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Determination of Wall Thickness and Height when Cutting Various Materials with Wire Electric Discharge Machining Processes

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DETERMINATION OF WALL THICKNESS AND HEIGHT LIMITS WHEN CUTTING VARIOUS MATERIALS WITH WIRE ELECTRIC DISCHARGE MACHINING PROCESS.

by

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GRADUATE COMMITTEE APPROVAL

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ABSTRACT

DETERMINATION OF WALL THICKNESS AND HEIGHT LIMITS

WHEN CUTTING VARIOUS METERIALS WITH WIRE

ELECTRIC DISCHARGE MACHINING

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Master of Science

This thesis looks at the capabilities of cutting thin webs on Wire EDM machines that are difficult or impossible to machine using conventional methods. Covered is an investigation of how different material and web thickness affect the capability of machining thin-walled parts.

Five different metals are used for the test; Aluminum 6061 T6, Yellow Brass SS360, 420 Stainless Steel, D2 unheat-treated tool steel 25-30 RC, and D2 heat-treated tool steel 60-65 RC. The small parts were cut to a 6mm (0.2362 inch) height with six different wall thicknesses: 0.30mm (0.0118 inch), 0.25mm (0.0098 inch), 0.20mm (0.0078 inch), 0.15mm (0.0059 inch), 0.10mm (0.0039 inch), and 0.05mm (0.0020 inch). A Sodick AQ325L Wire EDM machine was utilized for testing.

The methods employed during the study include the following:

- Machine settings and offsets were limited to the default setting selected from the Sodick AQ325L database.
- Two different pre-test cuts were taken on the material to check for web bending during the cutting process.
- Hardness was tested for comparison of the web heights.

This thesis shows that bending increased as webs became thinner and that bending occurred toward the wire as the second side of the web was cut. Bending does affect the height of the web. Physical properties of materials also impacted the height of the web with the hardest material staying intact during the cutting process. This study shows that two factors, physical properties of materials and web thickness, significantly affect cutting results for thin web parts.

ACKNOWLEDGMENTS

My dream of 30 years has finally come true. When I was 15 years old I thought that someday I would come to America and achieve this dream. I am grateful to my Heavenly Father for all the blessings He has given me and for this wonderful opportunity to be at BYU studying with wonderful professors, faculty and students. I thank all those who have been good examples to me and who have helped me.

I owe a great deal of gratitude to my beloved wife, Gyungsook, who has supported me and has been willing to sacrifice that I might attain my educational goals. This achievement is a good example for my children Dohyup, Yeagi, Yaeyoung, and Yearim. I appreciate their encouragement and support.

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Finally, I could not forget to show appreciation for those professors who served on my committee, Dr. Perry Carter and Dr. Mike Miles. They have been a big support of my efforts and have been so kind to me.

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CHAPTER 1

INTRODUCTION

Electrical Discharge Machining (EDM) uses thermal energy to achieve a high-precision metal removal process from a fine, accurately controlled electrical discharge. It is classified as a non-traditional machining process that does not cause friction between the workpiece and the tool. It cuts material without traditional cutting tools, similar to water jet cutting or laser cutting. EDM is commonly used for very hard, tough materials which have poor machineability. Materials may include tool steels and carbides. It is used to produce features such as complex shapes and small diameter holes, which are difficult or impossible to machine using conventional methods. Because EDM uses an electric discharge to cut the material, its use is limited to conductive materials (Mundt, 1998).

There are several EDM processes such as Wire Electrical Discharge Machining, Electrical Discharge Milling, Electrical Discharge Grinding (EDG), Electrical Discharge Dressing (EDD), Ultrasonic Aided EDM (UEDM), Abrasive Electrical Discharge Grinding (AEDG), Micro Electrical Discharge Machining (MEDM), Micro Wire EDM (MWEDM), Mole EDM, and Double Rotating Electrodes EDM (Brink, 1999). The focus of this thesis is on Wire Electrical Discharge Machining (WEDM) which is the process of removing materials by electrical discharge erosion action with a wire electrode traveling longitudinally through the workpiece.

