject to wire breaks when too much tension was applied. Another drawback was the poor flushability, due to the copper’s high thermal conductivity. A good amount of the heat from the EDM spark was transferred to the wire and taken away from work zone instead of using that to melt and vaporize the work piece. There is a huge set of wires to choose from with brass wire normally being used. Also, molybdenum, graphitized, and thick and thin layered composite wires are available for different applications [24].

Requirements for various wires include: optimizing for maximum cutting speeds, (coated or layered wire) cutting thick work pieces (high tensile strength with good flushability) or cutting large tapers (soft brass).

Diameter of the wire ranges from 0.004 inch to 0.014 inch with 0.010 inch being the most commonly used. The wire starts from a supply spool, and then passes through a tension device. Then it comes in contact with power feed contacts where the electric current is applied. The wire then passes through a precision set, round diamond guides, and then it is transported into a waste bin. The wire can only be used once, since it gets eroded from the EDM process [24].

Demand for automatic wire threading (AWT) and dependent reliability has been achieved with new improved designs. This feature also allows multiple openings to be cut
in die blocks, progressive dies, production, and prototype work pieces automatically and unattended without the intervention of an operator, resulting in higher production. With the addition of the programmable Z-axis, work specimens with different thickness, can also be machined.

Program Code controls the cutting and threading of the wire. If there is a wire break during machining, the machine returns to the start point of that opening, re-threads the wire and move through the program path to the position where it broke, powers up, and continues cutting as if the wire had never broken. Some EDM’s can also rethread the wire through the slot. The threading process of the automatic wire threader takes place automatically if there is a breakage in wire or by a command in the program. In a wire break situation, the end of the wire, while leaving a sharp point on the end of supply wire. The wire tip segment that was clamped is disposed of in a wire tip disposal unit. The supply wire is then directed into the lower guide. The wire then proceeds to the back of the machine where it is discarded in a sharp wire bin. AWT offers the ability to cut multiple openings in a work piece without operator intervention. Parts with multiple openings or even several jobs are cut overnight while many jobs can be cut over the weekend without operator intervention [24].

DIELECTRIC SYSTEM

When compared to Vertical EDM’s that use oil, Wire EDM uses de-ionized water as the dielectric fluid. The dielectric system has the water reservoir, filtration system, deionization system, and water chiller unit. During machining, the used water is drained into the unfiltered side of the dielectric reservoir where the water is then pumped and filtered through a paper filter, and returned to the clean side of the dielectric tank.

Followed by the filtration process, the clean water is measured for conductivity, and if required passes through a vessel that contains a mixed bed of anion and cation beads. This mixed bed resin (the ion exchange unit) controls the resistivity of the water to set values automatically [24].

The clean water fills the clean side of the dielectric reservoir and flows to the cutting zone. Used water is drained and returned to the unfiltered side of the dielectric
reservoir to complete the cycle. To thermally stabilize the standard equipment to keep the dielectric, work piece, worktable, control arms, and fixtures, a water chiller is provided.

During the cutting process the chips from the material that is being cut, gradually changes the water conductivity level. Resistivity levels of the water are set according to the cutting requirements of the work piece material being machined [24]. Figure 2 shows the Brother HS-70A Wire EDM machine installed at California State University, Northridge, California on which this thesis is conducted successfully.

Figure 2: Brother HS-70A Wire EDM Machine
1.4.1.3. PERFORMANCE PARAMETERS OF WIRE EDM

In this thesis it is very important to achieve the precise cut of involute spline profile on the machine insert on wire EDM machine. This is because a small error in accuracy of the involute profile results in the mismatch of the external and internal splines on the drive shaft and drive hub which have very narrow clearances of 0.020 inch in diameter. Therefore, proper machining parameters are to be selected based on what kind of kinds of materials and thickness of material. Some of the machining parameters which affect the precision cut are discussed now.

CUTTING SPEED

For Wire EDM, cutting speed is an important characteristic and it should be as high as possible to give least machining cycle time. The current cutting speed is digitally displayed on the machine display screen. The machining time “s” is recorded by the Wire EDM machine time indicator. The cutting speed is measured after the machining the specimen distance of and recorded. [5]

SPARK GAP

Spark gap or overcut is one of the responses which is very effective in this thesis. The spark gap is measured in order to study the correlation between machining parameters and the spark gap. Spark gap is shown in Figure 3. The unit used is inch. Spark gap can be calculated by the following formula. [5]

\[
\text{spark gap} = \frac{\text{kerf width} - \text{wire diameter}}{2}
\]  

\[\begin{align*}
\text{kerf width} &= \frac{\text{hole dimension} - \text{block dimension}}{2} \\
\text{hole dimension} &= \text{capacity of the EDM nozzle} + \text{clearance for overcut}
\end{align*}\]
MATERIAL REMOVAL RATE

The material removal rate of the work piece is the volume of the material removed per minute. The following are equations used to determine material removal rate (MRR) value.

\[
\text{Volume} = \text{Spark Gap} \times \text{Machine Distance} \times \text{Work Piece Thickness}
\]

From the material properties, the density of the machine insert (Solid Carbide) can be known. The mass of material that was removed by Wire EDM process can be known by,

\[
\text{Mass} = \text{Density} \times \text{Volume}
\]

\[
\text{MRR} = \frac{\text{Mass}}{\text{Machining Time}}
\]

SPARK CYCLE

Spark cycle is the measure used to gauge the number of times the current is switched on and off. During roughing operations, the on-time is usually extended for high rates of metal removal thus there are fewer of these cycles per second. Finishing operations are carried out at much shorter on and off times and have many cycles per
second [6]. During pulse on-time the metal removal process takes place whereas during pulse off-time the re-ionization of the di-electric takes place. In addition interval time also provides the time to clear the distinguished particles from the gap between the electrode and work piece for the efficient cut removal.

SPARK ENERGY

Spark energy is the size of the energy per one second discharge. This value set in the machine cannot be changed during the machining process when electrical charge is on. The amount of spark energy defines the amount of material removed per discharge. [5]

OPEN VOLTAGE

The present voltage determines the width of the spark gap between the leading edge of the electrode and the work piece. A high voltage setting increases the gap and hence the flushing and machining. Some material may require a high open voltage due to high electrical resistance and high discharge voltage.

WIRE FEED

Wire feed is the rate at which the wire electrode travels along the wire guide path and is fed continuously for sparking. The wire feed is expressed in units of inch/minute. It is desirable to set the wire feed to its maximum. This results in less wire breakage, better machining stability and slightly more cutting speed.

WIRE TENSION

Wire tension determines how much the wire is to be stretched between upper and lower wire guides. This is a gram-equivalent load with which the continuously fed wire is kept under tension so that it remains straight between the wire guides. As the thickness of job is more, tension required is also high. Improper wire tension setting may result in job inaccuracy or wire breakage [5].
FLOW RATE

Flow rate or flushing pressure represents the flushing pressure input of the dielectric. High flow rate of dielectric water is required for cutting with higher values of pulse energy and also while cutting the work piece of greater thickness.

1.4.1.4. WORKING OF WIRE EDM

In the wire electrode discharge machining, a thin single-stranded metal wire is fed through the work piece. This process is similar to contour cutting with a band saw, a slowly moving wire travels along a prescribed path, cutting the work piece. This process is used to cut plates as thick as 300mm and to make punches, tools, and dies from the hard metals that are too difficult to machine with other methods. It also creates intricate components for the electronic industries. The wire, which is constantly fed from the spool, is held between upper and lower diamond guides. Guides move in the x-y plane, usually being CNC controlled and on almost all modern machines like HS-70a the upper guide can also move independently in the z-u-v axis, giving rise to the ability to cut tapered and transitioning shapes and can control axis movements in x-y-u-v-i-j-k-l. This gives the wire-cut EDM the ability to be programmed to cut very intricate and delicate shapes [30]. The wire is controlled by upper and lower diamond guides that are usually accurate to 0.004mm, and can have a cutting path or kerf as small as 0.12mm using ø0.1mm wire, though the average cutting kerf that achieves the best economic cost and machining time is 0.335mm using ø0.25mm brass wire. The wire is usually made of brass, copper, tungsten, or molybdenum and multi-coated wire. The wire diameter is typically about 0.3mm for roughing cuts and 0.2mm for finishing cuts. The wire should have high electrical conductivity and tensile strength, as the tension on it is typically 60% of its tensile strength. The wire usually is used only once, as it is relatively inexpensive compared to the type of operation it performs. It travels at a constant velocity in the range of 0.15 to 9m/min, and a constant gap (kerf) is maintained during the cut. The trend in the use of dielectric fluids is towards clear, low viscosity fluids. The reason that the cutting width is greater than the width of the wire is because sparking also occurs from the sides of the wire to the work piece, causing erosion. This “overcut” is necessary, predictable, and easily compensated for. Spools of wire are typically very long. For example, an 8kg
A spool of 0.25mm wire is just over 19 kilometers long. Today, the smallest wire diameter is 20 micrometers and the geometry precision is not far from +/- 1 micrometer. The wire-cut process uses water as its dielectric with the water’s resistivity and other electrical properties carefully controlled by filters and de-ionizer units. The water also serves the very critical purpose of flushing the cut debris away from the cutting zone. Flushing is an important determining factor in the maximum feed rate available in a given material thickness, and poor flushing situations necessitate the reduction of the feed rate. Along with tighter tolerances multi-axis EDM wire-cutting machining center have many added features such as multi-heads for cutting two parts at the same time, controls for preventing wire breakage, automatic self-threading features in case of wire breakage, programmable machining strategies to optimize the operation.

1.4.1.5. MECHANISM OF MATERIAL REMOVAL

The mechanism of material removal in wire EDM machining mainly involves the removal of material due to melting and vaporization caused by the electric spark discharge generated by a pulsating current power supply between the electrodes. In Wire EDM, the negative electrode is a continuously moving wire and the positive electrode is the work piece. The sparks will generate between two closely spaced electrodes under the influence of dielectric liquid. Water is used as dielectric in WEDM, because of its low viscosity and rapid cooling rate [5].

1.4.1.6. ADVANTAGES OF WIRE EDM

- The machining of complex geometric forms
- Complex contoured shapes can be produced in one piece rather than several, in the exact configuration that is required.
- The rapid, economic production of prototypes and low run parts
- The ability to accurately machine complex designs, can be immediately used in assembly, with little or no additional finishing.
- Precise machining of pre-hardened materials
- Because hardened materials can be EDM eroded, the need for the heat treatment of machined parts is eliminated, avoiding potential distortion.
• Machining to tight tolerances, avoiding distortion and stress
• Very low machining forces allow tight tolerances of up to 2 microns to be achieved. With little or no stress imparted into the work only clamping is necessary. Thin materials can also be machined without distortion.
• The accurate and economic machining of exotic materials.
• Exotic materials including A-286 super alloys, medical grade stainless. Titanium, Hastelloy, Tungsten carbide, Molybdenum, Aluminum alloys and Copper can be machined. Better utilization of valuable materials is provided through chip less machining.
• Absolute consistency between machined parts.
• Because with wire EDM there is no contact between the cutting wire and the surface, there is no tooling wear and absolute consistency can be achieved on every machined part.

