Bachelor’s Degree Thesis

Designing an Electrode
For
Electrical Discharge Machining (EDM)

4/1/2014

Arcada University of Applied Sciences

Bishwas Shrestha

DEGREE THESIS	
Arcada University of applied Sciences	
Degree Program:	Plastics Technology
Identification Number:	10322
Author:	Bishwas Shrestha
Title:	Designing an electrode for EDM
Supervision:	Mathew Vihtonen
Commissioned by:	

Abstract:

This thesis is about designing an electrode for an Electric Discharge Machine. EDM is one of the most used methods for machining. It is a process of eroding material from the work piece with the help of series of sparks to bring out the desired shape. It is very useful for machining hard metals. There are various kinds of EMD, like, Wire EDM, electrode EDM. This thesis is based on Electrode EDM. Graphite is one of the most suitable materials for electrode in use.

It will be shaped on Arcada's logo for it shall be used to produce a sensor key for Arcada University of Applied Sciences. The process starts with a design in Solid Edge. Then MasterCAM is used to create a tool path so that CNC machine will produce electrode for EDM. This electrode will be used to carve a mould for injection moulding machine available in Arcada's Lab.

Keywords	EDM, Electrode, Graphite, Arcada
Number of Pages	47
Language	English
Date of acceptance	

Contents

List of Figures

List of tables

Table of Symbols

EDM	Electrical discharge machining
CAM	Computer Aided Manufacturing
CNC	Computer Numerically Controlled
SFM	Surface Feet per Minute
FPT	Feed per Tooth
rpm	Revolutions per Minute
rev	Revolution
m	Meter
mm	Millimeter
cm	Centimeter
min	Minute
fl	Fleet (tooth)
N	Number of teeth
3D	Three Dimensional

Foreword

I am fortunate to have this opportunity to express my gratitude to all those who have helped me during my time of study and showed me the path to walk my entire life.

First of all, I would like to thank my parents who put themselves through tough times to facilitate me with the best of the resources all my life. Without their blessing and love, I would be nowhere.

I would like to express my deepest gratitude to entire Arcada UAS staff for their continuous support and time thought out my schooling period. They have always been there whenever I needed any advice or help of any kind. I would like to thank especially to Mathew Vihtonen, Mikel Grönroos and Erland Nyroth for being there as a friend, a teacher and a mentor during my time of need.

My deepest love goes to my friends in Arcada for giving me a humorous, friendly and warm environment even in the darkest of time. It is because of their support, I was able to compete with them and understand my true potential

1. Introduction

"Designing an electrode for Electrical Discharge Machining" is a bachelor's degree thesis, primarily focusing on the step by step process of explaining the design process of an electrode for an EDM machine. The thesis will guide the reader to understanding the use and importance of electrodes in today's machining industry. By the end, the reader shall be well aware of how to design an electrode and process of achieving it from hard metal. The thesis also explains why electrical discharge machining process is preferred over other conventional and even new machining processes. The goal of this thesis is to produce an electrode that has the shape of Arcada's logo. The electrode could be used to make a cavity mould for an injection moulding machine for the production of sensor keys for Arcada. During this thesis various software, like Solid Edge, MasterCAM and CNC-code will be used and the terminology required will be explained in the theory section.

Electrical Discharge Machining, EDM, is a machining technique that works by using electric sparks to remove metal dust from the work piece and gives it a desired shape. This is the reason why it is also known as "spark machining". [1] It is usually used on hard and electrically conductive materials like titanium, hastelloy, kovar, Inconel and carbide. [7] This technique lets us create complex shapes, cavities and contours that are almost impossible to achieve with other machining techniques. Despite all its merits, EDM has one major limitation; it only works with electrically conductive materials.

EDM is no longer a "non-conventional" or "non-standard" machining process. It is the 4th most popular machining process, selling more than all other processes except milling, turning and grinding. [2]

The EDM process is usually used to make die and mould, but it is also widely used to make prototypes and production parts in aerospace and electronics industries with smaller amounts of production.

1.1. The history of EDM

The history of EDM goes back to the 1770's when the English scientist Joseph Priestley first introduced electrically discharged machining. His study has been considered too small and insufficient to take credit on today's widely used EDM. The EDM we know today was invented by two Russian scientists Dr. B. R. Lazarenko and Dr. N.I. Lazarenko in 1943.

They learned how to control the distance, intensity and frequency of a spark and applied it to the EDM. EDM drilling was the first technique that was developed to make blind holes and engravings.

A company named Agie designed the first die-sinking EDM machine in 1954. It was also the first company to design a numerically controlled wire-cut EDM machine in 1969. [6]

Metal industries as we see today started taking shape in the mid 1970's when EDM were developed commercially and the wire-cut EDM was becoming a viable technique. The EDM was widely available and appealing when it was transformed into a machine tool in mid 1980s.

2. Objectives

The main objective of this thesis is to:

- Design an electrode in the shape of Arcada's logo with 3D modelling software, Solid Edge, to be used to produce a sensor key.
- Simulate the machining process on the design in MasterCAM software.
- Generate the codes to assist a CNC machine in cutting the designed electrode out of a metal block which could be installed on an EDM available in Arcada's laboratory.

3. Literature Review

This thesis will focus basically on the electrode, its use, the materials that could be used and the materials that the electrode can work on. It also describes the machining process of the electrode.

3.1. Machining

This thesis will contain a detailed drawing of the Electrode in 3D modelling software, the toolpaths on MasterCAM and the G-code for the CNC machine. Brief introductions to the software will follow:

3.1.1. Solid Edge

Solid Edge is an efficient and simple 3D modelling software that will be used to create the working model of Arcada's Sensor key. This thesis will not be using Solid Edge references other than the drafts and pictures of the model where the 3D model is displayed clearly.

3.1.2. MasterCAM

MasterCAM is intended to create the towpaths for any specific 3D model created in 3D modelling software. The model can be drawn in MasterCAM or imported from other modelling software. This software helps choose the right tool, spindle speed and feed rate in order to create a product.

- **Tools:** There are plenty of tools that are commonly used to create a work piece. Cutting tools help chop off the pieces from the work piece, drilling tools help drill holes and face tools help smooth out the surface. This project will be using contour tools and face tools. Contour tools will be used to cut within a given depth around the line. Face tools help clearing off needless material.
- **Spindle Speed:** The spin rate of the tool is called spindle speed. Its unit is rpm.[12]
- **Feed Rate:** Feed rate is the rate of material cut from the work piece. It is the rate of spinning tool moving forward per minute. Its unit is mm per minute.[12]
- **G-code:** G-code is a language that allows a milling machine to understand how the tools should be driven over the work piece to give the required design. It can be derived from software like MasterCAM.

Table 1: Spindle speed and feed rate [12]

$Spindle\ Speed\left(\frac{rev}{min}\right) = \{\frac{Surface\ speed(m/\min)*1000}{\pi*Diameter\ (mm)}\}$ - (Equation 1)
$Feed\ Rate\ \left(\frac{mm}{min}\right) = \{Spindle\ speed\left(\frac{rev}{min}\right) * Chipload\ per\ tooth\left(\frac{mm}{tooth}\right) * Number\ of\ cutting\ teeth\ \}$ - (Equation 2)

3.1.3. CNC Machine

A CNC Machine is a milling machine used to mill a product according to the G-code obtained from MasterCAM. The G-code has to be fed into the machine via the USB port to program the tool drive.

3.2.EDM Machine

EDM, Electrical discharge machining, is a widely used machining process in the modern age of machining. It is a controlled metal removal process which uses electrical spark erosion to do the job.

An EDM machine has following major aspects.

- Controlled axis
- Electrical generator
- Control panel
- Work table
- Dielectric fluid container

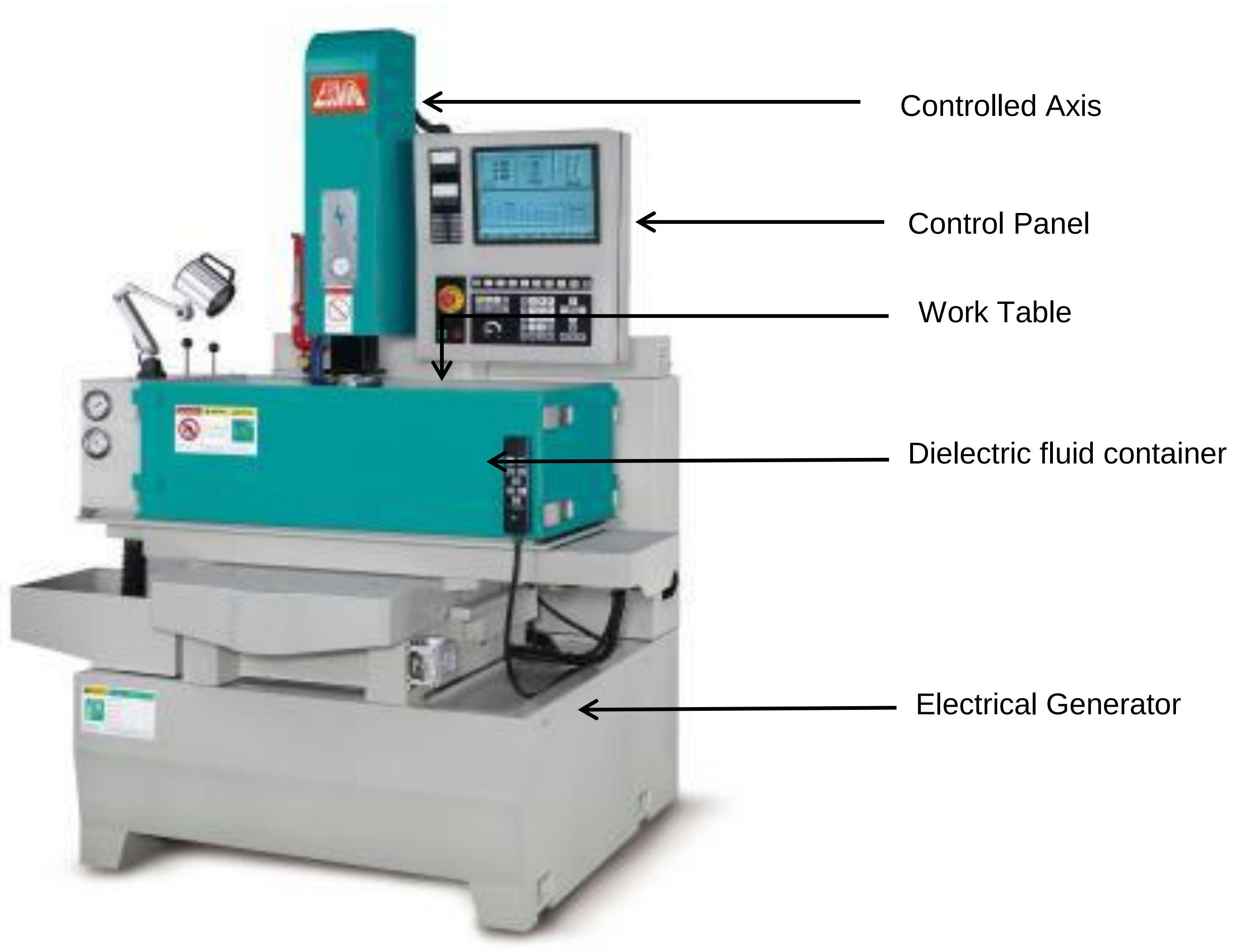


Figure 1: EDM machine

An electrode is attached to the controlled axis that moves up and down according to need. Its movement is controlled with the help of a control panel. The control panel also controls the amount of electricity supplied to the electrode and the work piece. The work table is inside the di-electric fluid container and holds the work piece in place. The di-electric fluid container, as name applies, contains the di-electric fluid. Both electrode and work piece are submerged in the fluid container for the process. The electrical generator is plugged in the power source and supplies the amount of electricity needed in the process.

3.2.1. The Process

EDM is a thermal process i.e. material is removed by heat. When electrode is brought closer to the work piece, sunk in the dielectric fluid, current is passed to the electrode and the work piece, which generates heat in the form of frequent series of sparks that vaporizes the pieces at the closest point of work piece and electrode. After removing the piece at the closest distance between electrode and work piece, the next spark occurs simultaneously at the next closest point between them and so on. This process results on forming a cavity on the work piece with the shape of the electrode. That is how the end result is obtained as required. Since the job is done by the series of electric sparks, the electrode and work piece must be electrically conductive. This is also the limitation of the Electrical discharge machining process. It does not work with non-conductors.