The control of the spark erosion path is stabilized by a dielectric fluid (deionized water), which is forced into the cutting gap to flush out the eroded metal. When the current starts to flow to the workpiece (on switch), heat builds up in the cutting zone, and particles of metal become molten. When the voltage drops to zero (off switch), the molten particles are flushed away by the dielectric fluid. There is virtually no cutting force on the part of the machine because the wire electrode and workpiece never make contact (Kohkonen, 2001).

Although a tremendous advancement in WEDM technology has been made recently through the collective efforts of many dedicated engineers and researchers from some of the world's leading institutions and research centers, no research was found on cutting very thin webs. WEDM machines can cut very thin parts and delicate parts, but cannot cut extremely thin parts without encountering some types of problems. Early experiments found when cutting parts less than 0.25mm (0.010 inch) thick, bending of the web occurred and consequently its resulting length varied in height.

1.1 PROBLEM STATEMENT

WEDM is a rapidly-growing machining method used for cutting high-precision metallic parts from hard materials. However, it is a challenge to cut small precision parts from a variety of materials, especially when cutting very thin parts. What factors affect the cutting of thin-walled parts?

However, there is very little information available regarding the cutting of small parts less than 125mm (5.00 inch) square and with a less than 1.5mm (0.060 inch) wall or part thickness (Kohkonen, 2001). Thus, research is needed on cutting very thin parts using different materials. Problems that occur during thin part cutting of different materials could be caused by material properties and the web thickness.

The primary objective of this study is to determine how different materials and web thicknesses affect the capability of cutting thin walled parts. Web heights to be compared include: (a) the height of small parts of five different metals, and (b) the height of 6 different web thicknesses. Figure 1.1 shows the Sodick AQ325L WEDM machine which is used for cutting during each of the experiments.

Figure 1.1 Sodick AQ325L

1.2 THESIS STATEMENT AND HYPOTHESIS

To state in the form of a null hypothesis, the hypothetical proposition for this study is that there is no significant difference of WEDM cutting performance when using a WEDM, when utilizing and varying the number of programmed passes using rough pass only, rough and one skim pass, and rough and three skim passes. Figure 1.2 shows the workpiece to be used for each experiment with the designed web thickness to be cut on the Sodick.

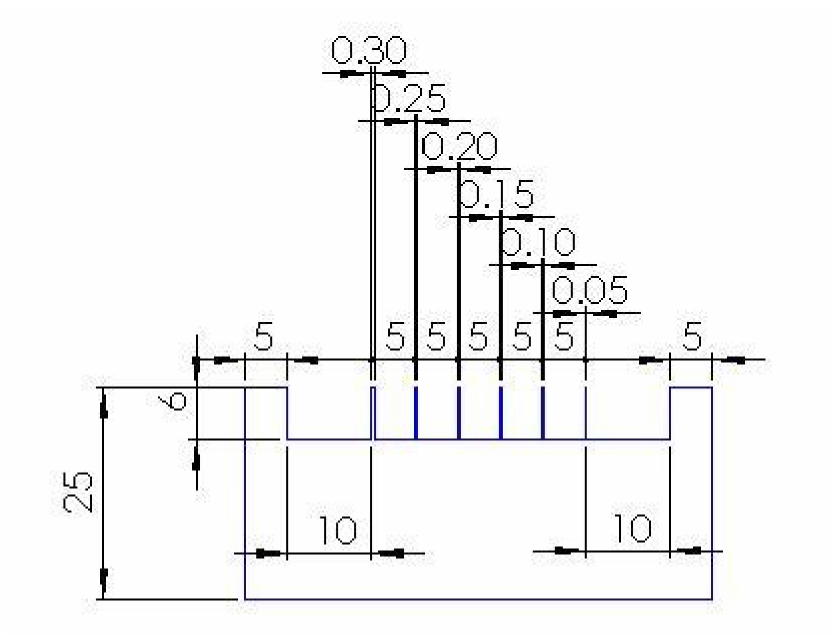


Figure 1.2 The designed web thickness (units: mm)

More specifically, the following hypotheses are tested in the study.