1.4.1.7. LIMITATIONS OF WIRE EDM

• Slow Material Removal Rate (MRR).
• Reproducing sharp corners on the work piece is difficult due to electrode wear.
• Limited for ferrous alloys but no reaction works in non-ferrous such as plastic, fiber, wood and so forth.
• Wire EDM machine can only be operated with the present of electricity.
• Unable to interpret technical or manual data/drawing. Wire EDM machine is enable to interpret and receiving drawing from such as CATIA, AutoCAD, Unigraphics, Solid Edge, Solid Works and etc.
• The control system of the electrode may fail to react quickly enough to prevent the tool and work piece to get in contact with a consequent short circuit. It is unwanted because a short circuit contributes to the removal differently from the ideal case. The flushing action can be inadequate to restore the insulating properties of the dielectric so that the flow of current always happens in the point of the inter-electrode volume (this is referred to as arcing), with a consequent unwanted change of shape (damage) of the tool-electrode and work piece.
1.4.1.8. APPLICATIONS OF WIRE EDM

Wire EDM has a wide range of applications which are growing by time day by day. It is extensively used in automotive, aerospace, molds, tool and die making industries. Wire EDM also has applicability in the medical, optical, dental, jewelry industries. The machine’s ability to operate unattended for hours or even days further increases the attractiveness of the process. Accuracy of high value with intrinsic design and on exotic material has increased its applicability in medical and R&D areas. Conventional EDM technique process requires many hours of electrode fabrication as well as many hours of manual grinding and polishing. With Wire EDM the overall fabrication time is reduced by around 37% and the processing time is reduced by 66%.

- Parts with complex geometry
- Parts requiring tolerances in the range of tenths
- Parts where burrs cannot be tolerated
- Delicate parts that are susceptible to tool pressure
- Progressive, blanking and trim dies
- Extrusion dies
- Precious metals
- Narrow slots and keyways
- Mold components
- Tooling for forging or injection molding operations
- Medical and dental instrumentation
- Cutting hardened materials such as carbide
- Cutting difficult to machine materials like hastily, Inconel and titanium
- Aerospace, defense and electronic parts
- Prototypes of different parts
- Production parts

1.4.2. CNC MILLING

CNC stands for Computer Numerical Control which refers to a computer “controller” that reads G-code instructions and has been around since the early 1950’s.
Prior to this, it was called NC, which is called Numerical Control [8]. In other words, a CNC machine is a numerical control system in which the data handling control sequences, and response to input is determined by an on-board computer system [9]. CNC Mills are the most common form of CNC machines [10].

Everything that an operator would be required to do with conventional machine tools could be programmable with CNC machines. Once setup and initialized, a CNC machine is quite simple to keep running. All CNC machine types share this commonality: they all have two or more programmable directions of motion called axes. An axis of motion can be linear (along a straight line) or rotary (along circular path). In other words CNC mills are classified according to the number of axes that they possess. Axes are labeled as X and Y for horizontal movement, Z for vertical movement, and B for fourth axis (rotational movement) and W for fifth axis which is an extra axis in the form of a horizontal pivot for the milling head [9]. The axes of the typical CNC machine are shown in Figure 4.

A CNC machine wouldn’t be very helpful if all it could do is to move the work piece in two or more axes. Almost all CNC machines are programmable in several other ways. For different applications, different tools are required so most machining centers can hold many tools in their tool magazine. When required, the desired tool can be automatically placed in the spindle for machining. The spindle is one of the main parts in CNC machines. CNC spindles can rotate in a forward (CW) or reverse (CCW) direction based on the machining purposes. Sometimes their rotational speed can reach up to 25000 revolutions per minute in high speed machining processes [8].

Machining processes that have traditionally been done on conventional machine tools that are improved with CNC machining centers include all kinds of milling (face milling, contour milling, slot milling, etc.), drilling, tapping, reaming, boring, and counter boring.
Figure 4: Orientation of Different Axes on a Typical CNC Machine [12]

There are many ways to classify milling machines, depending on criteria. The most common classification is horizontal and vertical mill. In the vertical mill the spindle axis is vertically oriented. Milling cutters are held in the spindle and rotate on its axis. Therefore are two sub categories of vertical mills: the bed mill and the turret mill. Turret mills are generally smaller than the bed mills. In a turret mill the spindle remains stationary during cutting operations and the table is moved both perpendicular to and parallel spindle axis to accomplish cutting. In the bed mill, however, the table moves only perpendicular to the axis spindle’s axis, while the spindle itself moves parallel to its own axis [12].

Table 1: Classification of CNC machines

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>Manual</td>
</tr>
<tr>
<td></td>
<td>Mechanically automated via cams</td>
</tr>
</tbody>
</table>
A horizontal mill has the same sort of x-y table, but the cutters are mounted on a horizontal arbor across the table. A majority of horizontal mills also feature a +15/-15 degree rotary table that allows milling at shallow angles. While end mills and the other types of tools available to a vertical mill may be used in a horizontal mill, their real advantage lies in arbor-mounted cutters, called side and face mills, which have a cross section rather like a circular saw, but are generally wider and smaller in diameter [12]. But other distinctions are also important, as shown in Table 1.

Some of the Cutting equations used in Milling machine are,

Cutting Speed (surface feet per minute)

$$sfm = \frac{\pi \times D \times RPM}{12}$$

.... (5)

where D is the diameter of the cutter.

Feed speed = Chip Load* Number of teeth* Angular velocity

$$ipm = ipt \times nt \times RPM$$

.... (6)

Angular Velocity (Revolution per minute)

$$RPM = \frac{12 \times sfm}{\pi \times D}$$

.... (7)

Chip Load = \frac{Feed Speed}{Number of Teeth \times Angular Velocity}
\[ \text{ipt} = \frac{\text{ipm}}{\text{nt} \times \text{RPM}} \]  

\[ \text{Instant material removal rate} = \text{Axial depth of cut} \times \text{Radial width of cut} \times \text{Feed Speed} \]  

\[ \text{MRR} = \text{ADOC} \times \text{RWOC} \times \text{ipm} \]  

\[ \text{Cutting Horsepower} = \text{Unit Horsepower} \times \text{Material Removal Rate} \]  

\[ \text{HP}_c = \text{HP}_u \times \text{MRR} \]  

With \( \text{HP}_u = \frac{1}{K_{\text{factor}}} \), then  

\[ \text{HP}_c = \frac{1}{K_{\text{factor}}} \times \text{MRR} \]  

1.4.3. BROACHING

Broaching was originally developed for machining internal keyways. However, it was soon discovered that broaching is very useful for machining other surfaces and shapes for high volume work pieces [11]. Because each broach is specialized to cut just one shape either the broach must be specially designed for the geometry of the work piece or the work piece must be designed around standard broach geometry. A customized broach is usually only viable with high volume work pieces, because the broach can cost $15,000 USD to $30,000 USD to produce [1].

Broaching is a machining process that uses a toothed tool, called “broach”, to remove material. There are two main types of broaching: linear and rotary. In linear broaching, which is the most common process, the broach is run linearly against a surface of the work piece to effect the cut. In rotary broaching, the broach is rotated and pressed into the work piece to cut axis symmetric shape as shown in Figure 5. A rotary broach is used in lathe or screw machine. In both processes the cut is performed in one pass of the broach, which makes it very difficult. Commonly machined surfaces include circular, non-circular holes, splines, keyways, and flat surfaces. Broaches are shaped similar to a saw, except the teeth height increases over the length of the tool [13]. Moreover, the
broach contains three distinct sections: one for roughing, another for semi-finishing and final one for finishing. Broaching is unusual machining process because it has the feed built into the tool. The profile of the machined surface is always the inverse of the profile of broach. The rise per tooth (RPT), also known as step or feed per tooth, determines the amount of material removed and the chip size. The broach can be moved relative to work piece or vice-versa. Because all the features are built into broach no complex motion or skilled labor is required to use it [14]. A broach is effectively a collection of single-point cutting tool arrayed in sequence, cutting one after the other.

![Figure 5: Rotary Broaching Machine Setup](image)

Figure 5: Rotary Broaching Machine Setup [13]

Broach speeds may vary from 20 to 120 surface feet per minute (SFPM). This results in a complete cycle time of 5 to 30 seconds. The only limitations of broaching are that there are no obstructions over the length of the surface to be machined. The geometry to be cut does not have curves in multiple planes and the work piece is strong enough to withstand the forces involved.

1.4.4. HOBBING

Hobbing is one of the very old manufacturing techniques used to manufacture gears. It is started with manual hobbing to make gears prior to the gears of the 19th century and earlier. Hobbing is a machining process for making gears, splines and sprockets on a hobbing machine, which is a special type of milling machine. The teeth or
splines are progressively cut into the work piece by a series of cuts made by a cutting tool called a hob. It is the most widely used spline cutting process for creating spur gears and helical gears [17].

![Figure 6: Shape of a Hob](image)

The hob is the cutter used to cut the teeth into the work piece. It is cylindrical in shape with helical cutting teeth as shown in Figure 6. These teeth have grooves that run the length of the hob, which aid in cutting and chip removal. Hobbing uses a hobbing machine with two skew spindles, one mounted with a blank work piece and the other with the hob. The angle between the hob’s spindle and the work piece’s spindle varies, depending on the type of product being produced. If the hob has multiple threads then the speed ratio must be multiplied by the number of threads on the hob. The hob is then fed up into the work piece until the correct tooth depth is obtained. Each gear hobbing machine typically consists of a chuck and tailstock to hold the work piece or a spindle on which the hob is mounted and a drive motor as shown in figure 7[18].

1.4.5. GEAR SHAPING

A shaper is a type of machine tool that uses linear relative motion between the work piece and a single-point cutting tool to machine a linear tool path. Its cut is analogous to that of a lathe, except that it is linear instead of helical. A shaper is analogous to a planer but
smaller, and with the cutter riding a ram that moves above a stationary work piece, rather than the entire work piece moving beneath the cutter.

Figure 7: Barber Coleman Hobbing machine [13]

A shaper operates by moving a hardened cutting tool backwards and forwards across the work piece. On the return stroke of the ram the tool is lifted clear of the work piece, reducing the cutting action to one direction only. The work piece mounts on a rigid, box-shaped table in front of the machine. The height of the table can be adjusted to suit this work piece, and the table can transverse sideways underneath the reciprocating tool, which is mounted on ram. Table motion may be controlled manually, but is usually advanced by automatic feed mechanism acting on the feed-screw. The ram slides back and forth above the work. At the front end of the ram is a vertical tool that may be adjusted to either side of the vertical plane along the stroke axis. The tool slider holds the clapper box and tool post, from which the tool can be positioned to cut a straight, flat surface on the top of the work piece. The tool-slide permits feeding the tool downwards.
to deepen a cut. This adjustability, coupled with the use of specialized cutters and tool holders, enable the operator to cut internal and external gear tooth profiles, splines, dovetails and keyways. A typical gear shaper machine illustration is shown in figure 8.

Figure 8: Gear Shaping Machine

1.4.6. SPLINE ROLLING

Rolling is the term used to designate forming (generally cold) of a round part by tools, rotating or otherwise, in various numbers and arrangements around the work-piece. Forming can also be carried out at medium temperature on a certain materials. Rolling is used increasingly because it brings many advantages compared with machining:

- Improved surface condition
- Increased mechanical strength by work hardening by avoiding fracture starts generally due to tool marks or scratches and by fibring obtained on rolling.
- Economy of matter since the blank diameter is less than that of the finished part.
- Shorter cycle time on machining in many applications.
- Better quality is achieved than with conventional machining.
In spline rolling, the tool has one (or several) release profiles and is driven in rotation as shown in Figure 9. Contact between the tool and the work piece the latter in rotation and a mirror profile of the tool is progressively impressed on the work piece through the force applied to the tools and the variable profile of the tool. Between tool profiles, the part material is displayed to from the outer diameter of the profile. This displacement is parallel to the surface in contact between the tool and the work piece. It flows all the more easily as the angle between the tool and work piece contact surfaces and the direction of the force (or the variation of profile) approaches 90 degrees. If not used to develop a profile, displacement of the material can be used to tie two parts. The rolling cycle breaks down into three parts.

- Penetration: The tool is brought to the work piece and presses against it either to print its profile on the previously smoothed blank or for burnishing or calibrating the surface.
• Calibration: The work piece is made round, which is not the case momentarily during penetration.
• Decompression: The tool and the work piece move apart in order to free the work piece and machine elasticity.