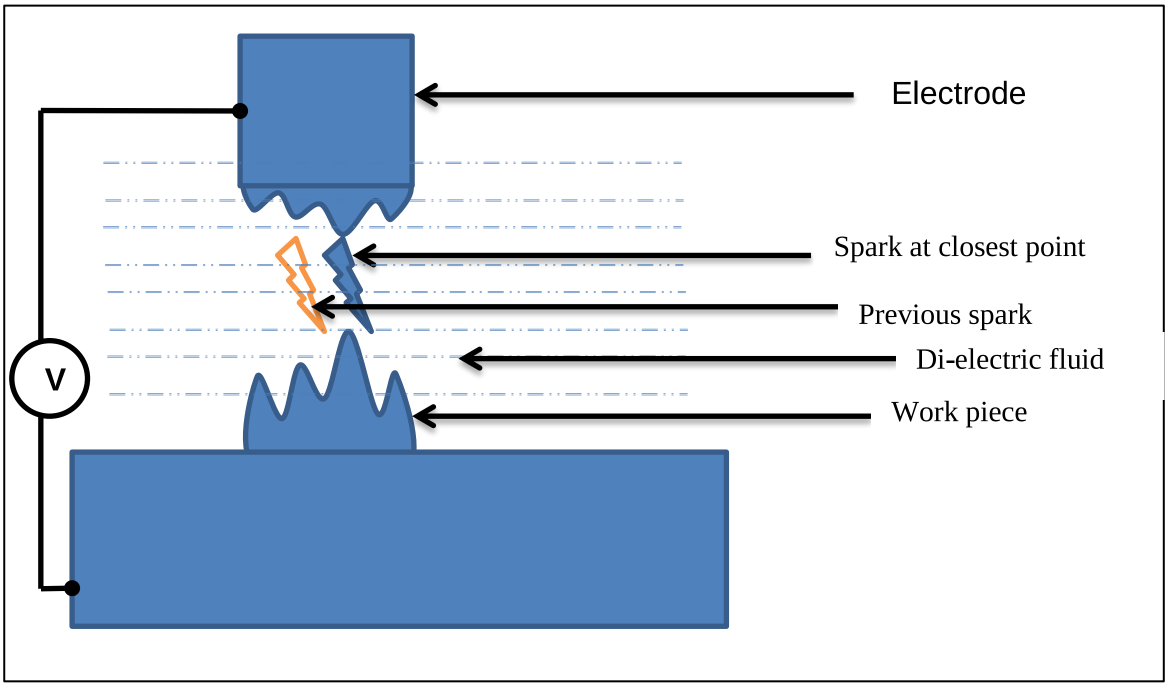


Figure 2: Electrical Discharge Machining process

During the electric discharge process, the electrode is not supposed to touch the work piece; instead it must be at the closest distance to successfully produce the spark. This distance is called the "sparking gap". [4] If the electrode touches the work piece, there will not be a spark or material vaporization, which is the main idea of this process. The di-electric fluid is required to maintain the sparking gap between the electrode and the work piece.

3.2.2. Di-electric Fluid

The main function of di-electric fluid is to maintain the insulation between electrode and work piece until enough electrical voltage is applied to change the fluid into electrical conductor. These di-electric fluids have the property to remain electrical insulator until enough electric voltage is applied to change into a conductor at the nearest point between electrode and work piece. This point of transformation from non-conductor to conductor is called "**ionization point**". During the spark, the sparking point becomes extremely hot which di-electric fluid quickly cools down with slight possibility of metallurgical changes due to extreme heat. After the spark the fluid de-ionizes and returns to its original state of non-conductor until the next spark. [4]

3.2.3. Flushing

Flushing is another aspect that plays vital role for EDM to work efficiently. It is a process of removing chipped pieces of material by gunning clean filtered di-electric fluid with adequate amount of pressure into the spark gap. Flushing helps quicken the process by removing chips, preventing from resulting in short circuiting the erosion process. [5]

3.2.4. The Servo Mechanism

This is a process that is available on both conventional and wire-cut EDM process. It keeps the electrode and work piece at the distance equivalent to the width of single human hair. This is very important for EDM in order to successfully produce sparks between the electrode and the work piece. It advances the electrode into the work piece and maintains the sparking gap. [5]

3.3. Electrode

An EDM can use either a pre-shaped electrode, also known as ***conventional EDM***, or a continuous travelling wire electrode with the diameter of small needle or less which is controlled by computer to run in a pre-programmed path, also known as ***wire-cut EDM***. Both processes take place in a di-electric fluid, with the supply of current on the electrode and the work piece, generating series of sparks. The difference between these two processes is that, in conventional EDM, the electrode is shaped to obtain the required end result and put on top of the work piece in a certain distance. Therefore, when electricity is applied, the spark would vaporize and create a cavity on work piece shaped like design of electrode. Whereas, wire EDM is designed to follow a path programmed by computer, vaporizing through the work piece to result on desired shape. This is the reason why it is possible to obtain the most complex shapes and contours on work piece. They also use two different types of di-electric fluids. Conventional EDM uses Hydro-carbon oil whereas wire-cut process uses De-ionized water. [5]

Electrode is the most important aspect in EDM. Property of an electrode material affect greatly on the machining process. Some electrode wear fast but give good machining while others wear slowly but give bad finishing, both cases are not acceptable for a good job. Therefore an electrode must be with a property of great result, good timing and cost effective. [11]

3.3.1. Electrode Overcut

The cavity on the work piece is always larger than the size of the electrode. This excess cut is called “overcut” or “overburn”. The main reason for overcut is the amount of electrical current. Overcut is always measured per side. It can range from 0.20 mm to 0.63 mm which is huge. Higher amperage results in the larger overcut. Overcut entirely depends upon material and the power setting, therefore, it remains constant in every use, and hence, variation of 0.0025 mm can be achieved in conventional EDM. This increases the machining time and hence increases the cost.

3.3.2. Sinker Electrode Material Properties [9]

As discussed earlier, EDM is a process of the electrode and the work piece wearing each other off, therefore, it is best if the physical, chemical, and mechanical properties of the electrodes are taken to be the most durable. This will help the process result in excellent results with least amount of resources.

- **Electrical Conductivity** is one of the most important factors for any material to be suitable for an electrode. Higher conductivity and lower resistivity helps on efficient cutting.
- **Melting Point** for an electrode must be higher than that of work piece, because if electrode melts before the work piece the whole system fails. It is best if electrode has as high melting point as possible with excellent conductivity.

- **Chemistry** of an electrode does not look into the context, but if an electrode starts changing its chemical properties when introduced to di-electric fluid or current then the electrode is not suitable at all for the job.
- **Structural Integrity** is also a very demanding quality on an electrode. Even though EDM exerts no physical pressure on the work piece, hence the name “Zero Force” process, thousands of sparks result in serious stress on the material at a microscopic level. A suitable electrode must suffer these thousands of sparks without losing its structural integrity.

Besides these key factors, an electrode must also have very good mechanical properties like tensile strength, Transverse rupture strength, finer grain size and adequate hardness. In sinker EDM, an electrode has to be cut into the shape of the desired product. Therefore, it has to have a good machinability, stability.

3.3.3. Electrode Wear

Sinker EDM is a process of transcribing the shape of the electrode to the work piece with the help of electrical sparks. The temperature of the spark is considered to be close to 6000°C. When the spark occurs, the closest point between electrode and work piece is dissolved/evaporated. This is how the shape of electrode is transcribed to the work piece, but it also dissolves the electrode. This is called “Electrode wear”. The spark lasts for 10^{-6} second to 10^{-3} second according to the need. The longer the spark, faster the dissolving goes on. [10] Electrode Wear more on corners because at corner, it has to erode larger area compared to other part. Electrodes wear in two different ways, end wear and corner wear.

The ratio of amount of electrode wear and machining of the work piece is called “electrode wear ratio”. It largely depends upon combination of electrode and work piece, the polarity of the voltage to apply and the duration of the spark. [10]

End wear ratio [9] = $\frac{length\ of\ electrode\ material\ lost}{depth\ of\ the\ cavity\ burned}$x 100% – (Equation 3)

Corner wear ratio [9] =

$\frac{length\ lost\ of\ a\ 90\ degree\ external\ corner\ on\ the\ electrode}{length\ of\ the\ corresonding\ sharp\ internal\ corner\ produced\ in\ the\ cavity}$x100% – (Equation 4)

Electrode wear is generally the process of depletion, but in rare case it is also re-plating of electrode. This process is called “**Low Wear Burns**”. Electrode re-plating is the function of power supply setting, electrode-work piece combination, polarity of electrode, on-time and peak current. In these cases, the material lost from electrode can be re-plated back to the electrode. But the materials that are re-plated are not only the material lost from electrode, but from work piece and di-electric fluid. Therefore it could change the properties of the electrode material. Re-plating is also a disadvantage because it changes the dimension of the electrode which effects on the shape and size of the product. [9]

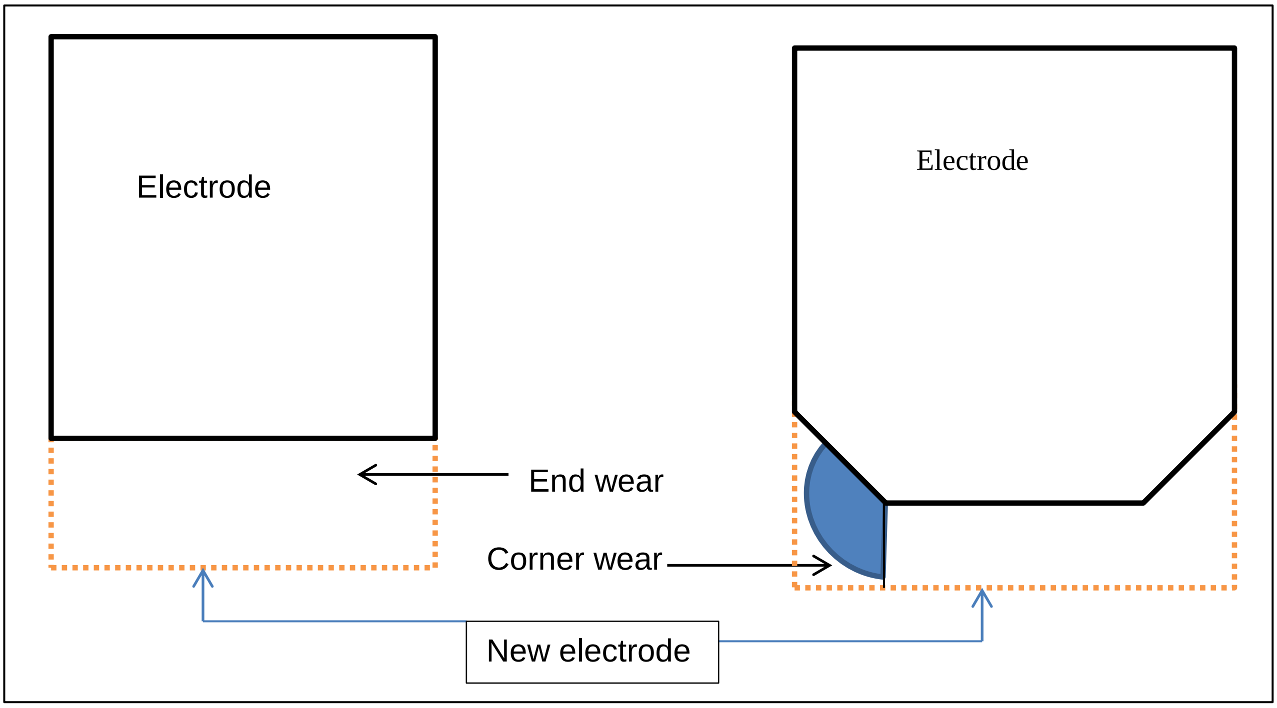


Figure 3: Electrode wears [9]

3.3.4. Electrode Materials

Electrode materials are generally of two types, Metallic and Graphite. Most common materials for an electrode are brass, copper, tungsten, zinc and graphite for their electrical conductivity and high melting point. Some alloys are also used as electrode material for more efficient machining. [11]

Graphite electrodes have the greater metal removal rate in relation to its wear than other material. It does not melt in the spark gap, rather evaporates at the temperature of 3350°C. This relatively high resistivity to heat as compared to copper makes it a better choice as an efficient electrode material for most machining tasks. Although Tungsten has similar melting point as graphite, its low machinability puts it below graphite as a suitable electrode material. [11]