H1: There are no significant differences in the height of the cutting webs as the thickness becomes smaller.

H2: There are no significant differences in height of the cutting webs for different metals.

1.3 JUSTIFICATION

This thesis investigates the height of the remnant web parts for five different materials during WEDM cutting. Because the cutting procedure of a WEDM uses spark erosion, it becomes possible to cut thin-walled parts with less than 0.30 mm (0.012 inch) wall thickness. Using the cutting procedure of one rough pass and three secondary or skim passes, precision in thin wall workpieces can be achieved.

The result of the thesis will enhance the information available on the effect of varying material types and properties in the cutting of thin-walled parts, and will give product designers more accurate estimates to design small parts that can be cut with the WEDM. This thesis also shows the effects of spark erosion heat and web bending on tab height and thickness.

1.4 DELIMITATIONS

The Sodick AQ325L WEDM machine will be utilized to carry out all experimentation. Metals to be tested include Aluminum 6061 T6, Yellow Brass SS360, 420 Stainless Steel, D2 unheat-treated tool steel 25-30 RC, and D2 heat-treated tool steel 60-65 RC. Workpieces will have dimensions of 25mm (0.9843 inch) × 25mm (0.9843 inch) × 55mm (0.9843 inch). The small webs will be cut to a height of 6mm

(0.2362 inch) with six different wall thicknesses. Wall thicknesses will include 0.30mm (0.0118 inch), 0.25mm (0.0098 inch), 0.20mm (0.0078 inch), 0.15mm (0.0059 inch), 0.10mm (0.0039 inch), and 0.05mm (0.0020 inch). The electrode to be used in the Sodick AQ325L is an Intech Super Brass 900 wire with a 0.25mm (0.010 inch) diameter. To make this study more applicable to everyday use of a WEDM, this study will use the preset power and offset parameters of the Sodick WEDM most commonly used.

The study is limited to the use of 0.25 mm (0.01 inch) diameter wire. Smaller diameter wires may have different effects on the results and due to the limitations on time will not be included in this study. The machined parts will be measured with a Starret HB 400 Optical Measuring Machine and precision digital calipers.

1. 5 DEFINITION OF TERMS

Accuracy – Degree of conformity to a specification.

Arc – The flow of electricity across the gap between the electrodes and the workpiece.

Arc Gap – The space between the electrode and the workpiece where EDM occurs.

Contamination – Particles and debris found in the dielectric fluid that reduces its effectiveness.

CTE – Coefficient of Thermal Expansion

Discharge – Controlled flow of current across a gap causing a spark.

Deionization – Process of removing ions.

Deionized Water – Water that has had the ions removed.

Dielectric Fluid – A liquid of low conductivity, which acts as a coolant to solidify particles and then flushes them out of the working gap.

Dielectric System – Dielectric liquid is circulated to remove contamination and control debris size in the working gap during machining. This system is composed of a pump, filter, hoses, tank, and gauges.

EDM – Acronym for Electrical Discharge Machine or Electrical Discharge Machining. EDM is a process for eroding and removing material by transient action of electric spark on electrically conductive materials.

Electrode – Electrically conductive tool used to carry current to the workpiece material.

Electrode Wear – The amount of electrode material consumed during the EDM process.

Heat Affected Zone – A shallow layer in the workpiece that has been thermally affected by the arc, which changes its properties.

Ionization – Occurs when the dielectric fluid becomes conductive after being subjected to high voltage.

Material Removal Rate – The volume of workpiece that is removed in a given unit of time (e.g., cubic inches per hour).

Parallelism – Running in the same direction in an equal and consistent manner.

Precision – Consistency of results in repeated experiments.