1.4.7. APPLICATIONS OF SPLINES

Typically splines are designed with shorter teeth and with large pressure angles than standard gears to carry higher loads. In general, the standard pressure angles for involute splines are 30, 37.5 and 45 degrees, while gears typically utilize pressure angles of 14.5, 20 and 25 degrees. Splines are special class of gears that do not engage in conjugate action or smooth continuous motion, but the teeth in spline coupling remain fixed relative to each other [21]. Internal splines and External splines are designed to allow the shaft to engage with the hub over the entire circumference. Unlike gears, the point of contact between mating spline teeth remains constant and multiple teeth engage in order to transmit torque; therefore splines are ideal for applications involving high torque loads. As an example spline couplings are used in braking systems for large industrial vehicles like the huge dump trucks used for mining operations. Exploded view of such braking application, which uses two sets of spline couplings in order to provide a braking force is shown in Figure 10.

The inner set of spline couplings contains the shaft and the friction plates, while the outer set of couplings is comprised of the separator plates and hub. The hub couplings remain fixed, while the shaft coupling rotates. The hub and shaft couplings are comprised of internal and external splines which transfer torque without any slipping. Prior to applying the brakes, the shaft coupling rotates freely inside of the hub coupling. When brakes are applied, the separator plates are squeezed together, applying pressure to the rotating friction plates, creating the braking force needed to stop the rotation of the shaft [20].
Figure 10: Applications of Internal and External Splines in Industrial Braking System [20]
2. SPLINES

2.1. INTRODUCTION TO SPLINES

According to the American Heritage dictionary of the English Language (4th edition, 2000), a spline is defined as: 1a. Any of a series of projections on a shaft that fit into slots on a corresponding shaft, enabling both to rotate together. b. The groove or slot for such a projection. 2. A flexible piece of wood, hard rubber, or a metal used in drawing curves [1].

A spline shaft is one having series of parallel keys formed integrally with the shaft and mating with corresponding grooves cut in a hub or fitting as shown in Figure 11. This arrangement is in contrast to a shaft having a series of keys fitted into slots cut into the shaft. The latter construction weakens the shaft to a considerable degree because of the slots cut into it and consequently, reduces its torque-transmitting capacity.

![Figure 11: Internal and External Spline](image)

Splined shafts are most generally used in three types of applications: 1. For coupling shafts when relatively heavy torques are to be transmitted without slippage; 2. For transmitting power to slidably-mounted or permanently-fixed gears, pulleys and other rotating members; and 3. For attaching parts that may require removal for indexing or change in angular position [1].
Splines having straight-sided teeth have been used in many applications; however, the use of splines with teeth of involute profile has steadily increased since 1) involute spline couplings have greater torque-transmitting capacity than any other type; 2) they can be produced by the same technique and equipment as it used to cut gears; and 3) they have a self-centering action under load even when there is backlash between mating members [1].

2.2. TYPES OF SPLINES

2.2.1. PARALLEL KEY SPLINES

These types of splines have equally space teeth that are straight sided. The teeth on the shaft have an equal tooth thickness at any point measured radially out from the axis of rotation as shown in Figure 12. Conversely, the internal parallel spline has corresponding straight spaces. This type of spline is similar to keyway drive, with the exception that the keys are integral to the shaft and equally spaced around the circumference. The piloting feature can be the outside diameter of the shaft and major diameter of the internal spline or the minor diameter of the internal spline and the minor diameter of the shaft. Types of fit are permanent, to slide when not under load, to slide when under load [19].

![Figure 12: Parallel Key Splines with 4, 6 and 8 tooth [1]](image-url)
2.2.2. INVOLUTE SPLINE

These types of splines have equally spaced teeth. But they are not straight sided. The teeth have an involute form, just like a gear tooth as shown in Figure 13. The teeth do not have a same proportion as a gear tooth; they are shorter in height combined with involute form sides provide greater strength. They have a pressure angle of 30-, 37.5 and 45 degrees. There are no sharp inside corners at the base of the teeth as found in parallel key spline drives. Instead there is a smooth transition through a radius. This decreases the possibility of fatigue cracking in these areas [19].

![Figure 13: External and Internal Involute Splines](image)

2.2.3. CROWNED SPLINES

These splines are typically involute. They can be flat root, fillet root or major diameter fit. The purpose of this type of spline is to allow for angular misalignment between the shaft and mating detail. This is accomplished by “crowning” male tooth. The tooth (usually) has a symmetrical crown about the center-line of the spline face-width. At this centerline the tooth thickness is at its maximum. Moving towards the ends the tooth thickness gradually decreases with the thinnest sections occurring at each end face. The tooth thickness is measured at the pitch diameter. Usually the outside diameter of the spline is also crowned, with the largest diameter occurring at the same location as the designed misalignment towards each end face [19]. Crowned splines are shown in Figure 14.
2.2.4. SERRATION

This type of spline has a tooth form that is non-involute as shown in Figure 15. The teeth of the male detail are in the form of an included angle, with the female serration having spaces of the same included angle. Serrations are generally used on smaller diameter drives, where an involute form would not add strength. Because the teeth are simple included angle form, more teeth can be used on a small circumference, providing a greater contact area. Serrations are used in instrument drives, valve shafts and the like [19].

Figure 14: Crowned Splines

Figure 15: Serrations
2.2.5. HELICAL SPLINES

These types of splines can either be parallel or involute tooth form. The helical spline has a specific lead and helix angle. These splines are used for several applications. In drives where spline shaft may become torsional wound-up, a straight spline may lead to drive shaft breakage in areas other than spline. This is because the load along the entire length of the spline, resulting in full contact along the drive side of the tooth. This load sharing distributes the rotational torque along a greater length of shaft, which now includes the spline [19].

![Helical Cut Splines](image)

Figure 16: Helical Cut Splines

2.3. WHAT IS AN INVOLUTE?

In the differential geometry of curves, an “involute” (also known as evolvent) is a curve obtained from another given curve by attaching an imaginary taut string to the given curve and tracing its free end as it is wound on to that given curve; or in reverse, unwound. It is a roulette wherein the rolling curve is a straight line containing the generating point.

The involute of a circle forms a shape which resembles an “Archimedean spiral”. In Cartesian coordinates, the involute of a circle has the parametric equation:

\[ x = r(cos \ t + t \ sin \ t) \]
\[ y = r(sin \ t - t \ cos \ t) \]
Where ‘r’ is the radius of the circle and ‘t’ is an angular parameter in radians.

In polar coordinates, ‘r’, ‘θ’ the involute of a circle has the parametric equation:

\[ r = a \sec \alpha \]

\[ \theta = \tan^{-1} \left( \frac{\sin t - t \cos t}{\cos t + t \sin t} \right) \]

Figure 17: Generation of Involute Spline Curve

2.4. AMERICAN NATIONAL STANDARD INVOLUTE SPLINES

These splines or multiple keys are similar in form to internal and external involute gears. The general practice is to form the external splines either by hobbing, rolling, or on a gear shaper. The internal spline is held to basic dimensions and the external spline is varied to control the fit. Involute splines have maximum strength at the base, can be accurately spaced and are self-centering, thus equalizing the bearing and stresses, and they can be measured and fitted accurately [1].

In American National Standard ANSI B92.1-1970(R1993), many features of the 1960 standard are retained; plus the addition of three tolerance classes, for a total of four. The term “involute serration,” formerly applied to involute splines with 45-degree
pressure angle, has been deleted and the standard now includes involute splines with 30-, 37.5-, and 45-degree pressure angles.

The standard recognizes the fact that proper assembly between mating splines is dependent only on the spline being within effective specifications from the tip of the tooth to the form diameter. Therefore, on side fit splines, the internal spline major diameter now is shown as a maximum dimension and the external spline minor diameter is shown as minimum dimension. The minimum internal major diameter and the maximum external minor diameter must clear the specified form diameter and thus do not need any additional control [1].

2.5. INVOLUTE SPLINES TERMINOLOGY

The following are the few terms most commonly used in this thesis.

ACTIVE SPLINE LENGTH

Active spline length ($L_a$) is the length of spline that contacts the mating spline. On sliding splines, it exceeds the length of engagement.

ADDENDUM

Addendum (a) is the radial or perpendicular distance between pitch circle and the top of the teeth.

For involute splines,

$$a = \frac{D_o - D}{2}$$

Where ‘N’ is the number of spline tooth.

TOOTH THICKNESS

Actual tooth thickness (t) is the circular thickness on the pitch circle of any single tooth considering an infinitely thin increment of axial spline length.

$$t = 0.5 \times p$$

BASE CIRCLE

Base circle is the circle from which involute spline tooth profiles are constructed.
BASE DIAMETER

Base diameter \( (D_b) \) is the diameter of the base circle of the spline.

\[
D_b = D \cdot \cos \phi
\]

CIRCULAR PITCH

Circular pitch \( (p) \) is the distance along the pitch circle between corresponding points of adjacent spline teeth.

\[
p = \frac{\pi}{P}
\]

DIAMETRAL PITCH

Diametral Pitch \( (P) \) is the number of spline teeth per inch of the pitch diameter. The diametral pitch determines the circular pitch and the basic space width or tooth thickness. In conjunction with the number of teeth, it also determines the pitch diameter.

\[
P = \frac{N}{D}
\]

DEDENDUM

Dedendum \( (b) \) is the radial or perpendicular distance between the pitch circle and the bottom of the spline tooth.

\[
b = \frac{D - D_i}{2}
\]

MAJOR DIAMETER

Major diameter \( (D_o) \) is the diameter of the major circle formed by the outermost surface of the spline. Major circle is the outside circle of the external spline or the root circle of the internal spline.

\[
D_o = \frac{N + 1}{D}
\]
MINOR DIAMETER

Minor diameter ($D_i$) is the diameter of the minor circle formed by the innermost surface of the spline. Minor circle is the root circle of the external spline or the inside circle (tooth tip circle) of the internal spline.

$$\frac{N - 1.35}{2}$$

Table 2: American National Standard Involute Spline Symbols

<table>
<thead>
<tr>
<th>$D$</th>
<th>Description</th>
<th>$N$</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_b$</td>
<td>Base Diameter</td>
<td>$P$</td>
<td>Diametral Pitch</td>
</tr>
<tr>
<td>$D_i$</td>
<td>Minor Diameter, Internal Spline</td>
<td>$P_s$</td>
<td>Stub Pitch</td>
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<tr>
<td>$D_o$</td>
<td>Major Diameter, External Spline</td>
<td>$p$</td>
<td>Circular Pitch</td>
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<tr>
<td>$D_{re}$</td>
<td>Minor Diameter, External Spline</td>
<td>$t$</td>
<td>Actual Tooth Thickness, Circular</td>
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<td>(root)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$D_{ri}$</td>
<td>Major Diameter, Internal Spline</td>
<td>$\phi$</td>
<td>Pressure angle</td>
</tr>
<tr>
<td></td>
<td>(root)</td>
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<td></td>
</tr>
<tr>
<td>$L$</td>
<td>Spline Length</td>
<td>$\phi_D$</td>
<td>Standard Pressure Angle</td>
</tr>
</tbody>
</table>

PITCH

Pitch ($P/P_s$) is a combination of a one-to-two ratio indicating the spline proportions; the upper or first number is the diametral pitch, the lower or second is the stub pitch and denotes, as that fractional part of an inch, the basic radial length of engagement, both above and below the pitch circle.

PITCH DIAMETER

Pitch diameter ($D$) is the diameter of the pitch circle which is the reference circle from which all transverse spline tooth dimensions are constructed.

$$D = \frac{N}{P}$$
PRESSURE ANGLE

Pressure angle (φ) is the angle between a line tangent to an involute and a radial line through the point of tangency. Unless otherwise specified it is the standard pressure angle.