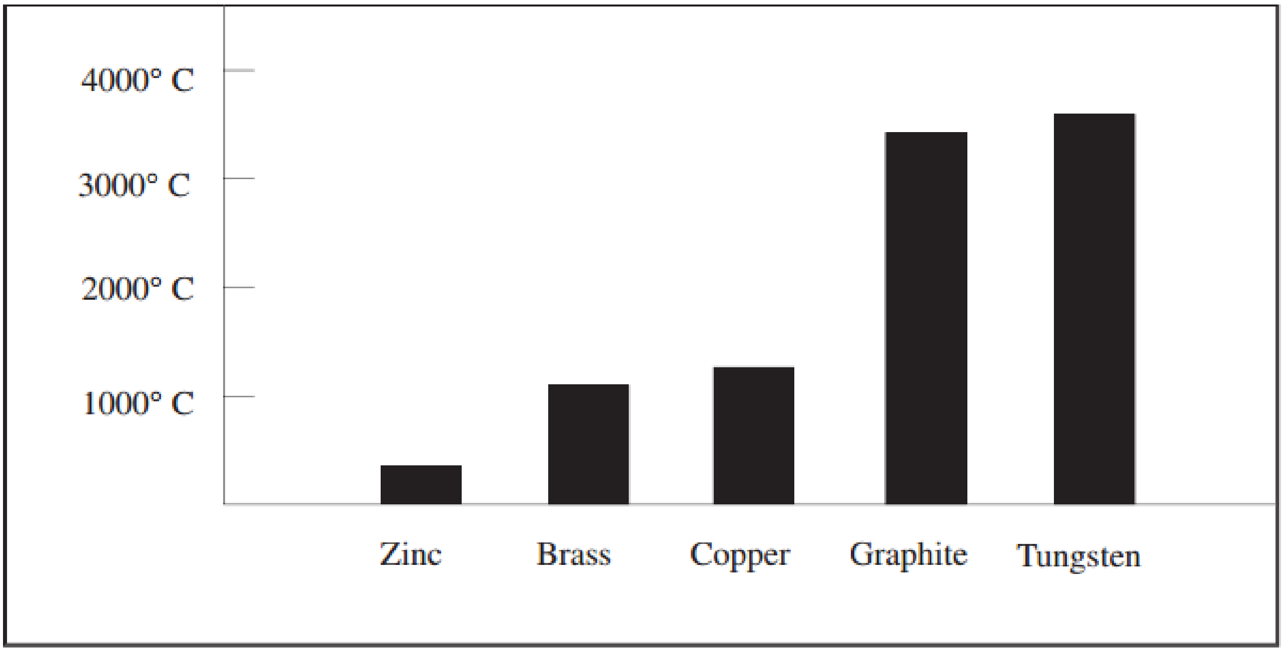


Figure 4: Electrode materials melting point [11]

With the growing use of EDM process, the machine has been modernized in various aspects. Modern Electric Discharge Machine like one available at Arcada can be programmed to cut through a high melting point material like steel with a lower melting point material like copper (Cu). This benefits user hugely. It allows cutting material without the electrode erosion which is economical and time saving.

Despite of graphite being a good material for electrode, this thesis shall be experimenting with Aluminium or copper as an electrode material.

3.4.Graphite Electrode

Graphite is the most commonly used material for electrode. Graphite was introduced in EDM industry around 50 years ago. General Electric was the first, well known manufacturer to introduce graphite in EDM industry. It was known by its trade name "Gentrode". [9]

Unlike other metal based electrode material, graphite has certain unique properties which keep it above others as a suitable material for EDM electrode. Its heat resistivity is thousands of degrees higher than other materials. It does not melt like other materials; instead it turns straight into gas from solid state. This is also a disadvantage because, instead of creating chips and staying under the di-electric, it causes a dusty cloud to form in work place. This is hazardous if not followed precaution. Vacuuming the dust is a good idea to prevent from breathing graphite in while at work place. [9]

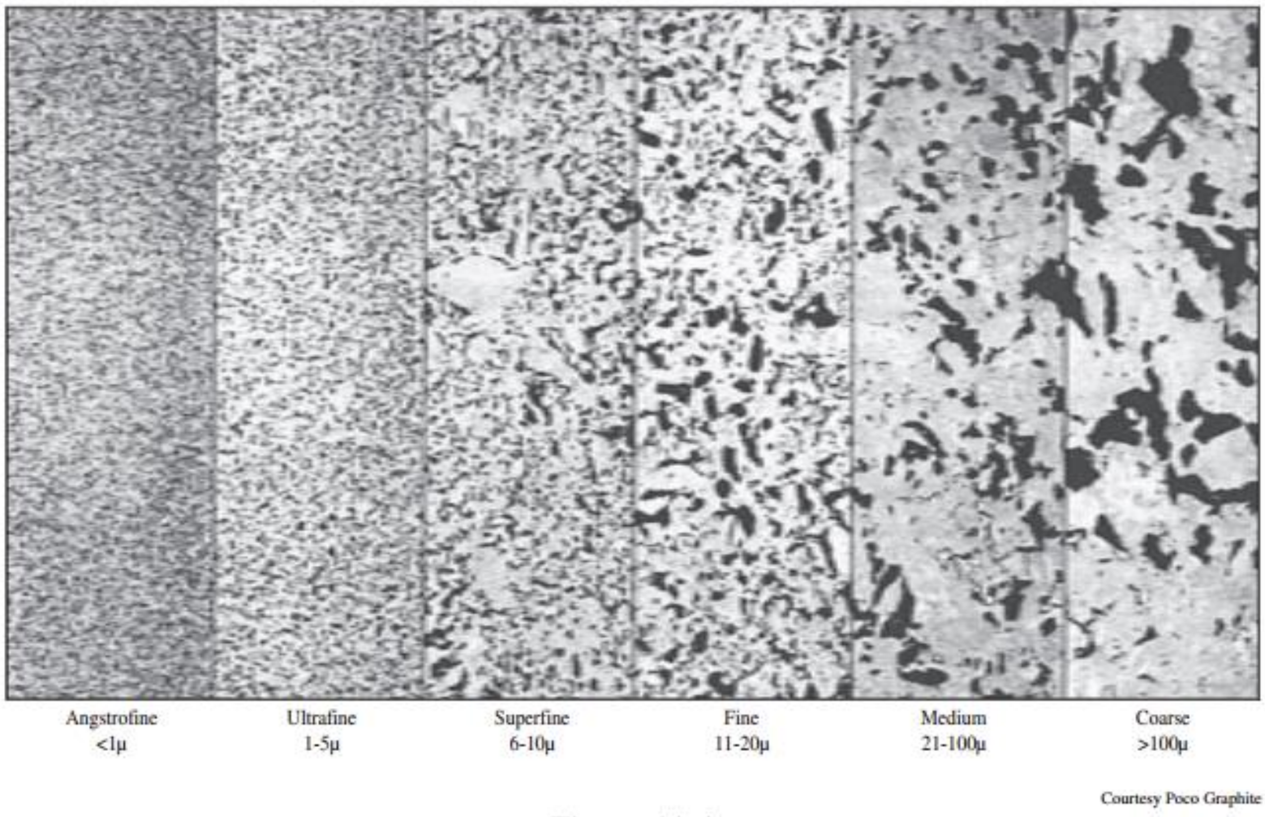
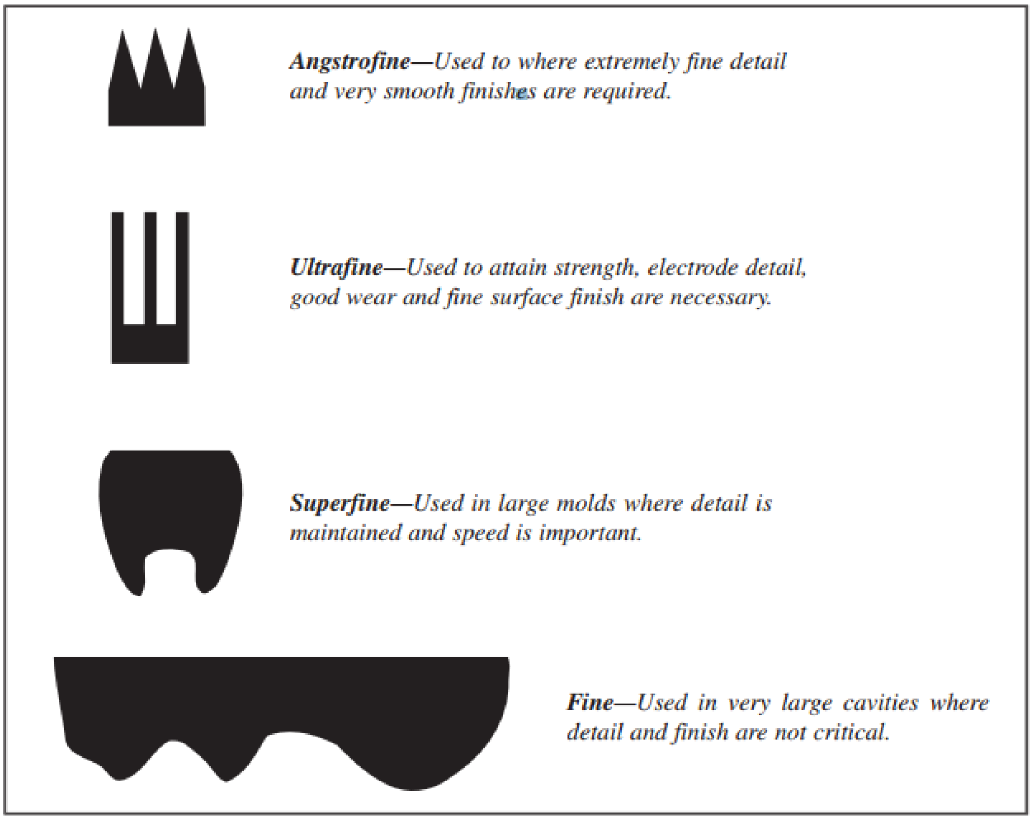


Figure 5: Graphite grain sizes x 100 [11]

Graphite, despite being the best option as an electrode material, has some limitations in molecular level. It is porous so when immerged in di-electric fluid it can cause problematic impurities. Trapped moisture can create steam when cutting which damages the electrode. Due to this problem, it is better to use denser graphite which shows little penetration even after long hours of soaking. One other way of using graphite without facing problem is to heat the electrode in oven for an hour at 121°C. [11]

3.4.1. Graphite Grades

Grain size and density defines the quality of graphite as an electrode. It also determines its price and cutting efficiency. Graphite with finer grain size results on better finishing and wear resistance, but graphite with larger grin size costs less. [11]



Courtesy Poco Graphite

Figure 6: Graphite grades in uses [11]

- **Sub-Micron**: This grade of graphite is the most expensive one and has the grain size of less than one micron i.e. Angstrofine graphite.
- **Premium**: Graphite with less than or equal to 5 microns, i.e. Ultrafine, falls under premium grade of Graphite.

- **High performance**: Superfine to fine Graphite with 10-20 microns size is high performance Graphite.
- **General purpose**: Graphite with grain size of larger than 20 microns are general purpose Graphite.

3.4.2. Electrode Wear

As discussed earlier, electrodes wear off while working. This cannot be prevented, but could be reduced. Switching to suitable polarity, it could be brought to minimum with higher output. Below are the general polarity guidelines of Graphite and others, [9]

Table 2: Electrode wear on different material [9]

Graphite on Steel: general purpose and low wear	Electrode positive
Graphite on Steel: high speed and 20% wear	Electrode Negative
Graphite on Copper	Electrode Negative
Copper on Steel	Electrode Positive
Copper Tungsten on Steel	Electrode Positive
Copper Tungsten on Carbide	Electrode Negative

3.4.3. Milling Graphite

Despite of wide range of use of graphite, this thesis will only be focusing on graphite as an electrode for this project. Although, graphite is too easy to cut, due to its abrasive particles, it wears off the milling tools very quick. The Carbon-to-carbon bond makes graphite very abrasive and only way to effectively mill graphite is diamond coated tools. It makes the tool last 15-20 times longer. Key principles to have smooth graphite milling are [13]

- Keep cutting tool edge speed (m/min) high but below 400 m/min
- Always keep enough feed per tooth.

Table 3: Milling graphite parameters [14]

Parameter	Value	Metric unit
Cutting speed	100-300 {Reference value used in calculation -100(minimum)}	m/min
Feed rate	0-1	mm/min
Depth of cut	5-10	mm

Table 4: Milling aluminium parameters [12]

Parameter	Value	Metric unit
Cutting speed	75-105 {Reference value used in calculation- 90(average)}	m/min
Feed rate	0.2	mm/min

4. Methods

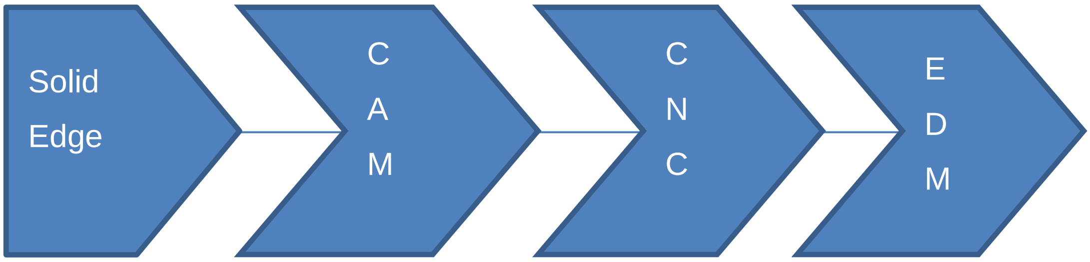


Figure 7: Process flow

4.1.Design

The key was designed in Solid Edge in two different parts, the Cap and the key. Arcada is using a 2.5 cm sensor for the key hence same measurement was taken while designing the key. The key is roughly in triangular shape. The end to end length of the key is roughly 39.64 mm and the height of the key is 35.86 mm. The 3 mm deep logo and 2.5 mm cavity was fused together to create the key where the logo is embossed 0.5 mm on top of the circular cavity.