Pulse Generator – Creates a surge of electrical current.

RMS – Roughness is indicated by the root-mean-square (RMS) average, which is the square root of the average value squared, of a series of measurements of deviations from the roughness centerline.

Skim - to remove form the surface, trim

Start Hole – Predrilled opening in workpiece that provides a location to thread wire.

Speed – The advance rate of the workpiece perpendicular to the wire, measured in inches per minute.

Tab - A small insert, addition, or remnant; Web

Tensile Strength – The maximum engineering stress in tension, which may be sustained without fracture; often termed ultimate (tensile) strength.

Thermal Conductivity – For steady-state heat flow, the proportionality constant between the heat flux and the temperature gradient. Also, a parameter characterizing the ability of a material to conduct heat.

Tolerance – The permissible deviation from an ideal.

WEDM – An EDM process wherein the electrode is a wire that cuts through the workpiece and is renewed constantly to avoid rupture.

Web - A thin metal sheet, plate, or strip; Tab

Workpiece – Material being formed into a part.

Working Gap – The gap between the electrode and the workpiece.

CHAPTER 2

BACKGROUND AND REVIEW OF LITERATURE

A literature review was conducted to gain knowledge about the wire EDM process and previous research in the area of the materials most often used. There were a lot of articles about EDM, but very few about small part cutting that directly relate to this research. A background review of literature pertaining to this study includes a search of holdings in the Harold B. Lee Library at Brigham Young University in Provo, Utah, the Compendex Engineering Database, Techstreet Standard Documentation Database, and the Academic Search Elite (EBSCO) database. Several articles were also obtained through Interlibrary Loan.

In addition to the literature search done at the library, information for this study was gathered from Internet searches, interviews with Professor Kent Kohkonen, and EDM expert Dean Brink of the EDM Technology Transfer Office. Internet sources utilized for this research include EDM machine companies, EDMTT, and the Sommer websites. The *Wire EDM Handbook* by Carl Sommer and Steve Sommer, and several articles from *EDM Magazine* also provided insightful knowledge.

Even though the majority of existing research on WEDM does not directly relate to this project, many articles with peripheral information will aid the reader in understanding this research and are reviewed for this study. The literature review will include six areas: (a) WEDM process, (b) surface finish, (c) cutting speed, (d) accuracy, (e) multiple passes, and (f) materials as they related to the machining performance of cutting small parts.

2.1 WEDM PROCESS

WEDM is a process for eroding and removing material using the heat created by a transient action of electric sparks between electrically conductive materials. This process is achieved by applying consecutive spark discharges between a workpiece and an electrode immersed in a dielectric liquid and separated by a small gap. Eroded particles are then flushed away by the dielectric fluid. The result of this process is that each discharge leaves a small crater on both the workpiece and the electrode. This crater affects final surface quality.

WEDM has greatly improved the tooling and manufacturing industry, resulting in dramatic improvements in accuracy, quality, and productivity. Today's WEDM equipment uses advanced Computer Numerical Control (CNC) to improve efficiency and accuracy. "In 1969, the Swiss firm Agie produced the world's first industrial path-controlled electrical discharge cutting machine. The first machines were extremely slow. In the early 70s a typical machine cut two square inches per hour, in the early 80s, six square inches per hour, and some WEDM manufacturers claim nearly 193.5 square centimeters (30 square inches) per hour. Some of the machines are accurate up to ± 0.005 mm (± 0.0002 inch) and producing surface finishes to 15 RMS and lower. Today's high-speed WEDM machines have become so efficient that they have revolutionized many machining procedures" (Sommer, 2000).

2.1.1 EDM Wire

EDM wire is used as the electrode to generate spark erosion between the wire and the workpiece. The wire transfers electric energy to the material for sublimation and is constantly unspoiled or is constantly moving through the material at a given rate in order to prevent wire rupture. It affects cutting speed, surface quality, and wire shortcut (Mundt, 2002).