STUB PITCH

Stub pitch (Pₙ) is a number used to denote the radial distance from the pitch circle to the major circle of the external spline and from the pitch circle of the minor circle of the internal spline. The stub pitch for splines is twice the diametral pitch.

\[ Pₙ = 2P \]

2.6. INVOLUTE TOOTH CLASSIFICATION

There are 17 pitches: 2.5/5, 3/6, 4/8, 5/10, 6/12, 8/16, 10/20 12/24, 16/32, 20/40, 24/48, 32/64, 40/80, 48/96, 64/128, 80/160, and 128/256. The numerator in this fractional designation is known as the diametral pitch and controls the pitch diameter; the denominator, which is double the numerator, is known as the stub pitch and controls the tooth depth. For convenience in calculation, only the numerator is used in the formula given and is designated as P [1].

Table 3 shows the symbols and the formulas for the basic tooth dimensions of involute spline teeth of various pitches with 30 degrees pressure angle with flat root major diameter fit type. Table 4 shows the basic dimensions of the involute spline teeth with different pitches.

Table 3: Formulas for Flat Root Major Diameter Fit with 30-deg Pressure Angle

<table>
<thead>
<tr>
<th>Term</th>
<th>Symbol</th>
<th>Flat root major Diameter Fit (3/6-16/32 Pitch) (30-Deg Pressure Angle)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stub Pitch</td>
<td>Pₙ</td>
<td>2P</td>
</tr>
<tr>
<td>Pitch Diameter</td>
<td>D</td>
<td>N/νP</td>
</tr>
<tr>
<td>Base Diameter</td>
<td>Dₚ</td>
<td>Dcosφ</td>
</tr>
<tr>
<td>Circular Pitch</td>
<td>p</td>
<td>π/P</td>
</tr>
</tbody>
</table>
Circular Thickness \( t \) \( 0.5 \times p \)

<table>
<thead>
<tr>
<th>Term</th>
<th>Symbol</th>
<th>( 2p )</th>
<th>( N/P )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stub Pitch</td>
<td>( P_s )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pitch Diameter</td>
<td>( D )</td>
<td></td>
<td>( N/P )</td>
</tr>
<tr>
<td>Base Diameter</td>
<td>( D_b )</td>
<td>( D \cos \phi_D )</td>
<td>( D \cos \phi_D )</td>
</tr>
<tr>
<td>Circular Pitch</td>
<td>( p )</td>
<td>( \pi/P )</td>
<td>( \pi/P )</td>
</tr>
<tr>
<td>Minimum Effective Space Width</td>
<td>( s_e )</td>
<td>( \pi/(2p) )</td>
<td>( \pi/(2p) )</td>
</tr>
<tr>
<td>Major Diameter, Internal</td>
<td>( D_{ri} )</td>
<td>( (N + 1.35)/P )</td>
<td>( (N + 1)/P )</td>
</tr>
<tr>
<td>Major Diameter, External</td>
<td>( D_o )</td>
<td>( (N + 1)/P )</td>
<td>( (N + 1)/P )</td>
</tr>
<tr>
<td>Minor Diameter, Internal</td>
<td>( D_i )</td>
<td>( (N - 1)/P )</td>
<td>( (N - 1)/P )</td>
</tr>
<tr>
<td>Minor Dia. Ext.</td>
<td>2.5/5 thru 12/24 pitch</td>
<td>( D_{re} )</td>
<td>( (N - 1.35)/P )</td>
</tr>
<tr>
<td></td>
<td>16/32 pitch and finer</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10/20 pitch and finer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Form Diameter, Internal</td>
<td>( D_{fi} )</td>
<td>( (N + 1)/P + 2cF )</td>
<td>( (N + 0.8)/P - 0.004 + 2cF )</td>
</tr>
<tr>
<td>Form Diameter, External</td>
<td>( D_{fe} )</td>
<td>( (N - 1)/P - 2cF )</td>
<td>( (N - 1)/P - 2cF )</td>
</tr>
</tbody>
</table>

Figure 18: Equations of Involute Splines as per ANSI

Table 4: Basic Dimensions of Involute Splines of 30-deg Pressure Angle

<table>
<thead>
<tr>
<th>Pitch, ( P/P_s )</th>
<th>Circular Pitch, ( P )</th>
<th>Min Effective Space Width (Basic), ( S_v ) min</th>
<th>Pitch, ( P/P_s )</th>
<th>Circular Pitch, ( P )</th>
<th>Min Effective Space Width (Basic), ( S_v ) min</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5/5</td>
<td>1.2566</td>
<td>0.6283</td>
<td>20/40</td>
<td>0.1571</td>
<td>0.0785</td>
</tr>
<tr>
<td>3/6</td>
<td>1.0472</td>
<td>0.5236</td>
<td>24/48</td>
<td>0.1309</td>
<td>0.0654</td>
</tr>
<tr>
<td>4/8</td>
<td>0.7854</td>
<td>0.3927</td>
<td>32/64</td>
<td>0.0982</td>
<td>0.0491</td>
</tr>
<tr>
<td>5/10</td>
<td>0.6283</td>
<td>0.3142</td>
<td>40/80</td>
<td>0.0785</td>
<td>0.0393</td>
</tr>
<tr>
<td>6/12</td>
<td>0.5236</td>
<td>0.2618</td>
<td>48/96</td>
<td>0.0654</td>
<td>0.0327</td>
</tr>
</tbody>
</table>
2.6.1. TOOTH NUMBERS

The American National Standard covers involute splines having tooth numbers ranging from 6 to 60 with a 30 or 37.5–degree pressure angle and from 6 to 100 with a 45-degree pressure angle. In selecting the number of teeth for the given spline application, it is to be known that there are no advantages of using odd numbers of teeth and that the diameters of splines with odd numbers, particularly internal splines are troublesome to measure with pins no two tooth spaces are diametrically opposite each other [1].

2.7. TYPES AND CLASSES OF INVOLUTE SPLINE FITS

Two types of fits are covered by American National Standard for the involute splines: the side fit, and the major diameter fit.

SIDE FIT

In the side fit, the mating members contact only on the sides of the teeth; major and minor diameters of the teeth act as drivers. The minor diameters are clearance dimensions.

MAJOR DIAMETER FIT

Mating parts for this type of fit, contact at their major diameters to centralize. The sides of the teeth act as drivers. The minor diameters are clearance dimensions. The major diameter fit provides a minimum effective clearance that will allow for contact and location at the major diameter with a minimum amount of location or centralizing effects by the side of the teeth. The major diameter fit has only one space width and tooth thickness tolerance which is the same as side fit class.
2.8. SPREADSHEET CALCULATIONS

All spline parameters used in this thesis were based on the CSUN FSAE vehicle drivetrain, thus the spline tool was designed to meet those specifications.

All these calculations are carried out on Microsoft Excel 2010 Spreadsheets. Using the formulae for spline parameters discussed earlier in this chapter, involute profile parameters are taken into consideration and input data including number of teeth, diametral pitch and pressure angle. The following are the inputs values taken into account, tabulated and calculated.

### Table 5: Input Parameters for Involute Spline

<table>
<thead>
<tr>
<th>INPUTS</th>
<th>UNITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Teeth</td>
<td>27</td>
</tr>
<tr>
<td>Diametral Pitch</td>
<td>24</td>
</tr>
<tr>
<td>Pressure Angle</td>
<td>30</td>
</tr>
</tbody>
</table>

Using the above data, basic parameters needed to get the geometry of the Involute Spline are calculated and tabulated.

### Table 6: Basic Geometry parameters of Involute Splines

<table>
<thead>
<tr>
<th>BASIC GEOMETRY PARAMETERS</th>
<th>UNITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pitch Diameter</td>
<td>1.125</td>
</tr>
<tr>
<td>Base Circle Diameter</td>
<td>0.974</td>
</tr>
<tr>
<td>Major Diameter</td>
<td>1.167</td>
</tr>
<tr>
<td>Minor Diameter</td>
<td>1.069</td>
</tr>
<tr>
<td>Addendum</td>
<td>0.021</td>
</tr>
<tr>
<td>Dedendum</td>
<td>0.028</td>
</tr>
<tr>
<td>Whole Depth</td>
<td>0.049</td>
</tr>
</tbody>
</table>

Once the above geometry parameters are calculated pitch on base circle and pitch circle is calculated according to the number of teeth required to find out the tooth thickness accordingly.

### Table 7: Pitch and Tooth Thickness values of Involute Spline

<table>
<thead>
<tr>
<th>PITCH</th>
<th>UNITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pitch on Base Circle</td>
<td>0.113</td>
</tr>
<tr>
<td>Pitch on Pitch Circle</td>
<td>0.131</td>
</tr>
</tbody>
</table>

40
### TOOTH THICKNESS

<table>
<thead>
<tr>
<th></th>
<th>UNITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tooth Thickness on Base Circle</td>
<td>0.057</td>
</tr>
<tr>
<td>Tooth thickness on Pitch Circle</td>
<td>0.065</td>
</tr>
</tbody>
</table>

**Table 8: Spline Equation and its Parameters**

<table>
<thead>
<tr>
<th>SPLINE EQUATION</th>
<th>VALUES</th>
<th>UNITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>x=r*(cos(t)+t*sin(t))</td>
<td></td>
<td></td>
</tr>
<tr>
<td>y=r*(sin(t)-t*cos(t))</td>
<td></td>
<td></td>
</tr>
<tr>
<td>r</td>
<td>0.487</td>
<td>Inches</td>
</tr>
<tr>
<td>t1</td>
<td>0</td>
<td>--</td>
</tr>
<tr>
<td>t2</td>
<td>0.659</td>
<td>--</td>
</tr>
</tbody>
</table>

Besides the usual spline parameters, it is important to have the Parametric Spline parameters to get the profile of the spline tooth. In the parametric spline equations, \( t_1 \) and \( t_2 \) are the parameters which decides the length of the involute curve.
3. DESIGN PHASE-SOLIDWORKS

Design and analysis phase is the next important step in this thesis. Here, in this phase of pre-manufacturing, actual models are built. All the built models are designed and iterated with different set of dimensions and machining parameters using design tables. To create a tool insert with the Involute Spline profile, first we need to design an Internal or External Spline. Using that spline, a profile is generated on tool insert and is manufactured in the ESPRIT phase. So this chapter discusses the steps involved in creating the Involute splines and the corresponding spline profile on the required machine insert. This chapter on pre-manufacturing using SolidWorks involves,

- Drawing an involute spline sketch
- Creating a involute tooth profile
- Converting into External Involute Spline using circular pattern with required number of teeth
- Creating a Design table with number of teeth, diametral pitch and pressure angle as inputs

3.1. SOLIDWORKS GRAPHICAL USER INTERFACE

The SolidWorks application is mechanical design automation software, which takes advantage of the familiar Microsoft Windows graphical user interface and is developed by Dassault Systems SolidWorks Corp. A SolidWorks model consists of 3D solid geometry in a part or assembly document. Drawings are created from models or assemblies, or by drafting views in a drawing document [25].

A Solid model typically begins with a two-dimensional sketch, which is then associated with a base feature like extrusion or revolution. Then, more features are added to add or subtract material from the model. We can also begin with an imported surface or solid geometry. We can refine the design by adding, editing or reordering features. Associability between parts, assemblies and drawings assures that changes made to one document or views are automatically made to all other documents and views. Once can also generate drawings or assemblies at any time in the design process [25].
"Menu Bar" contains nearly all the SolidWorks commands. Menus and menu items are available depending on the active document type and workflow customization. Many commands are also available in command manager, tool bars, shortcut menus and task pane. We can customize menus to hide or show items and we can hide all menus.

"Command Manager" is a context-sensitive tool bar that dynamically updates based on the tool bar we want to access. By default, it has tool bars embedded in it based on the document type. When we click a tab below the command manager, it updates to show that particular tool bar. For example, if we click on sketch tab, the sketch tool bar appears on the screen. We also have a flexibility to add a custom tab to command manager and also custom command manager tool buttons.