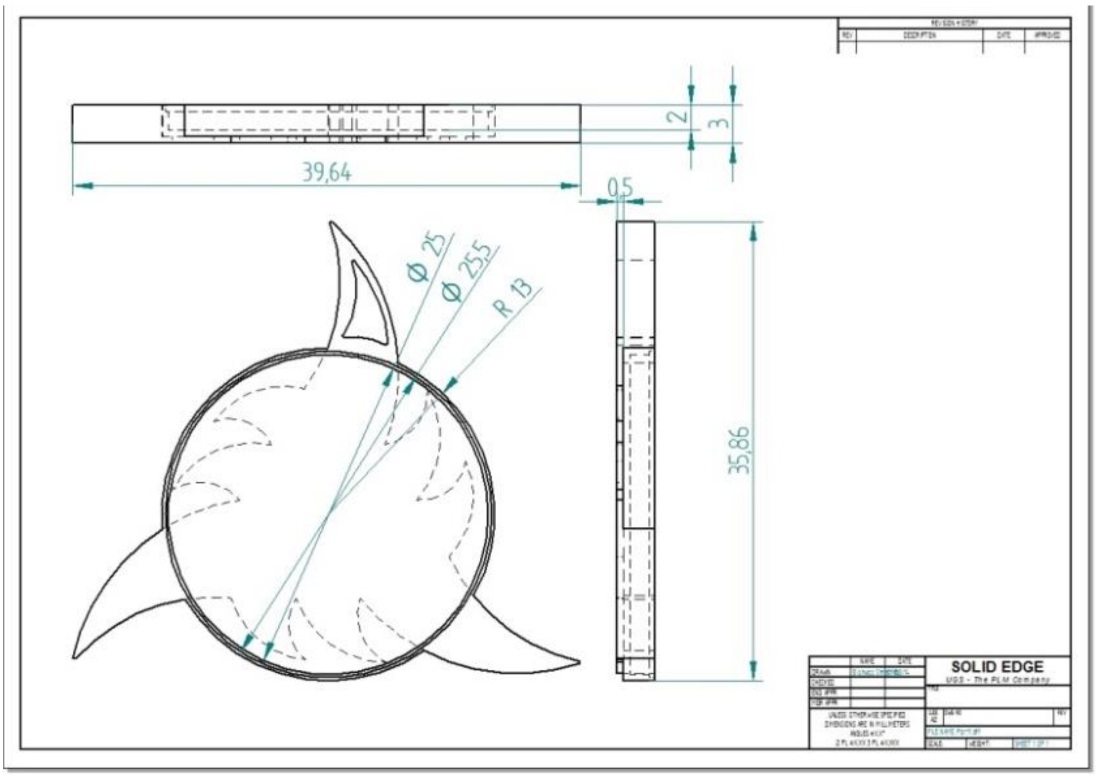


Figure 8: Draft of the key

The circular cavity is intended to contain a 2.5 cm diameter and 1 mm thick sensor in it. The cavity is 2 mm deep and 1 mm thick. The inner diameter is 25 mm. A 0.5 mm thick and 0.5 mm deep groove is cut around the cavity to support the cap while enclosing the sensor. A hole is cut on one end of the key to help support key chain.

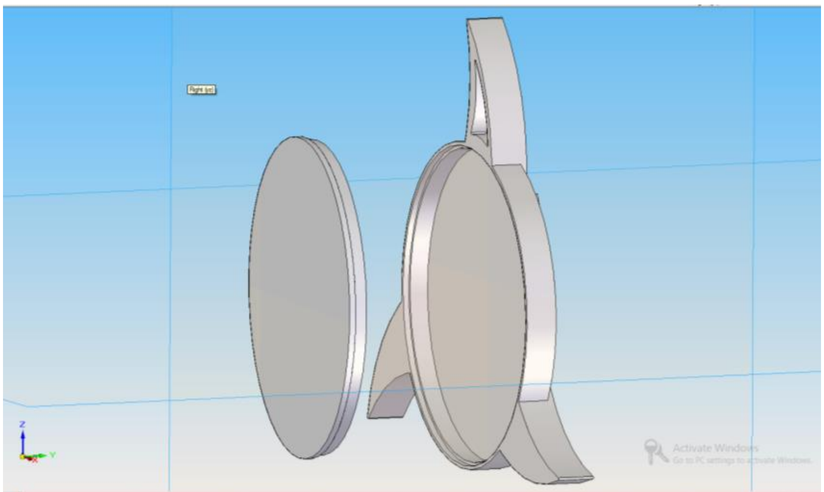


Figure 9: The cap and the cavity

The cap is a T shaped circular disc. It has 25.5 mm diameter and 1 mm depth. A 0.5 mm deep and 0.5 mm wide groove is cut around the bottom. The 1 mm cap is supposed to be glued together with the key enclosing the 1 mm sensor in the middle.

4.2. Tool Path

The work on MasterCAM started with a block of 50 mm x 50 mm x 50 mm. The toolpaths were drawn on top of this block. The tool was run through the block and material was chipped away to create the model.

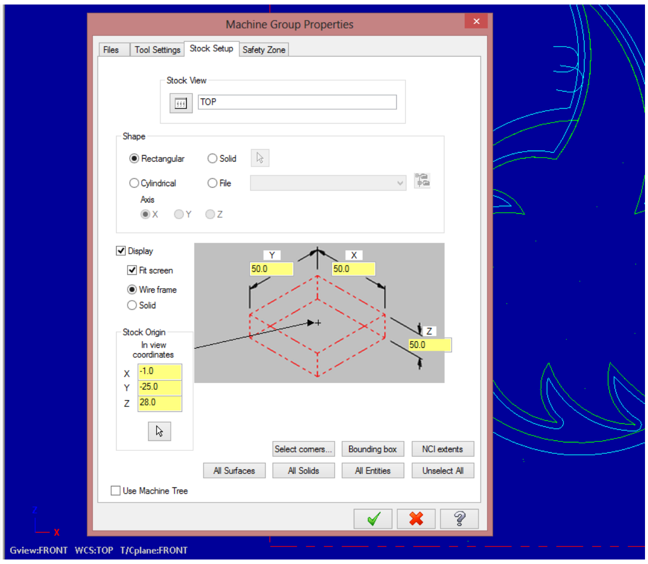


Figure 10: Stock setup

The design on Solid Edge was imported to the MasterCAM and re-drawn for the tool path. The design is intended for EDM electrode to create a mould, therefore it looks like the product itself. There are three different electrodes to complete this product, the top side electrode, the bottom side electrode and the cap electrode.

4.2.1. The Top

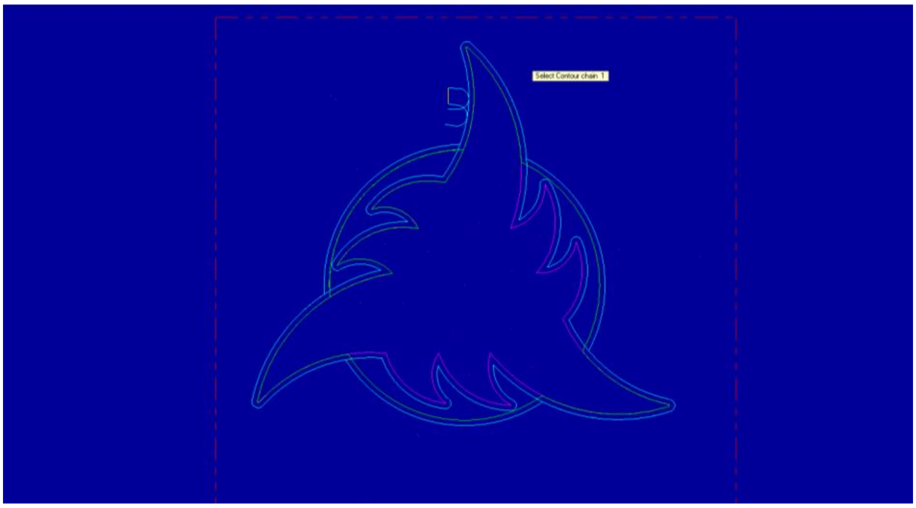


Figure 11: Toolpaths on MasterCAM

The top side electrode contains the logo. After obtaining the desired drawing of the product, the tool path for milling process began with 1 mm contour around the logo of arcada at the height of 2.5 mm.

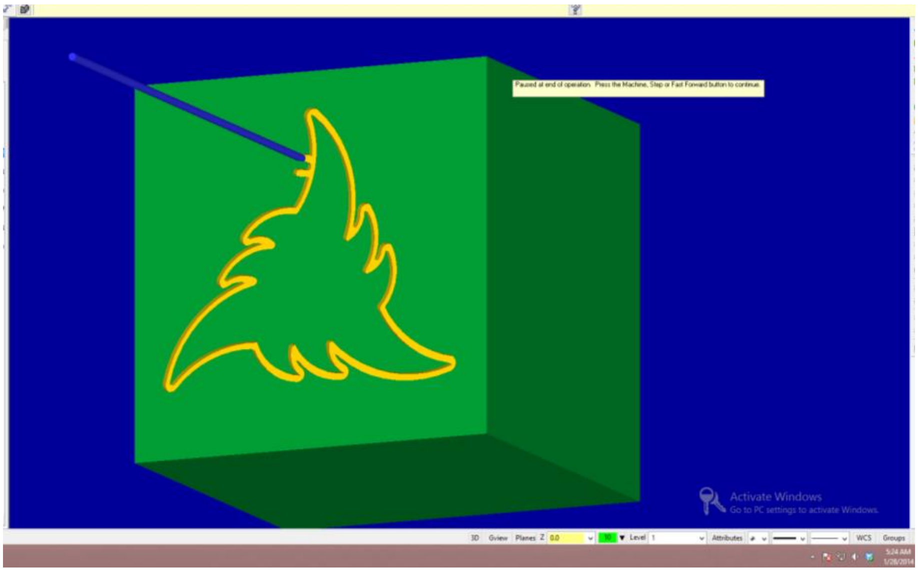


Figure 12: Top side contour

The tool was 1mm End mill with two teeth.

For Graphite,

Spindle Speed = $\frac{Surface\ speed(m/\min)*1000}{\pi*Diameter\ (mm)} = \frac{100\ x\ 1000}{\pi\ x\ 1}$ = 31830 rpm

Feed Rate = $\frac{rev}{min}\ x\ \frac{mm}{fl}\ x\ N$ = 31830 x 0.1 x 2 = 6366 mm/min

For Aluminium, (Taking 0.1 mm/tooth chip load because more might break the tool.)

Spindle Speed = $\frac{Surface\ speed(m/\min)*1000}{\pi*Diameter\ (mm)} = \frac{90\ x\ 1000}{\pi\ x\ 1}$ = 28647 rpm

Feed Rate = $\frac{rev}{min}\ x\ \frac{mm}{fl}\ x\ N$ = *28647 x 0.1 x 2* = 5729 mm/min

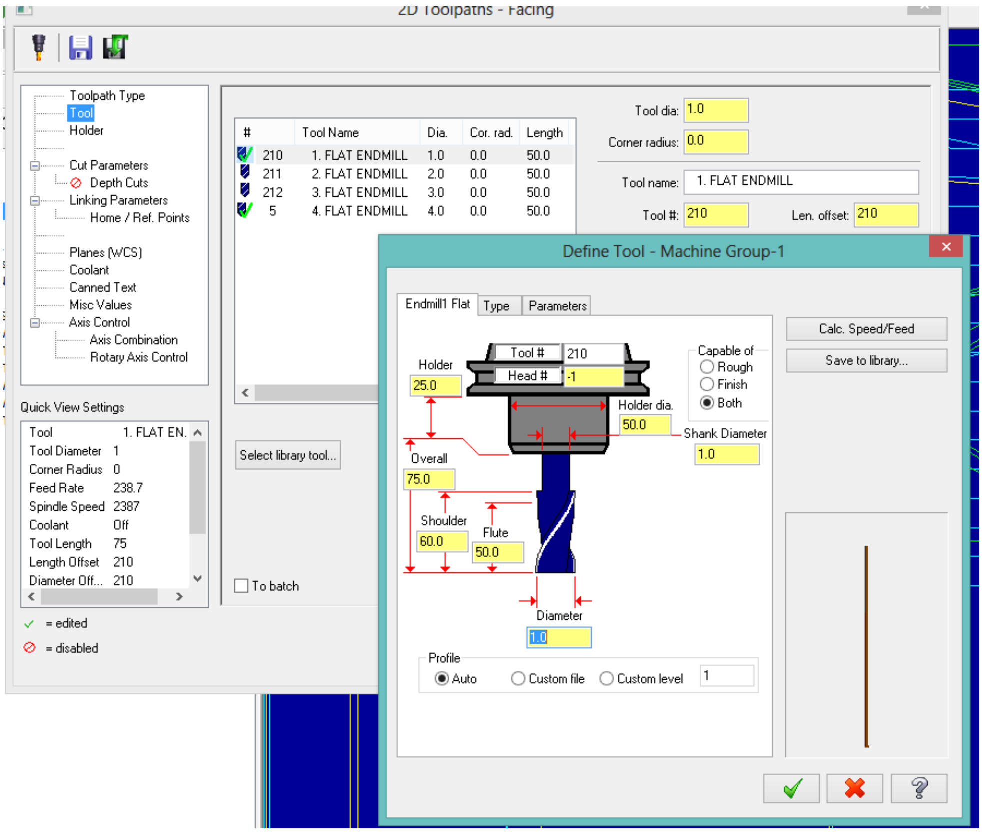


Figure 13: Tool selection for contour

After achieving the contour around the logo the same tool was used to make the key cavity circle as well. The key cavity was contoured 3 mm deep with 1 mm end mill but this process had a complication. After the contour operation, the remaining chips of material around the corners were almost impossible to machine clearly. But it was machined close enough to show roughly cut sharp edges and irregular shapes. Therefore, an alternative option was chosen.