Many types of electrically conductive materials are suitable for use as electrode wires. Generally three types of EDM wire are used, such as single component, thin layer composite and thick layer composite. The materials of the wire include copper, brass, bronze, steel, tungsten, molybdenum, and composites of those materials with steel and graphite.

The ideal wire electrode for WEDM will have a relatively thick surface layer with a low volumetric heat of sublimation, a high electrical conductivity, high tensile strength, and high fracture toughness (Tolman, D., 1999).

Brass is an alloy of copper and zinc. Generally, the higher the zinc percentage, the better the wire is for EDM. However, if the zinc concentration is too great, the wire may become difficult to fabricate consistently. The optimum balance between copper and zinc is an alloy in the range of 35–37% zinc and 63–65% copper. Depending on how the brass wire is annealed in manufacturing, different strengths or tempered properties can be built into the wire (EDM wire, 2005).

For this reason INTECH EDM SuperBrass 900 will be used on the WEDM machine, which has ∅ 0.25 mm (∅ 0.01 in), Cu 63% and Zn 37%, 1% elongation, and 900 N/mm^2 tensile strength.

2.1.2 Spark Generator

One of the central elements of any spark erosion machine is the generator, which supplies the necessary working energy. The spark generator has the function voltage values with the relevant waveforms required for the erosion process and controls the erosion gap. It is extremely important for the gap between the wheel electrode and the workpiece to be kept constant. In order to achieve the required surface finish values, the gap should be kept as small as possible. Currently, the computer-aided spark generators are used to control the spark.

The sparks produced by the spark generator at regular intervals create a succession of craters in the workpiece. Each spark produces a temperature between 8,000 and 12,000° C. The size of the crater depends on the energy turned out by the spark generator. The range of the sparks varies from a few microns to 1 mm (EDM principles, 2004).

2.1.3 Servo System/Linear Motor

To begin an EDM cut, the workpiece is placed in the EDM machine and then submerged in a dielectric fluid. The servo system brings the electrode down toward the workpiece. When the gap between the electrode and the workpiece is only a couple thousandths of an inch away, an electric field produced by the power supply punctures the water and electrical pulses start to flow. Both the electrode and workpiece are eroded during the process. After a certain time, dimensions of the electrodes will be changed considerably. The result is an increase in the gap between the electrode and the workpiece. This will increase the voltage required for sparking. Increasing the pulse voltage or decreasing the gap distance can solve this problem. Increasing the pulse voltage is not feasible since most of the electrical energy is used for overcoming breaking strength and producing plasma in dielectric liquid rather than machining. The gap, therefore, should be maintained constant during the process. This can be achieved by a servo system that maintains a movement of the electrode toward the workpiece at such a speed that the working gap and sparking voltage remain unaltered.

The servo system automatically positions the electrode just the right distance from the workpiece to maintain the proper gap during the EDM process. This gap is normally 0.0127mm (0.0005 inch) to 1.27mm (0.05 inch), depending on the main parameters. As the electrode cuts the workpiece, the servo system advances and maintains the gap. Because of the continued production of sludge in the gap, the servo system must continually adjust the gap to minimize short circuits, or DC arcs, created by the sludge particles (The Damm Company, 2003).

Sodick's linear motor technology provides instantaneous servo time, which maximizes cutting efficiency. Since there are no ball screws or couplings, backlash is totally eliminated. This provides several advantages, including improved positioning and cutting accuracy, while providing smooth and vibration-free table movement. This machine improved discharge frequencies due to the highly responsive servo system during the second-cut achieve a surface roughness of 3μmRy with only two cuts (Linear Motor, 2002).

2.1.4 Dielectric Fluid

Most WEDMs use water as dielectric fluid. Electrolysis occurs with all machines that use water as dielectric fluid. This phenomenon causes metallurgical changes in the surfaces machined, which can reduce the life of dies and punches made by wire EDMs.