"Property Manager" appears on the Property manager tab in the panel to the left of Graphics Area. It opens when we selects entities or commands defined in the Property
Manager. We can choose whether it opens in other cases in tools, options, system options and general.

“Graphics Area” is the section where we create the part. We can switch the views of the part, save templates and import other parts etc. on to the graphics area. There is also a viewpoint providing all common tools necessary for manipulating the view. We can also have shaded and dynamic previews of the part.

“Feature Manager” design tree on the left side of the SolidWorks window provides an outline view of the active part, assembly, or drawing. We can identify and change the order of features created. We can drag items in the Feature Manager Design tree list to reorder them. This changes the order in which features are regenerated when the model is rebuilt. The dimensions of the features are displayed by double-clicking the feature’s name. Items are renamed by slowly clicking two times on a name to select it and then entering a new name.

3.2. EXTERNAL INVOLUTE SPLINE

According to the thesis objective defined, to manufacture a Spline cutter we need to know the profile of the involute spline. For this, we need to make an external involute spline from which a spline profile is traced on to the cutting insert by using convert entities and SolidWorks assembly.

Initially, based on the parameters calculated in previous chapter, a preliminary sketch is drawn using 2-Dimensional SolidWorks sketch in part modeling. Making the sketch constrained, parts are modeled using extrusion command and converted into 3-Dimensionals figures. Using the dimensions of the part and adding equations and relations to those dimensions a Design Table is created.

3.2.1. CREATING 2-D SPLINE TOOTH SKETCH

To create a sketch a new part model is opened inside SolidWorks. A ‘Sketch’ option is selected on Top plane (XY-Plane). Using the inputs parameters defined by FSAE team and the calculations done in previous chapters, a basic sketch is created on sketching plane as shown is Figure 20.
Here, using parametric equations of spline command under sketching tool and with the required tooth thickness measured in terms of angle, a tooth profile is generated with major diameter, pitch circle and minor circle. Once the tooth form is generated, it is converted into 3-Dimensional tooth using ‘Extrude’ command as shown in Figure 21.
3.2.2. CONVERTING TO 3-D EXTERNAL INVOLUTE SPLINE

Once the spline tooth profile is created, based on the number of tooth required that is 27 as a part of this thesis, a circular pattern is used to generate a full involute spline as shown in Figure 22. As the major and minor diameters are known, the height of the tooth which is determined by the addendum and dedendum is adjusted.

Figure 22: External Involute Spline with 27 Teeth

3.2.3. DESIGN TABLES

The idea of this thesis is to automate the whole process of designing the involute spline in SolidWorks. This makes an easy way to alter the dimensions of the spline. As a
part of this thesis, SolidWorks Design Tables are chosen as a tool to automate this whole process of designing a spline.

A design table is one which allows us to build multiple configurations of parts or assemblies by specifying parameters in an embedded Microsoft Excel Worksheet. Design table command is located under “tables” in the “Insert” drop down menu. One they are created they can be edited at “Configuration Manager” tab in the “Feature Manager” located on the left side of the screen. Design tables can also be created as a separate Excel file and can be saved as an external excel worksheet. Once the design tables are created, they can be modified or can be edited at any time with or without opening SolidWorks to change the configurations.

Table 9: Design Table with Involute External Spline Parameters

<table>
<thead>
<tr>
<th>Spline</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
<th>Test 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>half_tooth_angle@Sketch2</td>
<td>6.667</td>
<td>6.667</td>
<td>6.667</td>
<td>6.667</td>
</tr>
<tr>
<td>base_dia@Sketch2</td>
<td>0.974</td>
<td>0.899</td>
<td>0.835</td>
<td>0.779</td>
</tr>
<tr>
<td>half_base_pitch@Sketch2</td>
<td>13.333</td>
<td>13.333</td>
<td>13.333</td>
<td>13.333</td>
</tr>
<tr>
<td>pitch_circle@Sketch2</td>
<td>1.125</td>
<td>1.039</td>
<td>0.964</td>
<td>0.944</td>
</tr>
<tr>
<td>D1@Boss-Extrude1</td>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
<td>0.5</td>
</tr>
<tr>
<td>D1@Cut-Extrude1</td>
<td>27</td>
<td>27</td>
<td>27</td>
<td>27</td>
</tr>
<tr>
<td>D1@Boss-Extrude2</td>
<td>1.167</td>
<td>1.077</td>
<td>1.000</td>
<td>0.933</td>
</tr>
<tr>
<td>D1@Cut-Extrude2</td>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>minor_dia@Sketch3</td>
<td>1.069</td>
<td>0.987</td>
<td>0.916</td>
<td>0.855</td>
</tr>
<tr>
<td>major_dia@Sketch3</td>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>D1@Boss-Extrude3</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>D1@Cut-Extrude3</td>
<td>24</td>
<td>26</td>
<td>28</td>
<td>32</td>
</tr>
<tr>
<td>Pressure_angle</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Diametral_pitch</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Axial_length</td>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
<td>0.5</td>
</tr>
</tbody>
</table>

When we select the Auto-create or blank in the Design table property manager, the SolidWorks software automatically creates the Excel file with default configuration in it. The Table 9 is an auto-created design table showing all the all the parameters used to create the external involute spline. When SolidWorks software processes a design table, it processes each configuration in the column with configuration names (top to bottom), then processes each parameter row (left to right). With the SolidWorks design tables; we have the luxury of adding certain types of parameters into design table manually with the
appropriate active cells in the worksheet. In the above design table the cells which are colored green are the input parameters names for the required involute spline configuration and the cells with yellow color are the names of the calculated parameters. In the very first column, the names of the different set of configurations can be defined. The calculated parameters in the first row are defined from the dimensions used while creating the model inside the SolidWorks [27].

3.3. CUTTING TOOL

A cutting tool is designed once the external involute spline is designed as shown in Figure 19. Using that involute spline profile an insert and cutting tool holder assembly are imported into SolidWorks assembly and the involute profile is traced onto insert need as shown in Figure 23.

![Figure 23: 2-D SolidWorks Assembly Drawing showing formation of Cutting Insert with a Detail View](image)
Initially, a SolidWorks assembly file is opened. As a first part of assembly, the tool holder is imported as a part feature. Second, the cutting insert is imported and mated exactly fitting into the tool holder. Last, previously designed external involute spline is imported and aligned on to the surface of the insert such that at least one of the spline teeth is overlapped onto the face of the insert. Tracing is done, using a command called “Convert Entities” in sketch the spline profile is generated onto the surface of the insert.

Once the profile is traced onto the insert, “Edit Feature” command is used and the insert is re-designed at the corner forming a cutting tool as shown in Figure 24. This redesigned insert is saved as an ESPRIT compatible file “Parasolid” with the extension (*.x_t).

Figure 24: SolidWorks model of Machine Insert with Involute Spline Profile

3.4. FILE EXTENSIONS SUPPORTED BY SOLIDWORKS

Following are the file extensions supported by the SolidWorks. Any model created in the SolidWorks can be saved with the following extensions to be compatible with other softwares.

- SolidWorks files (*.sldprt, *.sldasm, *.sldrw)
- Part Files (*.prt, *.sldprt)
- Assembly Files (*.asm, *.sldasm)
- Drawing Files (*.drw, *.slddrw)
- DXF (*.dxf), DWG (*.dwg)
- Adobe Photoshop Files (*.psd)
- Adobe Illustrator Files (*.ai)
- LibFeat Part (*.lfp, *.sldlfp)
- Template (*.prtdot, *.asmdot, *.drwdot)
- Parasolid (*.x_t, *.x_b, *.smt_txt, *.xmt_bin)
- IGES (*.igs, *iges)
- STEP AP203/214 (*.step, *.stp)
- ACIS (*.sat), VDAFS (*.vda)
- VRML (*.wrl), STL (*.stl)
- Catia Graphics (*.cgr)
- Pro-Engineering Part (*.prt, *.prt.*, *.xpr)
- Pro-Engineering Assembly (*.asm, *.asm.*, *.xas)
- UGII (*.prt)
- Autodesk Inventor Part (*.ipt)
- Autodesk Assembly (*.iam)
- Solid Edge Part (*.par, *.psm)
- Solid Edge Assembly (*.asm)
- CADKEY (*.prt, *.ckd)
- Add-ins (*.dll)
- IDF (*.emn, *.brd, *.bdf, *.idb)
4. ANALYSIS PHASE-ESPRIT

ESPRIT is the second and next phase of Pre-manufacturing process. All the models generated and created in SolidWorks phase are made compatible to open and imported into ESPRIT. Here the CNC machining parameters are defined to the SolidWorks models appropriately to the specific CNC machining techniques we actually use during the real time machining. Milling and Wire EDM machining techniques which we use as a part of this thesis are defined with required parameters are given and the process is simulated. This chapter on pre-manufacturing using ESPRIT tool involves,

- Choosing a tool insert
- Importing tool insert and involute tooth into SolidWorks Assembly
- Creating a Involute spline profile on the insert
- Importing new insert into ESPRIT
- Creating an auto-chain around the involute profile on the insert
- Creating ‘contour’ operation under SolidWire
- Simulation of Wire EDM process
- Generating NC code for machining on Brother HS-70A

4.1. GETTING STARTED

ESPRIT is a high performance full spectrum, computer-aided manufacturing (CAM) system for a full range of machine tool applications. It delivers powerful spectrum programming for 2-5 axis milling, 2-22 axis turning, 2-5 axis wire EDM, multi-tasking mill-turn machining, and B-axis machine tool [28].

ESPRIT’s high performance capabilities include machining any part geometry (solid, surface, or wireframe), universal post processing to format G-code for virtually any machine tool, and solid simulation and verification with dry runs rendered in dynamic solids for optimal part quality and consistency. Its fast, accurate and reliable dynamic solid verification eliminates the need for expensive dry runs on the NC machine. It is possible to verify your machining process as we compare accurately rendered “as designed” versus “as machined” parts [28].
ESPRIT main screen is displayed when we create a new file or open an existing file as shown in Figure 25. The main window contains the following menus and default tool bars along the top of the screen and a graphic work area we can view our work and status area along the bottom of the screen that displays dynamic information about your part environment and the current command or action.

“Menus and Toolbars” tool bars are typically added to the right of the screen, but can be moved into work area or any area around the outside of the work area.

“Graphical Area” is the largest area on the screen. By default, the initial view orientation is set to the top view with the XYZ axes displayed. The X-axis is horizontal, Y-axis is vertical and Z-axis is normal to the screen.

Figure 25: ESPRIT Graphical User Interface
“Prompt Area is the most important area on ESPRIT screen. The prompts tell us what to do next. They are located on the left bottom of the screen.

“Status Area” provides the dynamic information about the current work environment. As we select the commands or move the cursor, the information is constantly updated. It is located on the bottom right side of the screen.

ESPRIT also provides a specialized window called “Project Manager” that provides additional information about the parts we work on and provides an excellent way to manage our work. It consists of a set of windows that lists every operation, feature and allows us to manage, sort, and reorder these items. Project manager can be viewed either by clicking “Project Manager” on “View” menu or by pressing F2 function key on keyboard [28].

4.2. OPENING AND SAVING FILES

When we start a new session in ESPRIT or create a new file, a new file template pops up showing up a blank document as shown in Figure 26. A template contains user defined elements and we can create templates for regularly used tools, machine setup configurations, simulation settings, and repeated geometry and knowledge base settings.

Figure 26: ESPRIT’s New File Template
We can also open native ESPRIT files (*.esp extension), native 2D and 3D files from other CAD systems like SolidWorks or Pro/E and translated files such as IGES and STEP as shown in Figure 27. Since ESPRIT is based on Parasolid kernel, it can open a variety of solid model files.