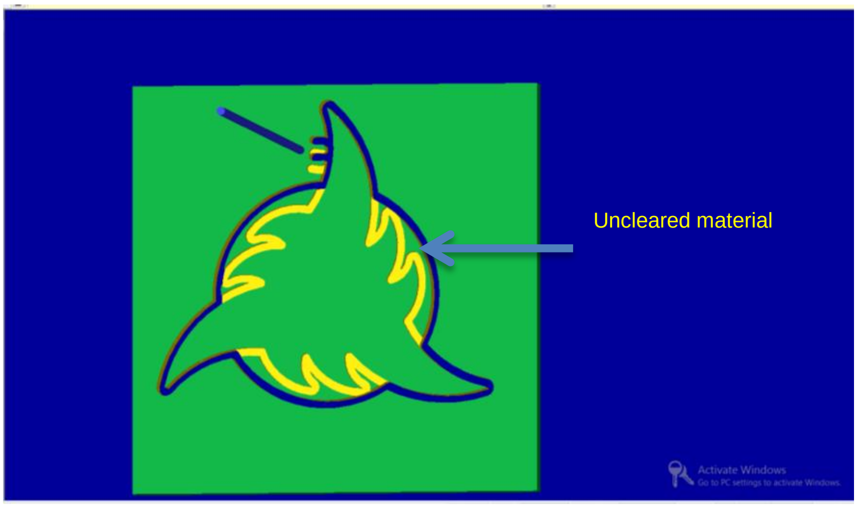


Figure 14: Key cavity contour

By leaving 0.5 mm of stock on the wall, it was possible to achieve safest result with closest look. Hence the design was varied by small measure of 0.5 mm around the original drawing.

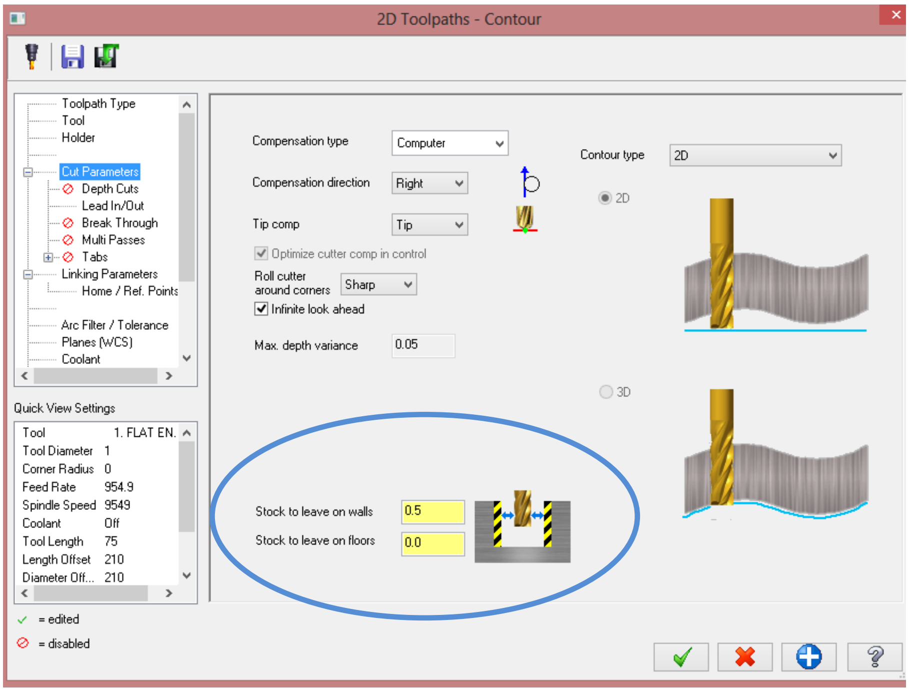


Figure 15: Altered cut parameter

The resulting cut piece is shown in the figure 15. This piece has the same design as the original design but now it is cut around 0.5 mm wider than the real drawing. This has given it a style of a logo carved out on a cylindrical tube. It is contoured all the way through for 10 mm depth with 2 mm End Mill tool. The cylindrical shape has a diameter of 27 mm and it will be fitted on the holder on EDM. Using 25% surface speed,

For Graphite,

Spindle Speed = $\frac{Surface\ speed(m/\min)*1000}{\pi*Diameter\ (mm)} = \frac{25x1000}{\pi\ x\ 2}$ = 3978 rpm

Feed Rate = $\frac{rev}{min}\ x\ \frac{mm}{fl}\ x\ N$ = 3978 x 0.1 x 3 = 1193 mm/min

For Aluminium, (Taking 25% of average surface speed and 0.1 mm per tooth chip load).

Spindle Speed = $\frac{Surface\ speed(m/\min)*1000}{\pi*Diameter\ (mm)} = \frac{22.5x1000}{\pi\ x\ 2}$ = 3580 rpm

Feed Rate = $\frac{rev}{min}\ x\ \frac{mm}{fl}\ x\ N$ = 3580 x 0.1 x 3 = 1074 mm/min

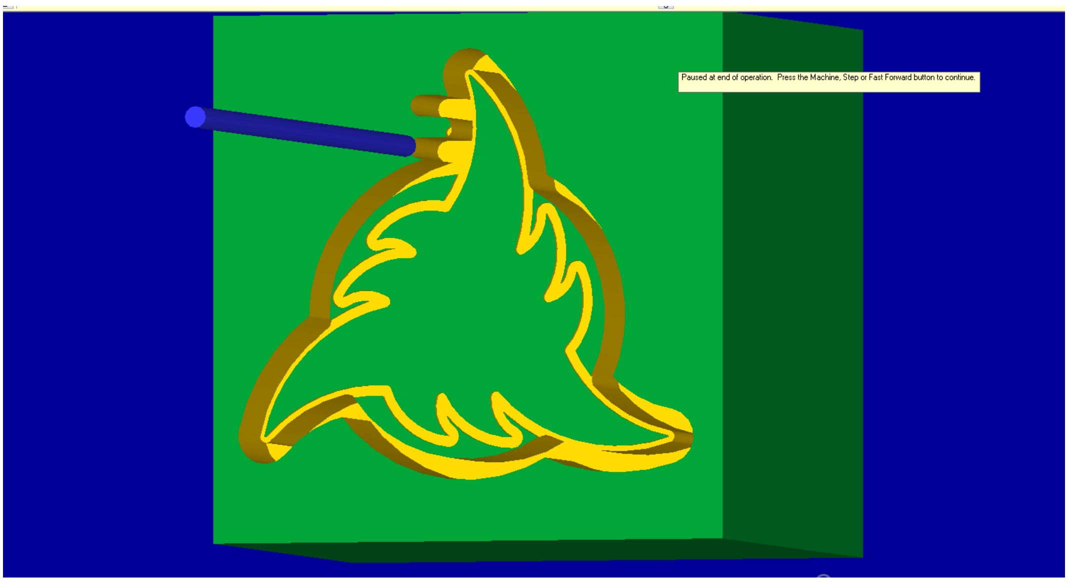


Figure 16: Alternative cut piece

The work piece has to be flipped upside down to cut a holder through it. Since the front has already 10 mm deep cut, the other side can have 40 mm depth cut and the piece is free. Pocket tool was chosen for this job. A 3 mm end mill was used to pocket cut between two circles with 46 mm diameter and 13 mm diameter as shown in figure 16.

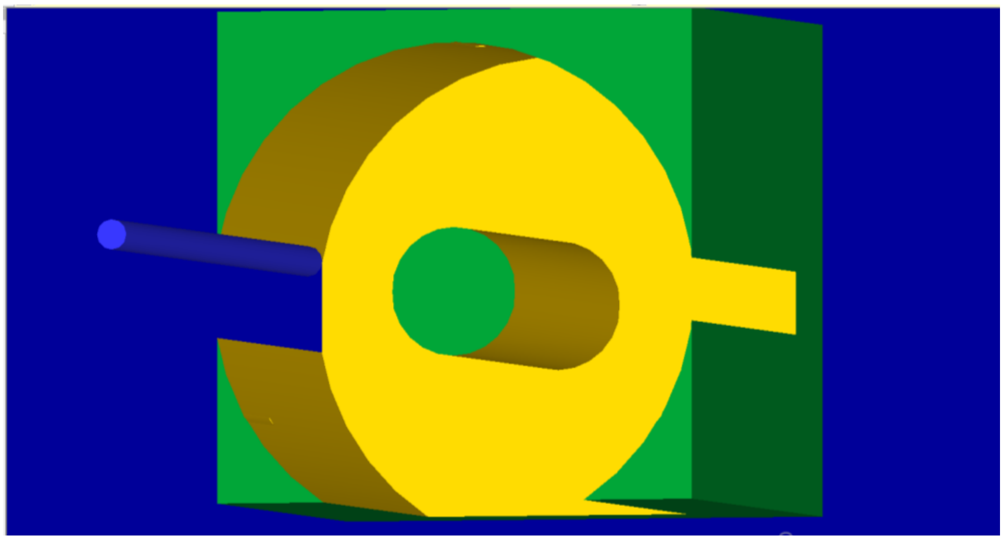


Figure 17: The electrode handle

For Graphite, (taking 50% of surface speed)

Spindle Speed = $\frac{Surface\ speed(m/\min)*1000}{\pi*Diameter\ (mm)} = \frac{50x1000}{\pi\ x\ 4}$ = 3978 rpm

Feed Rate = $\frac{rev}{min}\, x\, \frac{mm}{fl}\, x\ N$ = 1989 x 0.1 x 2 = 397 mm/min

For Aluminium, (Taking 50% of average surface speed).

Spindle Speed = $\frac{Surface\ speed(m/\min)*1000}{\pi*Diameter\ (mm)} = \frac{37x1000}{\pi\ x\ 4}$ = 3580 rpm

Top spindle speed for 4 mm diameter at Arcada is 4000 r/min.

Feed Rate = $\frac{rev}{min}\, x\, \frac{mm}{fl}\, x\ N$ = 2944 x 0.2 x 2 = 1432 mm/min

4.2.2. The Cap and the Cavity

The cap and the cavity electrodes are produced on a 50 mm X 50 mm X 50 mm cube. The electrode shall sink only 1.5 mm – 2 mm deep on the metal block that is supposed to be a mould for injection moulding machine. The process is started with facing the surface for 0.5 mm depth.

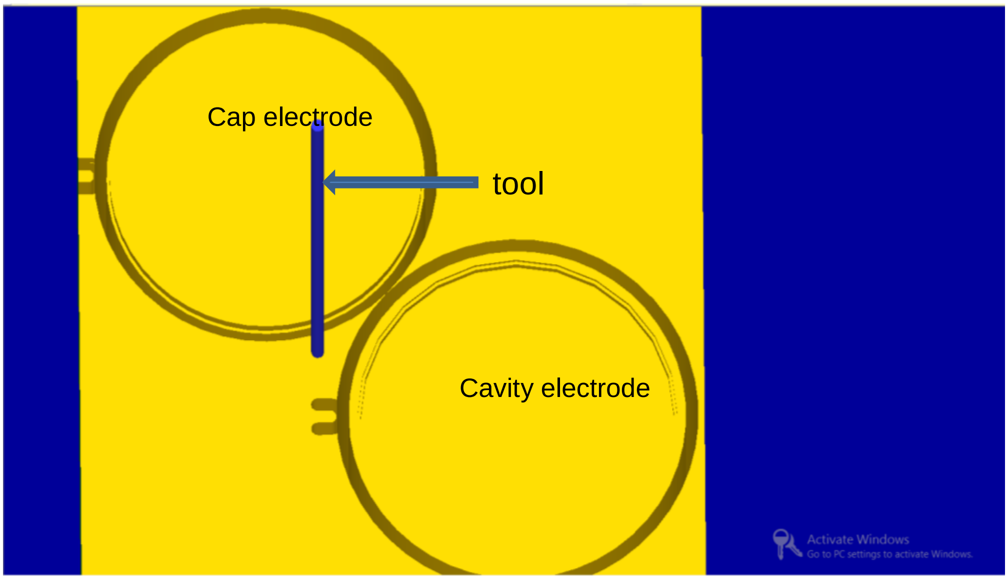


Figure 18: Cap and cavity electrode

The cap electrode is a 25.5 mm diameter cylindrical piece with 0.5 mm wide and 1 mm deep contoured. It forms an electrode which creates a cavity on a mould that shall produce a cap. A 1 mm diameter flat end mill was used to machine this piece.