The electrolysis effect is proportional to the conductivity of the water (i.e., its ion content). The ions may be invisible, but they make their presence felt by increasing the solution's electrical conductivity. That's why water must be deionized to ensure it contains as few ions as possible (Dewarrat, 1993).

The dielectric water must also provide the optimum conditions for the creation of an electrical field as quickly as possible in order to maintain the shield of deionized water between the wire and the workpiece. A filter is used to remove the suspended solids and a resin is used to control the electrical conductivity of the water. A cooler keeps the liquid at a constant temperature to maintain machine accuracy.

2.1.5 WEDM Applications

EDM has been called a nontraditional machining process because EDM erodes metal with electrical discharges instead of with cutting tools which form chips. It has been replacing drilling, milling, grinding, and other traditional machining operations in many industries throughout the world.

WEDM produces better surface finish and edge quality, smaller heat-affected zones, and better control of process parameters for less damage to the workpiece. Laser cutting is a much faster process, but its main problem lies in the poor profile of the cut edge and the larger heat-affected zone (Lau, W.S. and Lee, W.B., 1991).

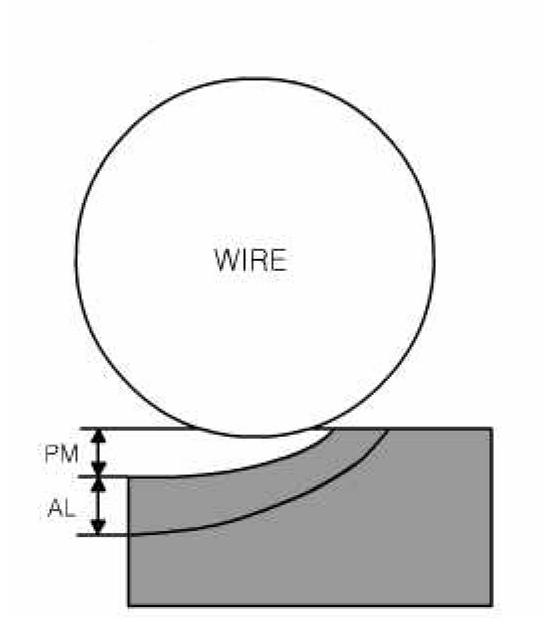
Once the capabilities of WEDM are understood, many unique applications can be created. It cuts conductive materials regardless of material hardness. It has the capability to cut very small parts to large parts with precision. It cuts gears and has revolutionized tool and die making.

2.2 SURFACE FINISH

During WEDM machining the surface of the material can be affected by many phenomena that modify the material structure. The main material defects that can be found in the affected layers are: micro cracking, cobalt depletion, redepositing of wire onto the part, recasting of melted cobalt, and water corrosion (F. Balleys and Ch. Piantchenko, 1995). These defects are caused by (a) thermal effects, (b) corrosion effects, (c) electrolysis effects, and (d) material properties.

2.2.1 Thermal Effect

When the spark occurs between electrode and the material to be cut, there is a lot of heat energy transfer to the material. Even though this is minimized by submerging the cutting processes in water, so the spark could be focused into a smaller area, the heat-affected zone still causes defects on the surface of the material. Figure 2.1 shows the removed material and affected layer thicknesses.



PM = Removed material thickness.

Al = Heat Affected layer thickness.

Figure 2.1 Removed material and affected layer thickness

The heat-affected zone of the melted material causes internal stresses, and it may be one of the main limitations on machining thin webs. This may cause some of the variation in web length from one material to the next due to the different thermal conductivity between materials.

2.2.2 Corrosion Effects

It is common knowledge that the existence of the dielectric fluid in the gap between the electrode and the workpiece is required in WEDM. The fluid acts as an insulator, provides the high-pressure flushing necessary for the removal of the molten material, and cools the gap to recover the insulating property after a discharge.

During the EDM process, corrosion effects also cause the surface defects because water is a chemical solvent. The water attacks cobalt binder. Water trapped inside micro-cracks is not deionized and will be more corrosive. It may cause varying levels of attrition depending on the material, but it will not be considered in this study.