![Open Native File Template](image)

**Figure 27: ESPRIT’s Open Native File Template**

It is always recommended to click on “Import as a Solid”, “wire frame” from the “Options” button on Open file template whenever we are opening a Parasolid, SolidWorks or Solid Edge files. This is to import the wire frame elements which are created along the surface edges of the models. Options window is shown in Figure 28.

“Save” command stores the current file as a native ESPRIT file or as another type of CAD format. ESPRIT files are saved with “.esp” file extension. When creating a Custom Milling Tool later on in this chapter, the contour is selected and saved with extension named custom tool (*.ect).
4.3. MAKING TOOL INSERT

The first and foremost step in ESPRIT phase of manufacturing is creating an insert and simulating. A Parasolid model of Insert created in SolidWorks phase is imported into ESPRIT with “Import as a Solid” and “Wire Frame” options checked. Once the part is imported, the graphical view is changed to Top View and it is oriented into specific location with the appropriate dimensions. This process is done using wire EDM technique which is one of the advanced machining techniques in ESPRIT. Wire EDM process can be started by selecting “SolidWire Gold” from “Machining” menu bar.

4.3.1. SOLIDWIRE PART SET UP

Part setup is the first step for every machining process. Part setup controls the NC code of the SolidWire operations. It also defines the initial position of the wire. Initial position can be defined either by giving X, Y and Z co-ordinates or by picking a point on the graphical area of ESPRIT. All the parameters for a part setup operation are located on one general tab.
4.3.2. SOLIDWIRE CONTOUR

For creating a contour operation in SolidWire, a chain feature is to be created along the profile of the part where machining has to be done. For creating a chain feature along the profile, “Manual Chain” or “Auto Chain” chain commands are used. In this case of creating an involute spline contour, an auto chain command is used. Auto Chain feature defines the start location, the direction, and the end location of the cutting path. Part setup and chain feature are shown in the Figure 30.

Once the chain feature is created along the cutting path, chain is selected either by clicking on it or by selecting from project manager and SolidWire contour operation is chosen. It is located in SolidWire Gold. SolidWire contour creates a 2-axis wire EDM contouring operation. SolidWire contouring operation can be used to cut one or more profiles with rough and skim passes, rough passes only, or skim passes only [28]. Cut-off passes can also be created for unattended machining or retain the stability of large parts.
while they are roughed and skimmed. The standard strategy simply performs the rough cut first followed by the number of skim cuts we choose.

![Figure 30: Part-Setup and SolidWire Contour of Insert](image)

SolidWire contour operation has basically four different tabs: General, Cut data, Approaches and Advanced. In the General tab,

- We choose the part type depending on which side of the part are we going to cut.
- Select the strategy of cut with the rough passes and number of skim passes if necessary. For the insert we machine in this thesis, we chose one rough cut and one skim cut for better finish.
- Set the Z-levels of the work piece bottom, thickness and reference plane where we hold the work piece and also the location of upper and lower nozzle of the wire EDM.
Figure 31: SolidWire Contour Operation with General Tab

Figure 32: SolidWire Contour Operation with Cut Data Tab
In Cut Data tab of SolidWire Contour,
- We define the primary cut strategy which is “Rough and 1Skim” in this project.
- We can also control the rough cut here in this tab by suppressing it.
- The primary cut settings like power and feed rate of the wire are defined here and also offset distance of the wire from work piece if necessary as shown in Figure 32.

![Figure 32: SolidWire Contour with Cut Data]

**Figure 33: SolidWire Contour with Approaches Data**

Under Approaches tab we define,
- Startup distance of the wire from the work piece is given with a value.
- Type of Entry and Exit of the wire. To cut the spline profile in this case we use entry and Exit type as “Position” and will be picked two co-ordinate points. Entry and Exit type are the initial and final positions of the wire before and after the machining process.
- Since there are two passes in this case, entry and exit positions are switched each other for rough and skim cuts.

Advanced tab is the last tab under the SolidWire contour operation. In this tab, wire path is controlled. Parameters like internal corner rounding, corner slow down, initial and final wire control and initial and final tank control are defined. Here we can choose an option to stop/ no-stop of the wire movement after each segment of machining.
(like “optional stop” of wire feed between rough and skim passes). This tab is shown in Figure 34.

4.4. CNC TOOL ASSEMBLY

Any CNC machine has a particular tool setup along with rotating spindle, chuck and tool holder. A machining insert called as “cutter” is fixed to a tool holder as shown in Figure 35. The general set up has Holder, Shank and Cutter. Since we need to have a special tool designed with involute spline profile on the cutting inserts, a Custom Milling Tool is selected from the ESPRIT “Milling Tools” option under “Machining” tab.

Using custom milling tool we can define our own milling tool or turning insert from a custom profile. For this, we first need to define the geometry for the custom tool and then save the tool profile as external tool geometry (*.ect). The tool geometry file can be then imported into the tool definition to create the custom tool.
For the milling tool, the geometry must be a continuous chain of elements with no gaps or overlaps. The profile must be positioned so that the origin point P0 marks the drive point of the tool. The profile can be composed of geometric elements or a chain feature [28].

Once the tool profile is made, custom milling tool window is opened and the profile is uploaded from the cutter tab. The profile uploaded can also be viewed from the
cutter tab in the custom milling tool window as shown in Figure 36. The dimensions of the tool diameter, cutting length, shank and holder diameter and length are to be entered from the holder and shank tabs.

![SolidMill Traditional Contouring-General tab](image)

**Figure 37: SolidMill Traditional Contouring-General tab**

### 4.4.1. SOLIDMILL CONTOURING

SolidMill Traditional Contouring command creates a contouring operation along the feature boundaries. Contouring operations are typically used to remove the material along vertical or tapered walls. This operation can be applied to features with open or closed shapes. Within a single operation, we can create separate roughing and finishing passes [28]. This operation can be defined by creating a chain feature along the cutting path on the feature. SolidMill contouring operation window has four different tabs to completely define the milling operation: General, Strategy, Advanced and Links.

In General tab, as shown in Figure 37 we select a milling tool first from the tool library. For this project since we are using the custom milling tool, “Tool 1” which corresponds to the custom milling tool defined in the previous section is chosen. And
then the cutting speed and feed rates in X, Y and Z directions are given. Cutting speed is usually defined in term of rotations per minute (RPM) or surface feet/meter per minute (SPM). And feed rates are defined in terms of per minute (PM) or per tooth (PM) with units inch/millimeter [28]. Though we define the cutting speed and feed rates in the ESPRIT, we still can change it accordingly when we do actual machining on the HAAS VF-2 milling machine.

In Strategy tab, parameters like cutting strategy, stock allowances, depths and compensations were defined. Strategies like number of passes finish pass and type of cutting pass either “climb” or “conventional” are selected. Also the depth of the cut from the bottom z-level for cutting passes is defined [28]. This value is measured from the selected feature boundary. For this project, since the midpoint of the cutting tool is not aligned with the A-axis (rotating axis) of the feature, the tool is given a starting depth of 0.27 inches initially. Since we don’t have any finish pass in this operation, we do not have any finish tab seen.

Figure 38: SolidMill Traditional Contouring-Strategy Tab
In Advanced tab, parameters like trochoidal strategy, open contour, blending and collision detection are defined. Trochoidal movement can be given to the tool path when the tool is fully engaged in the material. Trochoidal path will automatically create loops along the contour tool path by ESPRIT in order to maintain a constant rate of material removal. Trimming is used to trim the tool path [28]. If the stock allowances are given some value in the strategy tab, then the tool blend option is set to yes and blend radius is given as shown in Figure 40.

In Links tab, parameters like Clearances, Entry/Exit modes and Lead-in / Lead-out types can be defined. Full clearance is applied only when return plane, retract plane or retract ID for depth are set to full clearance. Clearance value is the absolute value
measured from z-zero, for the tool position. For this project on cutting the external splines, return plane and retract plane are set to “clearance”, which means the tool is positioned initially and also retracted at some clearance distance entered before. Entry and Exit mode controls how the tool approaches the part over the first lead-in move and last linear portion of mead-out move. Links tab is shown in Figure 41.

![SolidMill Traditional Contouring-Links Tab](image)

Figure 41: SolidMill Traditional Contouring-Links Tab

Once all the parameters are specified in SolidMill traditional contour, the contour operation is copied down to 26 copies (since 27 spline teeth) around the spline about the X-axis in ESPRIT. This makes the chain features and the contour operations on the chain features copied all around the addendum circle of the (root of the teeth) about its axis. We can view this set of 27 contour operations around addendum circle in the operations tab which is located on the bottom right side of project manager. This is shown in Figure 38.
Figure 42: List of contour operations around the external involute spline (left) and simulation of the external involute spline cutting in ESPRIT (right)

We can always change any machining simulation parameters by going to “simulation parameters” in simulation window.
5. MANUFACTURING PROCESS

5.1. OVERVIEW OF MACHINING TECHNOLOGY

The material removal processes are familiar of shaping operations in which excess material is removed from a starting work piece so that what remains is the desired final geometry. In other words, cutting processes remove material from the surface of a work piece by producing chips. Machining is a manufacturing process in which a sharp cutting tool is used to cut away material to leave the desired part shape. The predominant cutting action in machining involves shear deformation of the work material to form a chip; as the chip is removed, a new surface is exposed.

5.2. GENERATING AND SAVING NC CODES

After the designing of External Involute spline and machining insert in CAD software SolidWorks and defining the machining parameters in CAM software ESPRIT, the NC codes of the SolidWire contour for BROTHER HS-70A Wire EDM machine and NC code of the SolidMill Traditional contouring for Gene HAAS VF-2 Milling machine are generated from the ESPRIT using their respective post processors files (see Appendix C). These codes are copied into any external storage drives like Floppy drive or any USB drive. These NC codes are imported into CNC machine’s programs list and read.

ISO is an internationally recognized machine tool programming language. It uses a system commonly known as G and M codes. Some of the G-codes and M-codes used in the machining process on Wire EDM machine and VF-2 vertical milling machine are listed below.

For Wire EDM SolidWire contouring machining on BROTHER HS-70A machine [6],

- G92 Origin of the Program
- G00 Positioning (not cutting) rapid linear movement
- G01 Straight line cutting movement
- G02 Cutting an arc, in a clockwise direction
- G03 Cutting an arc, in a anti-clockwise direction
- G10 Use standard technology setting and change wire tension
• G40  No offset  
• G41  Left offset  
• G42  Right offset  
• G70  Corner Control ON. slows the cutting speed to minimize wire deflection  
• G71  Turns OFF corner control  
• M00  Program stops. Stops all the machine movements and actions  
• M01  Optional stop  
• M22  Automatic wire threading  
• M23  Wire cutting  
• M30  End of the program (same as M02)  
• M85  Cutting Electricity OFF  
• M86  Machine starts. Turns on Water, Wire and Electricity  
• M87  Machine stops. Turns off Water, Wire and Electricity  

For 4th axis SolidMill traditional contouring operation on HAAS VF-2 milling machine,  
• G00  Rapid motion positioning  
• G01  Linear interpolation position  
• G28  Return to machine zero position through optional G29 reference point  
• G29  Return from reference point  
• G40  Cutter comp cancel  
• G41  2D cutter compensation left  
• G52  Set work co-ordinate system  
• G54-59  Select work co-ordinate system  
• G154  Select work co-ordinates (P1-P99)  

5.3. EXPERIMENTAL SETUP OF WIRE EDM  

This thesis is carried out on the Wire EDM machine installed at Mechanical Engineering Department’s HAAS Laboratory in California State University Northridge, California. Table 6.1 has the specifications of the above mentioned Wire EDM machine.
With all the safety and precautionary steps with CNC machines, Brother HS-70A wire EDM machine is turned ON and the NC code is copied into the machine through the external storage drive. Before setting up the work piece onto the machine first we need to know the global co-ordinate system (GCS) of the machine and the co-ordinate system of the work piece. Then the work piece holder is fixed to the wire EDM machine rigidly with proper supports as shown in Figure 43. A wire is then generated before actually starting the machining process. Once the work piece is fixed the origin has to be declared to the machine according to the part set up done in ESPRIT.