For Graphite,

Spindle Speed = $\frac{Surface\ speed(m/\min)*1000}{\pi*Diameter\ (mm)} = \frac{100x1000}{\pi\ x\ 1}$ = 31830 rpm

Feed Rate = $\frac{rev}{min}\ x\ \frac{mm}{fl}\ x\ N$ = 31830 x 0.1 x 2 = 6366 mm/min

For Aluminium, (Taking average surface speed and 0.1 mm per tooth chip load)

Spindle Speed = $\frac{Surface\ speed(m/\min)*1000}{\pi*Diameter\ (mm)} = \frac{90x1000}{\pi\ x\ 1}$ = 28647 rpm

Feed Rate = $\frac{rev}{min}\ x\ \frac{mm}{fl}\ x\ N$ = 28647 x 0.1 x 2= 5729 mm/min

The cavity electrode is a 25.5 mm diameter piece with 0.5 mm wide and 0.5 mm deep groove cut on the inside of the electrode. The second pocket cut is a 25 mm diameter cut with 1.5 mm depth from the last cut surface, centred to the centre of the cylindrical electrode. This piece is designed to produce a core on mould for injection moulding machine that will help to create the cavity on the key. A 4 mm diameter flat end mill was used to machine this piece. Using 25-50 % surface speed,

For Graphite, (taking 50% of total surface speed)

Spindle Speed = $\frac{Surface\ speed(m/\min)*1000}{\pi*Diameter\ (mm)} = \frac{50x1000}{\pi\ x\ 4}$ = 3978 rpm

Top spindle speed for 4 mm diameter at Arcada is 4000 rpm.

Feed Rate = $\frac{rev}{min}\, x\, \frac{mm}{fl}\, x\ N$ = 3978 x 0.1 x 2 = 795 mm/min

For Aluminium, (Taking 50% of average surface speed.)

Spindle Speed = $\frac{Surface\ speed(m/\min)*1000}{\pi*Diameter\ (mm)} = \frac{45x1000}{\pi\ x\ 4}$ = 3580 rpm

Top spindle speed for 4 mm diameter at Arcada is 4000 rpm.

Feed Rate = $\frac{rev}{min}\, x\, \frac{mm}{fl}\, x\ N$ = 3580 x 0.2 x 2 = 1432 mm/min

Both electrodes were contoured outside of 25.5 mm outside diameter till the depth of 50 mm. This will separate the electrode from the metal block. The extended 50 mm long electrode tail is kept to be used for the holders to hold the electrode.

The process took total time of 3 minutes and 23 seconds. The spindle speed and feed rate can be adjusted at the CNC machine according to the machine comfort.

5. Results

This thesis has shown that Electrical discharge machining process is accurate, safe and easy to obtain complex shape. No shape is too small or too narrow. It is easy to get sharp corners and tiny cavities.

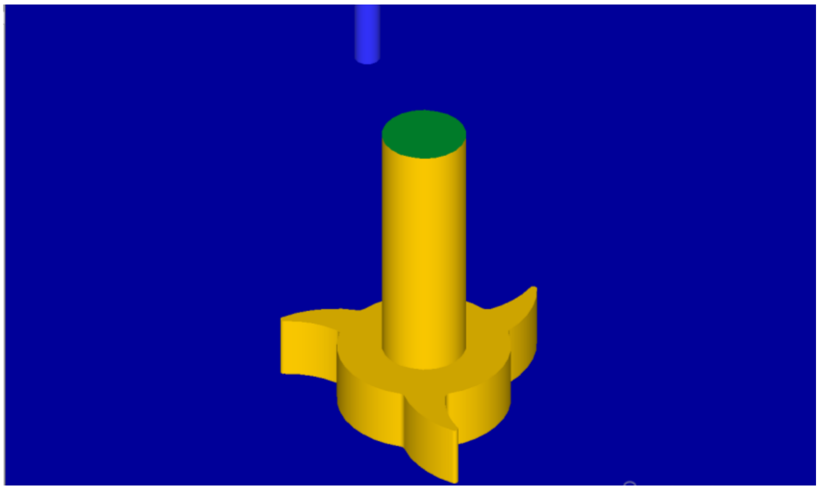


Figure 19: Finished top electrode

The key will require three electrodes. Figure 19 is the top electrode for the key. It will make a cavity on the mould to give the shape of Arcada's logo. It is 10 mm deep. The bar elongated is the handle for the EDM to hold on to. It is 13 mm in diameter.

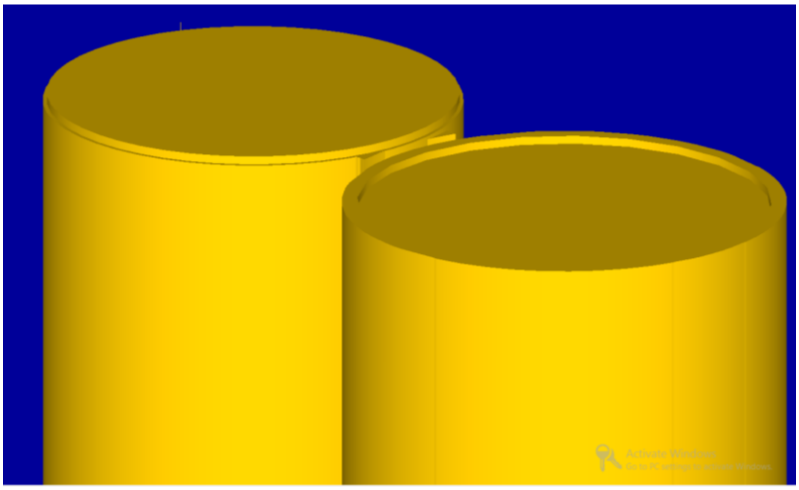


Figure 20: Finished cap and cavity electrode

These two electrodes in figure 20 are together because they are machined from one solid 50 mm x 50 mm x 50 mm metal piece. One on the left will create a cavity on the mould to create the cap for the. The electrode on the right will create a core. Moulds are then used in injection moulding machine to create sensor cavity on the key.

This electrode was milled in Arcada's lab on hard metal. The cutting parameters used for copper were as follows:

Table 5: Cutting parameters used in lab

Tool number	Tool diameter (mm)	Spindle speed (rpm)	Feed Rate (mm/min)
7	1	20000	300
15	2	4000	300
5	4	4000	250

Figure 21: Electrode milled in Arcada's lab.

6. Discussion

This chapter shall point out the discussion topic that are not explained in this thesis and are yet to be answered. Although the Electrical discharge machining process implies that electricity is conducted through the electrode and melt the chips of the work piece away, it is to be discussed how machine can be programmed to use a low melting point metal like copper (Cu) to machine higher melting point metals.

The significance of EDM is to achieve a complex shapes that regular methods cannot provide. For EDM to provide the shape, it has to have an electrode which has to be machined from some other method. Thus, the significance of EDM is very questionable and is a very important point for discussion.

The smoothness of the electrode is questionable. This affects the result for various other methods of machining. It is not the case in EDM. It is unlikely to get a smooth surface because its cutters are the series of sparks and they cannot be controlled in order to provide a smooth finished surface. Although, this provides a reasonable flexibility on the quality of the surface of the electrode, further researchers or designers could work on finding a way to discover an easier way to get smooth surface than sand papers.

7. Conclusion

From this thesis, the conclusion can be drawn that,

1. EDM is a relatively long machining process for simple designs like Arcada’s key. This process is best suited for complex shapes.
2. Although CNC machining has ability to machine as small as 1 mm diameter, the narrow corners cannot be obtained from CNC machining process.
3. Modern CNC can be adjusted so that electrode wear can be reduced to minimum. This provides the user to be more flexible on selecting the electrode material.
4. With minor variation, the electrode for EDM with Arcada University’s logo was successful designed and produced with the use of Solid Edge, MasterCAM and HAAS Milling machine. With the g-code generated from MasterCAM, now it is possible to manufacture a prototype or a useable electrode in the lab of Arcada.
5. A working electrode was created in Arcada’s lab on a cylindrical copper bar.

8. References

[1] *What is EDM (Electrical discharge machining)?* Available at http://www.wisegeek.org/what-is-edm.htm , accessed on, 12th January, 2013. {Online}

[2] *Trends in EDM* (2/15/2000 Modern Machine Shop, Harry C. Moser and Bill Boehmert) from Modern Machine Shop; Available at, http://www.mmsonline.com/articles/trends-in-edm , accessed on 12th January,2013.{Online}

[3] *Parameters affecting the quality of the electrical discharge machining process*, Published on Scientific paper, Advances in Production Engineering and Management (APEM) 5(2010) 4, 245-252 ISSN 1854-6250 by De Wolf, D*; Cardon, L.*; & Balic, J.**; Available at, http://maja.uni-mb.si/files/apem/APEM5-4_245-252.pdf, Accessed on 2nd June, 2013 {Online/pdf}

[4] *Electrical Discharge Machining* by Elman C. Jameson, SME, Jan 1, 2001, Accessed on 2nd September, 2013, {Book}

[5] *Electrical Discharge Machining* by Steve Krar; Available at, http://www.automationmag.com/images/stories/LWTech-files/91%20Electrical%20Discharge.pdf, Accessed on 2nd June, 2013 {Online/pdf}

[6*] Machinery's Handbook* (2004) 27th Edition. P. 1351-1355

[7] *Electrical Discharge Machining (The History of EDM Machining)*; Available at, http://www.edmmachining.com/history_of_edm.htm, Accessed on 2nd August, 2013. {Online}

[8] *Electrical Discharge Machine*, Image available at http://www.taiwantrade.com.tw/MAIN/en_front/searchserv.do?method=listProductProductDetail&company_id=4530&locale=2&catalog_id=77336&come_soon=0, Accessed on 2nd September, 2013 {Online}

[9*] Sinker Electrode Material Selection, EDM Today*, July/August 2008 by Roger Kern, Available at http://www.edmtodaymagazine.com/AAweb2_2010/TechTips2010/TechTips2008/TechTipsM-J-8.pdf, Accessed on 18th April, 2013 {Online/pdf}

[10*] EDM Tips-How to use electrical discharge machining* by KD Solution Co. Ltd. Available at http://www.edm.kd-solution.com/, Accessed on 3rd September, 2013.