2.2.3 Electrolysis Effects

WEDM machining is performed when a direct current pulse of anywhere from several tens to several hundreds of volts passes from the negative wire to the positive workpiece and an arc is generated across the gap. Generally, because water is used as the machining fluid, electrolysis occurs along with the processing.

Without any electrical activity, even the purest possible water contains ions in suspension. A minute proportion of water molecules split up naturally as follows:

$H_20 = H^+ + OH^-$

An electrochemical phenomenon occurs when a direct electrical current is passing through the water. This electrical current increases the amount of ions, and, under the effect of the electric field, they constantly bombard the part. Negatively charged ions will react with the machined material (F. Balleys and Ch. Piantchenko, 1995).

Electrolysis effects can be decreased with a Surface Integrity generator, which combines both antielectrolysis and surface integrity capabilities and offers a wide range of machining technologies.

2.3 CUTTING SPEED

WEDM can easily fabricate precision and complicated parts by choosing the appropriate machining conditions to effectively control the amount of removed material. Generally, cutting speed is determined by the square inches of cut per hour, and each WEDM machine made by a different company has its own cutting speed conditions according to the differences in workpiece thickness, in varying materials, and when producing sharp corners.

The conductivity and the melting properties of materials determine their cutting speed. Aluminum cuts much faster than steel because it is a better conductor and has a lower melting temperature than steel. Carbide, on the other hand, is a non-conductor. The binder, which is often cobalt, is melted away, which causes the carbides to fall out. Carbides cut at different speeds. The size of the carbide grains and the amount and type of binder determine the cutting speed (Sommer, 2000).

2.4 ACCURACY

Machining error was not considered because the Sodick AQ325L WEDM machine is extremely accurate. The individual tool planes incorporate hardened and precision-ground centering Vee blocks and separate Z-supports. This assures position centering of each tool. A repetitive accuracy (consistency) of < 0.002 mm (0.00008 inch) is achieved (Sodick manual).

Machine settings will affect the accuracy of the cut workpiece, but the Sodick EDM pulse generator settings and tool offsets for finish passes were limited to default settings for this research.

2.5 MULTIPLE PASSES

Rough cuts produce a fine surface, but for this research a finer finish and greater accuracy are desired. To accomplish these two extra conditions will be applied to a rough cut: one skim pass and three skim passes. An experiment using a rough and two skim passes will not be necessary because it is similar to one with three skim passes. The lengths of the thin webs need to be checked after each pass to compare with a baseline of a single rough pass. Figure 2.2 shows the wire EDM cutting sequence.