![Experimental Setup of the Wire EDM Machine](image)

Figure 43: Experimental Setup of the Wire EDM Machine

Using the corner finding techniques, the wire is allowed to move on x-axis and y-axis until it touches the work piece in both the directions in order to define the origin as shown in Figure 44. Now the tank is filled with the dielectric fluid (water) until the work piece is completely submerged in the dielectric fluid. Now reading the program
with NC codes from the external storage drive, the program can be viewed on the controls screen. Before actually starting the machining we can make the machine to “Dry Run” to see if everything goes fine without any errors or changes to be made [7].

![Diagram of Wire EDM Corner Finding Technique](image)

**Figure 44: Wire EDM Corner Finding Technique**

### 5.3.1. TECHNOLOGY NUMBER

The program has to be edited with the wire EDM “Technology Number”. It is a set of 8-digit number. Each digit in the technology has its own significance based on the parameters like: Wire Diameter, work piece thickness, angle of the wire and type of cut (see Appendix A). For this project, the following are the specifications of the Technology Number 13050002:

- **Wire Diameter =** 0.010 inch
- **Material of the Wire =** Brass
- **Insert (Work piece) Thickness =** 0.125 inch
- **Angle of Wire =** 0º
- **Insert material =** Solid Carbide
- **Type of Cut =** Normal C

Therefore the Technology Number for the Wire EDM Process is 13050002.
<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Maximum Work Piece Dimensions</strong></td>
<td><strong>580mm × 350mm</strong></td>
</tr>
<tr>
<td><strong>Maximum Work Piece Height</strong></td>
<td>170mm</td>
</tr>
<tr>
<td><strong>Maximum work piece Weight</strong></td>
<td>100kg</td>
</tr>
<tr>
<td><strong>Maximum Table Feed Rate</strong></td>
<td>600mm/min (Positioning)</td>
</tr>
<tr>
<td></td>
<td>300mm/min (Machining)</td>
</tr>
<tr>
<td><strong>Wire Diameter</strong></td>
<td>0.1mm, 0.15mm, 0.2mm, 0.25mm, 0.3mm</td>
</tr>
<tr>
<td><strong>Wire Feed Rate</strong></td>
<td>40 ~250mm/sec</td>
</tr>
<tr>
<td><strong>Wire Tension</strong></td>
<td>3<del>25N (300</del>2500gf)</td>
</tr>
<tr>
<td><strong>Water Supply Unit Capacity</strong></td>
<td>360L</td>
</tr>
<tr>
<td><strong>Least Input Increment</strong></td>
<td>0.0001mm (X, Y, Z, U, V axes), 0.00001º (B-axis)</td>
</tr>
<tr>
<td><strong>Least Command Input</strong></td>
<td>0.001mm (0.00001 inch)</td>
</tr>
<tr>
<td><strong>Input Power Supply</strong></td>
<td>440 ± 10% (50/60Hz ±1Hz)</td>
</tr>
<tr>
<td><strong>Total Input</strong></td>
<td>13.5kVA</td>
</tr>
<tr>
<td><strong>Open Voltage</strong></td>
<td>40V, 50V, 60V, 70V, 85V</td>
</tr>
<tr>
<td><strong>Machining Current</strong></td>
<td>30A</td>
</tr>
</tbody>
</table>

The Solid Carbide machine insert is fixed to the tool holder and is fixed to the machine. During the machining process, the wire starts the rough cut from its Entry position defined in ESPRIT and moves through the Exit Position. For the next cut which is finish cut or skim cut, wire starts from the Exit position of the rough cut and follows the same path of the first cut to reach the Entry position of the Rough cut. The Figure 45 shows the setup of work piece (machine insert) to the tool holder before machining and the insert after the machining with involute profiles on either corners.
5.4. EXPERIMENTAL SETUP OF HAAS VF-2 MILLING MACHINE

The Haas VF-2 is a vertical milling machine and it has 30” x 16” x 20” (762 x 406 x 508mm) travel dimensions and 36” x 14” x 5/8” (914 x 356 x 16mm) table dimensions. The maximum weight which is evenly distributed on the table is 3000 lb (1361 kg). The VF-2 is equipped by a 7500 RPM, 40 taper, and 20 HP (14.9kW) vector drive spindle. It also has a 20–station carousel tool changer and maximum rapids moves of 1000 in/min. Other features include a 1MB program memory, 15”colour LCD monitor, USB port, and memory lock key switch. The intended VF-2 control option is rigid tapping and its drive system is direct speed with belt drive [4]. Inside the main machine, a HRT 210 rotary A axis is mounted to the table. This allows the machine to have 4 degrees of freedom (X, Y, Z, A).
Figure 46: Haas VF-2 Machine Equipped with a 7500 RPM, 40 taper, and 20HP (14.9 kW) Vector Drive Spindle

To conduct the tests on Solid Carbide machine inserts with Involute profile, HAAS VF2 Vertical Milling Machine was chosen. Here in this machine, 4\textsuperscript{th} axis milling (rotational axis) is chosen to fix and rotate the test specimen. The tool was fixed to the rotating spindle in the Z-axis and the Specimen was fixed to a 3-jaw chuck in the B-axis rotating about X-axis. The tool fixture is shown in the below Figure 47.

Figure 47: Tool fixture to the VF-2 Milling Machine Shank

5.5.PROPERTIES OF 6061 ALUMINUM TEST SPECIMEN

By looking at the mechanical and physical properties of the different materials we chose 60601 Aluminum as a test specimen for testing the Solid Carbide Machine insert with Involute profile [29].

Physical Properties of 6061 Aluminum are tabulated below,
### Table 11: Physical Properties of 6061 Aluminum

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (lb/cu.in)</td>
<td>0.098</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>2.7</td>
</tr>
<tr>
<td>Melting Point (°F)</td>
<td>1090</td>
</tr>
<tr>
<td>Modulus of Elasticity Tension</td>
<td>10</td>
</tr>
<tr>
<td>Modulus of Elasticity Torsion</td>
<td>3.8</td>
</tr>
</tbody>
</table>

Mechanical Properties of 6061 Aluminum are tabulated below.

### Table 12: Mechanical Properties of 6061 Aluminum

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brinell’s Hardness</td>
<td>95</td>
</tr>
<tr>
<td>Rockwell B Hardness</td>
<td>60</td>
</tr>
<tr>
<td>Ultimate Tensile Strength (psi)</td>
<td>45000</td>
</tr>
<tr>
<td>Tensile Yield Strength (psi)</td>
<td>40000</td>
</tr>
<tr>
<td>Modulus of Elasticity (ksi)</td>
<td>10000</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>0.33</td>
</tr>
<tr>
<td>Fatigue Strength (14000)</td>
<td>14000</td>
</tr>
<tr>
<td>Machinability</td>
<td>50%</td>
</tr>
<tr>
<td>Shear Modulus (ksi)</td>
<td>3770</td>
</tr>
<tr>
<td>Shear Strength (psi)</td>
<td>30000</td>
</tr>
</tbody>
</table>

5.6. PROPERTIES OF 4340 STEEL SPECIMEN

Once the insert is tested on the 6061 Aluminum, it is tested on the actual work piece which is Drive shaft of the Formula one care made up of 4340 Steel [29]. Mechanical Properties and Physical properties of 4340 Steel are shown in table 13 and table 14.
Table 13: Mechanical Properties of 4340 Steel

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield Strength</td>
<td>700 N/mm^2</td>
</tr>
<tr>
<td>Tensile (Rm)</td>
<td>900-1100 N/mm^2</td>
</tr>
<tr>
<td>Elongation (A5)</td>
<td>12%</td>
</tr>
<tr>
<td>Charpy Impact</td>
<td>42J</td>
</tr>
<tr>
<td>Hardness</td>
<td>275-335HB</td>
</tr>
</tbody>
</table>

Table 14: Physical properties of 4340 Steel

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>7.85 Kg/dm^3</td>
</tr>
<tr>
<td>Modulus of Elasticity</td>
<td>210000 N/mm^2</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>42 W/(m.K)</td>
</tr>
<tr>
<td>Specific Heat Capacity</td>
<td>460 J/(Kg.K)</td>
</tr>
<tr>
<td>Modulus of Elasticity</td>
<td>165 to 200 *10^3 N/mm^2</td>
</tr>
<tr>
<td>Thermal Expansion</td>
<td>11.1 to 13.9 *10^6 m/(m.k)</td>
</tr>
</tbody>
</table>
6. EXPERIMENTAL RESULTS

6.1. WIRE EDM MACHINED INSERTS

The Solid carbide Machine inserts are successfully cut in the Wire EDM machine to get the involute spline profile. Total of three inserts were cut in Wire EDM in the process of manufacturing and testing.

INSERT #1

It is cut on three different corners and tested on first 6061 Aluminum specimen. On this specimen we observed an error on 4\textsuperscript{th} axis alignment with the center axis of the specimen.

INSERT #2

It is cut on one side and tested on second and third specimens of 6061 Aluminum.

Since the Insert #2 successfully cut the second and third 6061 Aluminum specimens and partially cut the actual drive shaft, the third piece; Insert #3 was cut on two corners to make sure that the two inserts together cut the remaining two drives shafts needed. Figure 48 shows the Insert #1 and Insert #2 machined on wire EDM.

Figure 48: Involute profile cut on Insert #1 (left) and Insert #2 (right)
6.2. TESTING ON 6061 ALUMINUM

Insert #1 and Insert #2 together cut the first and second 6061 Aluminum specimens successfully, insert #2 is continued for the final test on 6061 Aluminum specimen with more feed rate, more rapid and lubricant ON. The following are the VF-2 Milling machine inputs given when testing the machined Insert #1 and Insert #2 on 6061 Aluminum work specimen.

Table 15: VF-2 Milling Machine Inputs for 6061 Aluminum Testing

<table>
<thead>
<tr>
<th>6061 Aluminum</th>
<th>Spindle Speed</th>
<th>Feed</th>
<th>Rapid</th>
<th>Lubricant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specimen #1</td>
<td>200%</td>
<td>25%</td>
<td>25%</td>
<td>OFF</td>
</tr>
<tr>
<td>Specimen #2</td>
<td>200%</td>
<td>25%</td>
<td>25%</td>
<td>OFF</td>
</tr>
<tr>
<td>Specimen #3</td>
<td>200%</td>
<td>50%</td>
<td>50%</td>
<td>ON</td>
</tr>
</tbody>
</table>

Figure 49: 6061 Aluminum Test Specimens

6.3. TESTING ON 4340 STEEL DRIVE SHAFT

Since the Insert #2 is successfully tested on third 6061 Aluminum, it is now tested on actual work piece which is 4340 Steel drive shaft. Because 4340 Steel is more hard material than 6061 Aluminum, Insert #2 got damaged chipping off at its tip shown in Figure 49.
Figure 50: Insert #2 with Damage at its Tip

So Insert #3 is cut on two of its opposite corners. Using this Insert #3 we cut the External Involute Splines on the required two drive shafts. Figure 51 shows the tool insert #3 set up to the tool holder with the involute cut on two corners.

Figure 51: Insert #3 fixed to Tool Holder with Involute Cut on Corners

The machine inputs to the VF-2 Milling machine for cutting the drive shaft are,

- Spindle Speed: 230% (2300 RPM)
- Feed: 50%
- Rapid: 25%
- Lubricant: ON
The machining process of cutting external involute splines is done in multiple steps of depth increment .005inch to 0.010inch in order to achieve smaller clearance values and make it smooth fit. Since the drive shafts are heat treated after the machining, the diameter of the shaft gets increased by fraction of inches. In order to compensate this change in dimensions, some clearances are left out on the drive shaft splines to fit smoothly with drive hub even after the heat treatment.