[11] *Ram EDM Electrodes and Finishing*, Available at: http://www.reliableedm.com/Complete%20EDM%20Handbook/Complete%20EDM%20Handbook_11.pdf, Accessed on 4th September, 2013 {Online/pdf}

[12] *Feed Rate, spindle speed formula*, published at home page of Mathew Vihtonen Available at: https://people.arcada.fi/~mathew/intern/CAM/Speeds-Feeds-Tools/Speed%20&%20Feeds%20(Smid,%202003).pdf , Accessed on 8th January, 2014 {Online/pdf}

[13] *Graphite Milling, the proper way* by Shaiu-Wei Yin, IDI precisoin Machinery ltd, Available at: http://www.edmsalesinc.com/downloads/idi_precision_cvd_end_mills/736/Graphite_milling_the_proper_way.pdf , Accessed on 15th January, 2014 {Online/pdf}

[14]*Machining graphite and carbon, SubsTech(Substance & technology), Knowledge Source on Material Engineering*, Available at: http://www.substech.com/dokuwiki/doku.php?id=machining_graphite_and_carbon , Accessed on 15th January, 2014 {Online/pdf}

[15]*Spindle speed and feed rate calculator (mill & drill)_1.xls*, Downloaded from home page of Erland Nyroth. Available at: https://people.arcada.fi/~nyrothe/intern/HAAS/ , Accessed on 4th March, 2014 {Online}

[16]*List of tools available at Arcada's lab*. Downloaded from home page of Erland Nyroth. Available at: https://people.arcada.fi/~nyrothe/intern/HAAS/ , Accessed on 4th March, 2014 {Online}

[16] *SFM and FTP*, Miscellaneous HST Improvements (Mill), Available at: http://www.mastercam.pl/Whatsnew/WhatsnewX2MR2.pdf, Accssed on 11th March, 2014 {Online/pdf}

9. Appendix

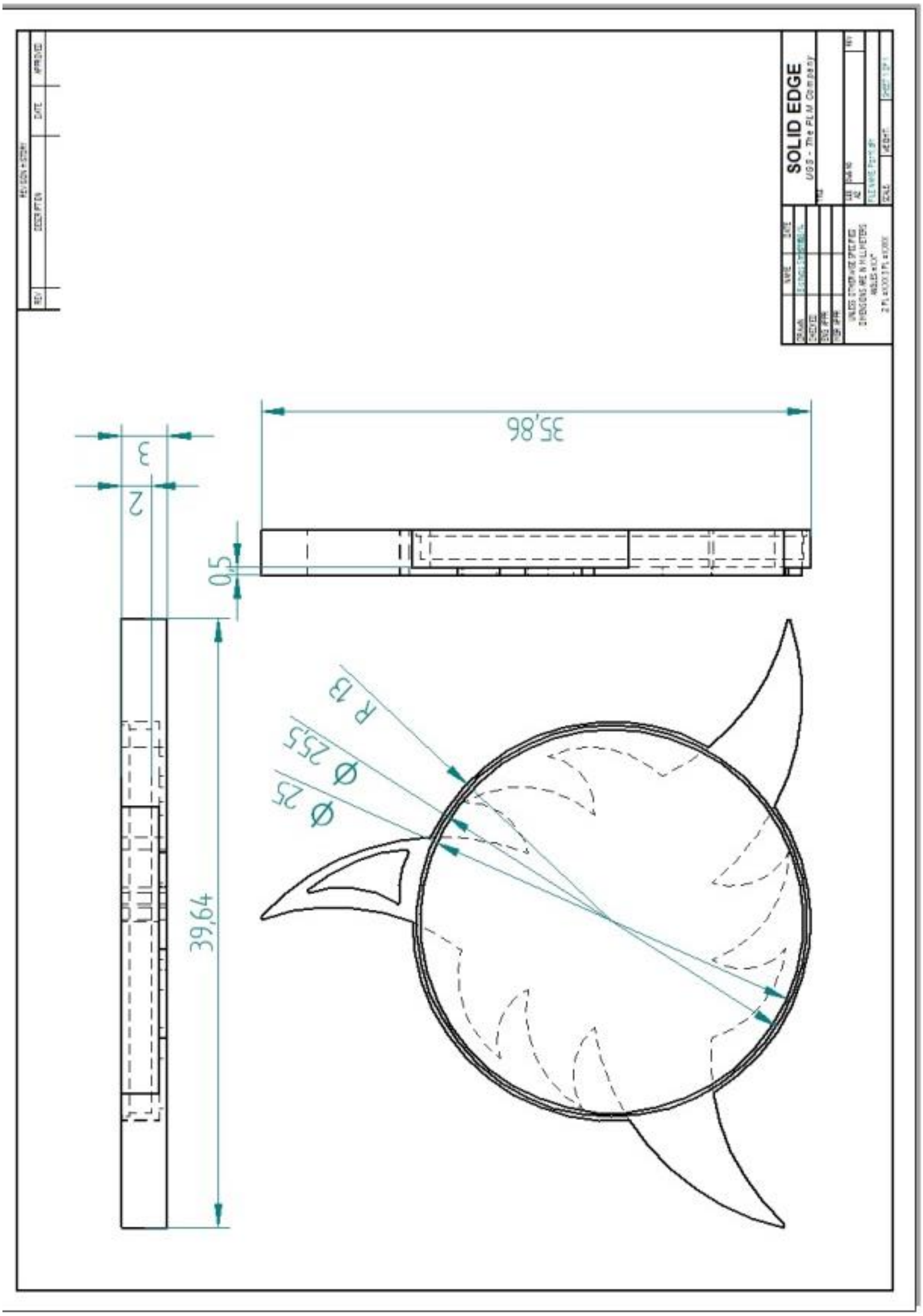


Figure 22: Draft of the key

Table 6: List of tools at Arcada[16]

T	D(mm)	Type	Material	Number of teeth (n)	Machining in Z axis	r/min	**Z - offset**
1	**80**	ShM	HM	5	No		-78,878
2	**50**	ShM	HM	5	No		-93,560
3	**25**	ShM	HM	2	No		-29,223
4	**20**	ShM	HSS Only for Al	2 +1	Y	3000	-69,020
5	**4**	EM	HSS	2	Y	3000	4,000
6	**10**	SP	HSS	2	**Y**		-62,716
7	**6**	EM/HS	HM	2	Y		8,761
8	**10**	E M	HSS	2	Y		-68,074
9	**16**	E M	HSS	3	(50) Y		-60,825
10	**10**	EM	HSS	3	Y		-65,674
11	**16**	EM/AL	HSS	3	(48) Y		-56,067
12	**3** / 8	Center drill	HSS	2	Y		-96,228
13	**10**	**TM/ 15 °**	HSS	4	Y	3000	11,345
14	**10**	EM	**HM**	3	(short) Y		-90,133
15	**2**	EM	HM	2	Y		-78,413
16	**16**	SP	HSS	2	(long) Y		38,531

Shell **M**ill = **ShM**
Mill = **EM**
High **S**pindle ratio **5 = HS**

HSS or CARBIDE
Taper **M**ill **x** ° **= TM**

Spherical = SP **E**nd
HM = Hard Metal

9.1.G-Code for Key

```
%
O1234(PART1)
(MATERIAL - ALUMINUM MM - 2024)
( T210 |     1. FLAT ENDMILL | H210 )
( T15 |     2. FLAT ENDMILL | H15 | XY STOCK TO LEAVE - .5 | Z STOCK TO
LEAVE - 0. )
( T5 |     4. FLAT ENDMILL | H5 )
N100 G21
N102 G0 G17 G40 G49 G80 G90
N104 T210 M6
N106 G0 G90 G54 X-10.813 Y15.175 A0. S20000 M3
N108 G43 H210 Z25.
N110 Z10.
N112 G1 Z-.597 F238.7
N114 X-9.881 Y15.537 F4000.
N116 G2 X-9.519 Y15.605 I.362 J-.933
N118 X-8.587 Y14.966 I0. J-1.001
N120 X-7.641 Y9.908 I-13.043 J-5.058
N122 X-7.68 Y8.865 I-13.989 J0.
N124 G3 X-12.544 Y2.776 I2.365 J-6.876
N126 X-12.547 Y2.722 I.497 J-.054
N128 X-12.047 Y2.222 I.5 J0.
N130 X-11.657 Y2.409 I0. J.5
N132 G2 X-9.271 Y3.554 I2.386 J-1.913
N134 X-8.427 Y3.435 I0. J-3.058
N136 G3 X-12.718 Y-3.559 I3.554 J-6.994
N138 X-12.218 Y-4.059 I.5 J0.
N140 X-11.78 Y-3.8 I0. J.5
N142 G2 X-8.496 Y-1.857 I3.284 J-1.803
N144 X-8.339 Y-1.86 I0. J-3.746
N146 G3 X-13.602 Y-13.863 I11.057 J-12.003
N148 X-12.814 Y-18.872 I16.32 J0.
N150 X-12.243 Y-19.288 I.571 J.184
N152 X-11.656 Y-18.813 I0. J.6
N154 G2 X-4.044 Y-9.116 I13.684 J-2.906
N156 G3 X.729 Y-10.902 I4.773 J5.485
N158 X3.661 Y-10.284 I0. J7.271
N160 G1 X3.795 Y-10.197
N162 X3.895 Y-10.072
N164 X3.95 Y-9.922
N166 X3.955 Y-9.762
N168 X3.909 Y-9.609
N170 X3.817 Y-9.478
N172 X3.688 Y-9.383
N174 X3.536 Y-9.332
N176 G2 X1.033 Y-7.048 I.464 J3.022
N178 G3 X5.313 Y-8.318 I4.28 J6.575
N180 X9.235 Y-7.267 I0. J7.845
N182 X9.485 Y-6.834 I-.25 J.433
N184 X8.985 Y-6.334 I-.5 J0.
N186 G1 X8.974
N188 G2 X8.894 Y-6.335 I-.08 J3.745
```

```
N190 X5.573 Y-4.324 I0. J3.746
N192 G3 X10.441 Y-5.067 I4.868 J15.576
N194 X22.53 Y.29 I0. J16.319
N196 X22.685 Y.693 I-.445 J.403
N198 X22.085 Y1.293 I-.6 J0.
N200 X21.886 Y1.259 I0. J-.6
N202 G2 X17.474 Y.504 I-4.412 J12.516
N204 X9.708 Y3.014 I0. J13.271
N206 G3 X9.843 Y4.408 I-7.149 J1.394
N208 X6.87 Y10.28 I-7.284 J0.
N210 X6.574 Y10.377 I-.296 J-.403
N212 X6.074 Y9.877 I0. J-.5
N214 X6.108 Y9.695 I.5 J0.
N216 G2 X6.316 Y8.586 I-2.85 J-1.109
N218 X5.381 Y6.385 I-3.058 J0.
N220 G3 X5.392 Y6.805 I-7.834 J.42
N222 X1.47 Y13.599 I-7.845 J0.
N224 X1.22 Y13.666 I-.25 J-.433
N226 X.72 Y13.166 I0. J-.5
N228 X.792 Y12.906 I.5 J0.
N230 G2 X1.335 Y10.964 I-3.203 J-1.942
N232 X.752 Y8.956 I-3.746 J0.
N234 G3 X-11.744 Y21.338 I-15.924 J-3.573
N236 X-11.87 Y21.351 I-.126 J-.587
N238 X-12.47 Y20.751 I0. J-.6
N240 X-12.271 Y20.306 I.6 J0.
N242 G2 X-8.587 Y14.966 I-9.359 J-10.398
N244 X-8.519 Y14.604 I-.932 J-.362
N246 X-9.158 Y13.672 I-1. J0.
N248 G1 X-10.09 Y13.31
N250 G0 Z25.
N252 M5
N254 G91 G28 Z0.
N256 A0.
N258 M01
N260 T15 M6
N262 G0 G90 G54 X-14.669 Y15.937 A0. S3000 M3
N264 G43 H15 Z25.
N266 Z10.
N268 G1 Z-10.097 F238.7
N270 X-12.909 Y16.887 F800.
N272 G2 X-11.959 Y17.127 I.95 J-1.76
N274 X-10.199 Y16.077 I0. J-2.
N276 X-8.969 Y12.811 I-11.431 J-6.169
N278 G3 X-15.168 Y.913 I8.319 J-11.898
N280 X-13.035 Y-6.664 I14.518 J0.
N282 X-14.602 Y-13.863 I15.753 J-7.199
N284 X-13.766 Y-19.179 I17.32 J0.
N286 X-12.243 Y-20.288 I1.523 J.491
N288 X-10.678 Y-19.02 I0. J1.6
N290 G2 X-6.825 Y-12.214 I12.706 J-2.699
N292 G3 X-.672 Y-13.585 I6.153 J13.119
N294 X12.073 Y-5.99 I0. J14.49
N296 X23.27 Y-.382 I-1.632 J17.242
```

```
N298 X23.685 Y.693 I-1.185 J1.075
N300 X22.085 Y2.293 I-1.6 J0.
N302 X21.553 Y2.202 I0. J-1.6
N304 G2 X17.474 Y1.504 I-4.079 J11.573
N306 X13.778 Y2.074 I0. J12.271
N308 G3 X-.672 Y15.419 I-14.45 J-1.151
N310 X-1.053 Y15.414 I0. J-14.496
N312 X-11.534 Y22.316 I-14.119 J-10.031
N314 X-11.87 Y22.352 I-.336 J-1.565
N316 X-13.471 Y20.751 I0. J-1.601
N318 X-12.94 Y19.562 I1.601 J0.
N320 G2 X-10.199 Y16.077 I-8.69 J-9.654
N322 X-9.959 Y15.127 I-1.76 J-.95
N324 X-11.009 Y13.367 I-2. J0.
N326 G1 X-12.769 Y12.417
N328 G0 Z25.
N330 M5
N332 G91 G28 Z0.
N334 A0.
N336 M01
N338 T5 M6
N340 G0 G90 G54 X-.66 Y-32.482 A0. S3000 M3
N342 G43 H5 Z25.
N344 Z10.
N346 G1 Z-40.097 F119.3
N348 X-.665 Y-22.482 F1000.
N350 X-.672 Y-8.595
N352 G3 X8.828 Y.905 I0. J9.5
N354 X-.672 Y10.405 I-9.5 J0.
N356 X-10.172 Y.905 I0. J-9.5
N358 X-.672 Y-8.595 I9.5 J0.
N360 G2 X-10.172 Y.905 I0. J9.5
N362 X-.672 Y10.405 I9.5 J0.
N364 X2.109 Y9.988 I0. J-9.5
N366 G1 X3.894 Y21.918
N368 X3.975
N370 X.963
N372 X.934
N374 X-2.197 Y22.318
N376 X-5.328 Y21.918
N378 X-5.486 Y9.095
N380 G3 X-10.172 Y.905 I4.814 J-8.19
N382 X-5.685 Y-7.165 I9.5 J0.
N384 G1 X-5.834 Y-19.282
N386 X-9.693 Y-18.082
N388 X-12.629 Y-16.482
N390 X-15.983 Y-13.682
N392 X-19.332 Y-8.882
N394 X-20.58 Y-6.082
N396 X-21.781 Y-.082
N398 X-21.395 Y4.718
N400 X-19.97 Y9.518
N402 X-17.035 Y14.318
N404 X-14.435 Y16.718
```

```
N406 X-9.263 Y19.918
N408 X8.233
N410 X11.247 Y18.318
N412 X14.618 Y15.518
N414 X16.988 Y12.318
N416 X19.063 Y8.318
N418 X20.397 Y2.318
N420 X20.294 Y-1.282
N422 X19.202 Y-6.082
N424 X16.616 Y-11.282
N426 X12.669 Y-15.282
N428 X8.927 Y-17.682
N430 X4.49 Y-19.282
N432 X-5.834
N434 X-4.939 Y-16.482
N436 X-9.209 Y-15.282
N438 X-14.042 Y-12.082
N440 X-18.012 Y-6.082
N442 X-19.37 Y.718
N444 X-18.283 Y7.118
N446 X-15.069 Y12.718
N448 X-11.415 Y15.918
N450 X-7.796 Y17.518
N452 X6.546
N454 X7.814 Y17.118
N456 X12.673 Y13.918
N458 X16.657 Y7.918
N460 X18.026 Y1.118
N462 X16.949 Y-5.282
N464 X13.748 Y-10.882
N466 X9.649 Y-14.482
N468 X3.595 Y-16.482
N470 X-4.939
N472 X-4.045 Y-13.682
N474 X-8.019 Y-12.482
N476 X-11.947 Y-9.682
N478 X-15.048 Y-4.882
N480 X-16.17 Y.718
N482 X-15.319 Y5.918
N484 X-12.575 Y10.718
N486 X-8.848 Y13.918
N488 X-5.419 Y15.118
N490 X4.075
N492 X6.612 Y14.318
N494 X10.579 Y11.518
N496 X13.693 Y6.718
N498 X14.826 Y1.118
N500 X13.858 Y-4.482
N502 X11.254 Y-8.882
N504 X7.555 Y-12.082
N506 X2.701 Y-13.682
N508 X-4.045
N510 X-3.15 Y-10.882
N512 X-6.804 Y-9.682
```

```
N514 X-9.852 Y-7.282
N516 X-12.084 Y-3.682
N518 X-12.97 Y.718
N520 X-12.228 Y5.118
N522 X-9.828 Y9.118
N524 X-6.753 Y11.518
N526 X-2.949 Y12.718
N528 X1.605
N530 X5.409 Y11.518
N532 X8.484 Y9.118
N534 X10.729 Y5.518
N536 X11.626 Y1.118
N538 X10.894 Y-3.282
N540 X8.508 Y-7.282
N542 X5.46 Y-9.682
N544 X1.806 Y-10.882
N546 X-3.15
N548 X-.677 Y-22.482
N550 G3 X22.723 Y.918 I0. J23.4
N552 X-.677 Y24.318 I-23.4 J0.
N554 X-24.077 Y.918 I0. J-23.4
N556 X-.677 Y-22.482 I23.4 J0.
N558 G0 Z-15.097
N560 Z10.
N562 X3.323 Y17.318
N564 G1 Z-40.097 F119.3
N566 Y21.318 F1000.
N568 G3 X-.677 Y25.318 I-4. J0.
N570 X-25.077 Y.918 I0. J-24.4
N572 X-.677 Y-23.482 I24.4 J0.
N574 X23.723 Y.918 I0. J24.4
N576 X-.677 Y25.318 I-24.4 J0.
N578 X-4.677 Y21.318 I0. J-4.
N580 G1 Y17.318
N582 G0 Z-15.097
N584 Z10.
N586 X-4.672 Y17.405
N588 G1 Z-40.097 F119.3
N590 Y13.405 F1000.
N592 G3 X-.672 Y9.405 I4. J0.
N594 G2 X7.828 Y.905 I0. J-8.5
N596 X-.672 Y-7.595 I-8.5 J0.
N598 X-9.172 Y.905 I0. J8.5
N600 X-.672 Y9.405 I8.5 J0.
N602 G3 X3.328 Y13.405 I0. J4.
N604 G1 Y17.405
N606 G0 Y17.404 Z25.
N608 Y17.405
N610 M5
N612 G91 G28 Z0.
N614 G28 X0. Y0. A0.
N616 M30
%
```

9.2.G-Code for Cap and Cavity

```
%
O1234(G-CODE FOR CAP AND CAVITY)
( T213 |     4. FLAT ENDMILL | H213 )
( T210 |     1. FLAT ENDMILL | H210 )
N100 G21
N102 G0 G17 G40 G49 G80 G90
N104 T213 M6
N106 G0 G90 G54 X-29.4 Y24.998 A0. S7000 M3
N108 G43 H213 Z25.
N110 Z10.
N112 G1 Z-.5 F119.3
N114 X29.4 F1500.
N116 G0 Z24.5
N118 X-29.4 Y22.057
N120 Z9.5
N122 G1 Z-.5 F119.3
N124 X29.4 F1500.
N126 G0 Z24.5
N128 X-29.4 Y19.116
N130 Z9.5
N132 G1 Z-.5 F119.3
N134 X29.4 F1500.
N136 G0 Z24.5
N138 X-29.4 Y16.175
N140 Z9.5
N142 G1 Z-.5 F119.3
N144 X29.4 F1500.
N146 G0 Z24.5
N148 X-29.4 Y13.234
N150 Z9.5
N152 G1 Z-.5 F119.3
N154 X29.4 F1500.
N156 G0 Z24.5
N158 X-29.4 Y10.293
N160 Z9.5
N162 G1 Z-.5 F119.3
N164 X29.4 F1500.
N166 G0 Z24.5
N168 X-29.4 Y7.352
N170 Z9.5
N172 G1 Z-.5 F119.3
N174 X29.4 F1500.
N176 G0 Z24.5
N178 X-29.4 Y4.411
N180 Z9.5
N182 G1 Z-.5 F119.3
N184 X29.4 F1500.
N186 G0 Z24.5
N188 X-29.4 Y1.47
```

```
N190 Z9.5
N192 G1 Z-.5 F119.3
N194 X29.4 F1500.
N196 G0 Z24.5
N198 X-29.4 Y-1.47
N200 Z9.5
N202 G1 Z-.5 F119.3
N204 X29.4 F1500.
N206 G0 Z24.5
N208 X-29.4 Y-4.411
N210 Z9.5
N212 G1 Z-.5 F119.3
N214 X29.4 F1500.
N216 G0 Z24.5
N218 X-29.4 Y-7.352
N220 Z9.5
N222 G1 Z-.5 F119.3
N224 X29.4 F1500.
N226 G0 Z24.5
N228 X-29.4 Y-10.293
N230 Z9.5
N232 G1 Z-.5 F119.3
N234 X29.4 F1500.
N236 G0 Z24.5
N238 X-29.4 Y-13.234
N240 Z9.5
N242 G1 Z-.5 F119.3
N244 X29.4 F1500.
N246 G0 Z24.5
N248 X-29.4 Y-16.175
N250 Z9.5
N252 G1 Z-.5 F119.3
N254 X29.4 F1500.
N256 G0 Z24.5
N258 X-29.4 Y-19.116
N260 Z9.5
N262 G1 Z-.5 F119.3
N264 X29.4 F1500.
N266 G0 Z24.5
N268 X-29.4 Y-22.057
N270 Z9.5
N272 G1 Z-.5 F119.3
N274 X29.4 F1500.
N276 Y-24.998
N278 X-29.4
N280 G0 Z24.5
N282 M5
N284 G91 G28 Z0.
N286 A0.
N288 M01
N290 T210 M6
N292 G0 G90 G54 X-25. Y11. A0. S31000 M3
N294 G43 H210 Z25.
N296 Z10.
```

```
N298 G1 Z-2. F477.4
N300 X-24. F6000.
N302 G2 X-23. Y10. I0. J-1.
N304 G3 X-10. Y-3. I13. J0.
N306 X3. Y10. I0. J13.
N308 X-10. Y23. I-13. J0.
N310 X-23. Y10. I0. J-13.
N312 G2 X-24. Y9. I-1. J0.
N314 G1 X-25.
N316 G0 Z25.
N318 X-25.25 Y11.
N320 Z10.
N322 G1 Z-50. F477.4
N324 X-24.25 F6000.
N326 G2 X-23.25 Y10. I0. J-1.
N328 G3 X-10. Y-3.25 I13.25 J0.
N330 X3.25 Y10. I0. J13.25
N332 X-10. Y23.25 I-13.25 J0.
N334 X-23.25 Y10. I0. J-13.25
N336 G2 X-24.25 Y9. I-1. J0.
N338 G1 X-25.25
N340 G0 Z25.
N342 M5
N344 G91 G28 Z0.
N346 A0.
N348 M01
N350 T213 M6
N352 G0 G90 G54 X9.959 Y-18.25 A0. S7000 M3
N354 G43 H213 Z25.
N356 Z10.
N358 G1 Z-1. F119.3
N360 X10.041 F1500.
N362 G3 X16.149 Y-15.5 I-.041 J8.25
N364 G1 X3.851
N366 G2 X2.222 Y-12.75 I6.149 J5.5
N368 G1 X17.778
N370 G3 X18.25 Y-10. I-7.778 J2.75
N372 G1 X1.75
N374 G2 X2.222 Y-7.25 I8.25 J0.
N376 G1 X17.778
N378 G3 X16.149 Y-4.5 I-7.778 J-2.75
N380 G1 X3.851
N382 G2 X9.959 Y-1.75 I6.149 J-5.5
N384 G1 X10.041
N386 G0 Z24.
N388 X7.25 Y-6.
N390 Z10.
N392 G1 Z-1. F119.3
N394 X3.25 F1500.
N396 G3 X-.75 Y-10. I0. J-4.
N398 X10. Y-20.75 I10.75 J0.
N400 X20.75 Y-10. I0. J10.75
N402 X10. Y.75 I-10.75 J0.
N404 X-.75 Y-10. I0. J-10.75
```

```
N406 X3.25 Y-14. I4. J0.
N408 G1 X7.25
N410 G0 Z25.
N412 X10.375 Y-10.
N414 Z10.
N416 G1 Z-2. F119.3
N418 G3 X9.25 Y-8.875 I-1.125 J0. F1500.
N420 X8.125 Y-10. I0. J-1.125
N422 X10.75 Y-12.625 I2.625 J0.
N424 X13.375 Y-10. I0. J2.625
N426 X9.25 Y-5.875 I-4.125 J0.
N428 X5.125 Y-10. I0. J-4.125
N430 X10.75 Y-15.625 I5.625 J0.
N432 X16.375 Y-10. I0. J5.625
N434 X9.25 Y-2.875 I-7.125 J0.
N436 X2.125 Y-10. I0. J-7.125
N438 X3.448 Y-14.59 I8.625 J0.
N440 X10. Y-18. I6.552 J4.59
N442 X18. Y-10. I0. J8.
N444 X10. Y-2. I-8. J0.
N446 X2. Y-10. I0. J-8.
N448 X3.448 Y-14.59 I8. J0.
N450 G0 Z23.
N452 X7.5 Y-6.
N454 Z10.
N456 G1 Z-2. F119.3
N458 X3.5 F1500.
N460 G3 X-.5 Y-10. I0. J-4.
N462 X10. Y-20.5 I10.5 J0.
N464 X20.5 Y-10. I0. J10.5
N466 X10. Y.5 I-10.5 J0.
N468 X-.5 Y-10. I0. J-10.5
N470 X3.5 Y-14. I4. J0.
N472 G1 X7.5
N474 G0 Z25.
N476 M5
N478 G91 G28 Z0.
N480 A0.
N482 M01
N484 T210 M6
N486 G0 G90 G54 X-6. Y-9. A0. S31000 M3
N488 G43 H210 Z25.
N490 Z10.
N492 G1 Z-50. F119.3
N494 X-5. F6000.
N496 G2 X-4. Y-10. I0. J-1.
N498 G3 X10. Y-24. I14. J0.
N500 X24. Y-10. I0. J14.
N502 X10. Y4. I-14. J0.
N504 X-4. Y-10. I0. J-14.
N506 G2 X-5. Y-11. I-1. J0.
N508 G1 X-6.
N510 G0 Z25.
N512 M5
```

```
N514 G91 G28 Z0.
N516 G28 X0. Y0. A0.
N518 M30
%
```