Following are the pictures taken during the testing process on HAAS VF-2 Milling machine in cutting the external involute splines on a driver shaft.

Figure 52: VF-2 spline manufacturing process in Left View (top) and Front View (bottom)
Once the two drive shafts are manufactured with external involute splines on it, they are assembled with the drive hubs to check for the clearances and tolerances. This assembly is shown in Figure 54.
Figure 54: Drive Shaft and Drive Hub Assembly showing External Involute Splines
CONCLUSION AND RECOMMENDATIONS

This thesis has resulting in the designing, analyzing and manufacturing a spline cutting tool by using the design tables from SolidWorks which reduced the amount of time taken for designing the tool successfully. These design tables are created with Microsoft EXCEL spreadsheets embedded inside SolidWorks. Then, manufacturing process of tool using wire EDM machine and testing on Milling machine was done.

As the first step of this thesis, study was performed to automate the different spline configurations within the EXCEL spreadsheets using design tables without manually creating the models by the user. One can enter the inputs like number of teeth, pressure angle and Diametral pitch to get the external splines. This automation process described above can be optimized in making splines as well as gears in future by using more powerful optimizing techniques using spreadsheets or any other techniques.

Later during the course of this thesis, manufacturing process using Brother HS-70A Wire EDM machine is carried out and successfully tested on Haas VF-2 Milling machine to cut external involute splines on drive shafts. These shafts are perfect fit for the drive hubs with internal involute splines in it. The clearances of this manufacturing process came up to 0.010 inch to fit the drive shaft and drive hub.

Once an insert has been created, it corresponds to only one spline of a specified design. The insert takes on the form of cut section of the shaft and cannot be used for other diametral pitches. However, it may be possible to use the same insert for all splined shafts which have the same diametral pitch. Thus, the study of using the same spline tool for shafts with the same pitch with different tooth numbers and pitch diameters is a recommended area for future research. Other areas may include:

- Optimization of spline cutting feeds and speeds
- Optimized rake angle of insert using 4 axis wire EDM
- Optimized tool holder design to allow for multiple cutting inserts
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ESPRIT Getting Started


Table 16: Wire EDM Machine Technology Number

<table>
<thead>
<tr>
<th>TECHNOLOGY NUMBER (1305002)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st Digit</td>
</tr>
<tr>
<td>0  User</td>
</tr>
<tr>
<td>1 Tec in Machine</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>2nd Digit (Wire Diameter)</td>
</tr>
<tr>
<td>0 0.004</td>
</tr>
<tr>
<td>1 0.006</td>
</tr>
<tr>
<td>2 0.008</td>
</tr>
<tr>
<td>3 0.01</td>
</tr>
<tr>
<td>4 0.012</td>
</tr>
<tr>
<td>8 0.010 half hard wire</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>3rd Digit (Angle of Wire)</td>
</tr>
<tr>
<td>0 0 degrees</td>
</tr>
<tr>
<td>2 5 degrees</td>
</tr>
<tr>
<td>4 10 degrees</td>
</tr>
<tr>
<td>6 15 degrees</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>4th Digit (Material)</td>
</tr>
<tr>
<td>0 Steel 1 (tool steel)</td>
</tr>
<tr>
<td>1 Steel 2 (High Carbon steel)</td>
</tr>
<tr>
<td>2 Copper (or brass)</td>
</tr>
<tr>
<td>3 Stainless</td>
</tr>
<tr>
<td>4 Aluminum</td>
</tr>
<tr>
<td>No.</td>
</tr>
<tr>
<td>-----</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>6</td>
</tr>
<tr>
<td>9</td>
</tr>
</tbody>
</table>

Table 17: Wire EDM Generator Settings

<table>
<thead>
<tr>
<th>WIRE EDM GENERATOR SETTINGS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Normal A</strong></td>
</tr>
<tr>
<td>One cut program size. Requires sealed flushing. This is the fastest and least accurate settings. Most likely to break wire</td>
</tr>
<tr>
<td><strong>Normal B</strong></td>
</tr>
<tr>
<td>One cut to program size. This is slower and more accurate than Normal A. Requires sealed flushing.</td>
</tr>
<tr>
<td><strong>Normal C</strong></td>
</tr>
<tr>
<td>One cut to program size. This is the slowest and most accurate rough cut. Least likely to break wire. Best for unattended cutting</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cuts</th>
<th>1st</th>
<th>2nd</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 Cuts</td>
<td>This is rough cut that leaves the proper amount of material for the 2nd cut</td>
<td>This is the Finish cut</td>
</tr>
<tr>
<td>3 Cuts</td>
<td>This is the rough cut that leaves the proper amount of material for 2nd cut</td>
<td>This is the Finish cut</td>
</tr>
<tr>
<td></td>
<td>This is the Polish cut</td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX B: DRAWINGS

Figure 55: SolidWorks Drawing of Drive Hub with Internal Involute Splines
Figure 56: SolidWorks Design of Drive Shaft with External Involute Splines
Figure 57: Tool Holder, Tool Insert and Spline Assembly showing Rake Angle Projection
APPENDIX C: NC CODES

CODE FOR CUTTING INVOLUTE SPLINE PROFILE ON SOLID CARBIDE INSERTS USING BROTHER HS-70A WIRE EDM MACHINE

G90
G92 X0 Y0
M23
G00 X-.491 Y.088
M22
M86
(ROUGH PRIMARY CUT)
M85
G10 U13050002
M86
G70 X70
G01 X-.42707 Y.0111
G41 X-.34135 Y-.092
G03 X-.31014 Y-.09531 I.07714 J.57821
G03 X-.28018 Y-.04792 I-.21669 J.17019
G03 X-.251 Y-.048 I.01597 J.53413
G03 X-.22128 Y-.09554 I.24729 J.12154
G03 X-.19019 Y-.09241 I-.04293 J.58175
M00
M86
G01 G40 X-.091 Y.088
M00
M86
G71 X100
(SKIM PRIMARY CUT [ 1])
M85
G10 U13050002
M86
G70 X70
G42 X-.19019 Y-.09241
G02 X-.22128 Y-.09554 I-.07402 J.57862
G02 X-.251 Y-.048 I.21757 J.16908
G02 X-.28018 Y-.04792 I-.01321 J.53421
G02 X-.31014 Y-.09531 I-.24665 J.1228
G02 X-.34135 Y-.092 I.04593 J.58152
G01 G40 X-.491 Y.088
M00
M86
G71 X100
G71 X100
M87
M30
**CODE FOR CUTTING SPLINES ON DRIVE SHAFT USING HAAS VF-2 VERTICAL MILLING MACHINE**

%  
O0001  
G90  
G00 G17 G20 G40 G49 G64 G80 G90 M05  
T01 M06  
S1091 M03  
G43 H01 M08  
G00 X0 Y0  
Z.1165  
A+0  
X-.35 Y1.0341  
G01 Z-.2535 F10.  
G41 X0 D01  
X2.19  
G00 G40 Y1.3841  
G01 Z.1165  
G00 X-.35 Y1.0341  
A-13.333  
Z.1165  
G01 Z-.2535  
G41 X0 D01  
X2.19  
G00 G40 Y1.3841  
G01 Z.1165  
G00 X-.35 Y1.0341  
A-26.667  
Z.1165  
G01 Z-.2535  
G41 X0 D01
X2.19
G00 G40 Y1.3841
G01 Z.1165
G00 X-.35 Y1.0341
A-40.
Z.1165
G01 Z-.2535
G41 X0 D01
X2.19
G00 G40 Y1.3841
G01 Z.1165
G00 X-.35 Y1.0341
A-53.333
Z.1165
G01 Z-.2535
G41 X0 D01
X2.19
G00 G40 Y1.3841
G01 Z.1165
G00 X-.35 Y1.0341
A-66.667
Z.1165
G01 Z-.2535
G41 X0 D01
X2.19
G00 G40 Y1.3841
G01 Z.1165
G00 X-.35 Y1.0341
A-80.
Z.1165
G01 Z-.2535
G41 X0 D01
X2.19
G00 G40 Y1.3841
G01 Z.1165
G00 X-.35 Y1.0341
A-93.333
Z.1165
G01 Z-.2535
G41 X0 D01
X2.19
G00 G40 Y1.3841
G01 Z.1165
G00 X-.35 Y1.0341
A-106.667
Z.1165
G01 Z-.2535
G41 X0 D01
X2.19
G00 G40 Y1.3841
G01 Z.1165
G00 X-.35 Y1.0341
A-120.
Z.1165
G01 Z-.2535
G41 X0 D01
X2.19
G00 G40 Y1.3841
G01 Z.1165
G00 X-.35 Y1.0341
A-133.333
Z.1165
G01 Z-.2535
G41 X0 D01
X2.19
G00 G40 Y1.3841
G01 Z.1165
G00 X-.35 Y1.0341
A-146.667
Z.1165
G01 Z-.2535
G41 X0 D01
X2.19
G00 G40 Y1.3841
G01 Z.1165
G00 X-.35 Y1.0341
A-160.
Z.1165
G01 Z-.2535
G41 X0 D01
X2.19
G00 G40 Y1.3841
G01 Z.1165
G00 X-.35 Y1.0341
A-173.333
Z.1165
G01 Z-.2535
G41 X0 D01
X2.19
G00 G40 Y1.3841
G01 Z.1165
G00 X-.35 Y1.0341
A-186.667
Z.1165
G01 Z-.2535
G41 X0 D01
X2.19
G00 G40 Y1.3841
G01 Z.1165
G00 X-.35 Y1.0341
A-200.
Z.1165
G01 Z-.2535
G41 X0 D01
X2.19
G00 G40 Y1.3841
G01 Z.1165
G00 X-.35 Y1.0341
A-213.333
Z.1165
G01 Z-.2535
G41 X0 D01
X2.19
G00 G40 Y1.3841
G01 Z.1165
G00 X-.35 Y1.0341
A-226.667
Z.1165
G01 Z-.2535
G41 X0 D01
X2.19
G00 G40 Y1.3841
G01 Z.1165
G00 X-.35 Y1.0341
A-240.
Z.1165
G01 Z-.2535
G41 X0 D01
X2.19
G00 G40 Y1.3841
G01 Z.1165
G00 X-.35 Y1.0341
A-253.333
Z.1165
G01 Z-.2535
G41 X0 D01
X2.19
G00 G40 Y1.3841
G01 Z.1165
G00 X-.35 Y1.0341
A-266.667
Z.1165
G01 Z-.2535
G41 X0 D01
X2.19
G00 G40 Y1.3841
G01 Z.1165
G00 X-.35 Y1.0341
A-280.
Z.1165
G01 Z-.2535
G41 X0 D01
X2.19
G00 G40 Y1.3841
G01 Z.1165
G00 X-.35 Y1.0341
A-293.333
Z.1165
G01 Z-.2535
G41 X0 D01
X2.19
G00 G40 Y1.3841
G01 Z.1165
G00 X-.35 Y1.0341
A-306.667
Z.1165
G01 Z-.2535
G41 X0 D01
X2.19
G00 G40 Y1.3841
G01 Z.1165
G00 X-.35 Y1.0341
A-320.
Z.1165
G01 Z-.2535
G41 X0 D01
X2.19
G00 G40 Y1.3841
G01 Z.1165
G00 X-.35 Y1.0341
A-333.333
Z.1165
G01 Z-.2535
G41 X0 D01
X2.19
G00 G40 Y1.3841
G01 Z.1165
G00 X-.35 Y1.0341
A-346.667
Z.1165
G01 Z-.2535
G41 X0 D01
X2.19
G00 G40 Y1.3841
G01 Z.1165
G28 G91 Y0 Z0
M30
%

100