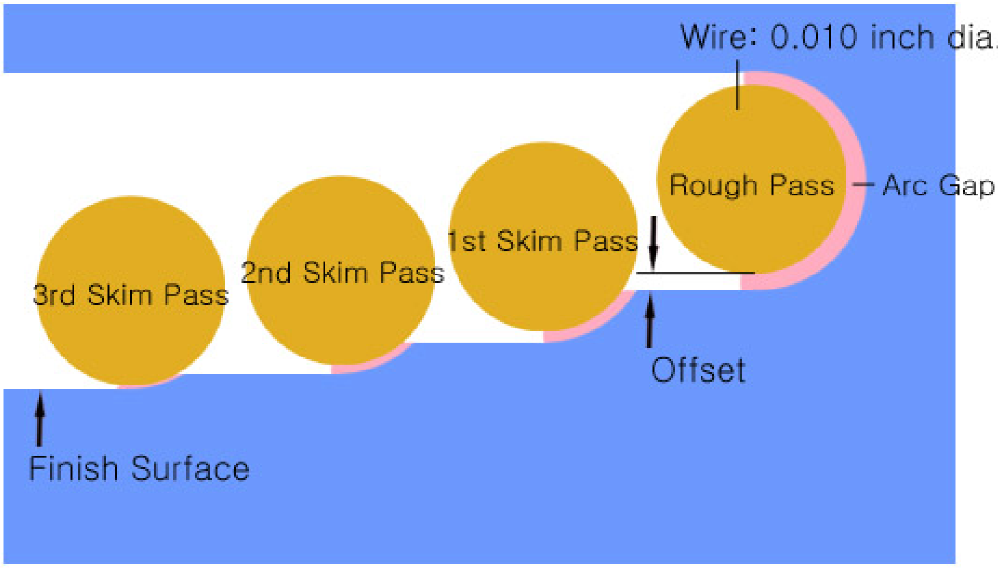


Figure 2.2 Wire EDM cutting sequence

2.6 MATERIALS

The following five different materials were used in the experiment for comparing web attrition.

1) Aluminum 6061 T6

2) Yellow Brass 360

3) 420 Stainless Steel

4) D2 unheat-treated tool steel 25-30 Rockwell

5) D2 heat-treated tool steel 60-65 Rockwell

Some of the properties of metals that are used for the experiment were found through MatWeb by using UNS numbers (Metallurgical Consultants, 2004). The UNS

("Unified Numbering System for Metals and Alloys") number is a systematic numbering scheme in which each metal is designated by a letter followed by five numbers. It is a composition-based system of commercial materials. Older nomenclature systems have been incorporated into the UNS numbering system to minimize confusion. For example, Aluminum 6061 (AA6061) becomes UNS A96061.

For this research, HRB hardness was tested and thermal conductivity, melting temperature, and CTE of each metal was found as referenced. Properties for each metal are shown in Table 2.1.

Table 2.1 Thermal conductivity, melting temperature, hardness, and CTE (Mechanical Properties Search, 2000)

	Thermal conductivity	**Melting temperature**	**Hardness**	**CTE**
Aluminum 6061 T6	167W/m-k	580-650^{0}C	Brinell 95	23.6µm/m.^{0}C
Yellow Brass SS360	123W/m-k	888^{0}C	Brinell 123	20.5µm/m.^{0}C
420 Stainless Steel	24.9W/m-k	1450-1510^{0}C	Brinell 223	10.3µm/m.^{0}C
D2 un-heat-treated tool steel	18.8W/m-k	1450^{0}C	Brinell 221	10.4µm/m.^{0}C
D2 heat-treated tool steel	18.8W/m-k	1450^{0}C	Brinell 658	10.4µm/m.^{0}C

CHAPTER 3

METHOD AND PROCEDURES

The following six sections describe the experimental method. The six sections are: (a) part design, (b) tested materials, (c) machine setting and cutting programs, (d) cutting condition and offset, (e) test procedure, and (f) test cut.

As mentioned in the previous chapter, WEDM is known as a precision process to cut conductive materials with the absence of shearing forces between the electrode and the material. The experiment was accomplished on a Sodick AQ325L WEDM machine with small parts. The web thickness of each part tab was confined to six different thicknesses measuring the width and the heights of each of the webs. Workpieces were limited to five different metals, Aluminum 6061 T6, Yellow Brass 360, 420 Stainless Steel, D2 unheat-treated tool steel 25-30 Rockwell C, and D2 heat-treated tool steel 60-65 Rockwell C. Test cuts determined the effects of spark erosion heat on web height and thickness for each of the five different materials.

The Sodick EDM pulse generator settings and tool offsets for finish passes were limited to the default settings in the database of the Sodick AQ325L. The electrode used was Intech Super Brass 900 wire with a 0.25mm (0.010 inch) diameter. Thermal conductivity, melting temperature, heat treatment, and CTE of each metal were considered using Internet searches and handbooks.

3.1 PART DESIGN

For this study, 55 mm (2 inch) × 25 mm (1 inch) × 25 mm (1 inch) hexahedron shape was used for each metal as shown in Figure 3.1. Six mm of the workpiece were cut from the top and the bottom part was used for holding the part during the cutting process. The web height was set to be 6mm. This was measured again during the testing for confirmation.

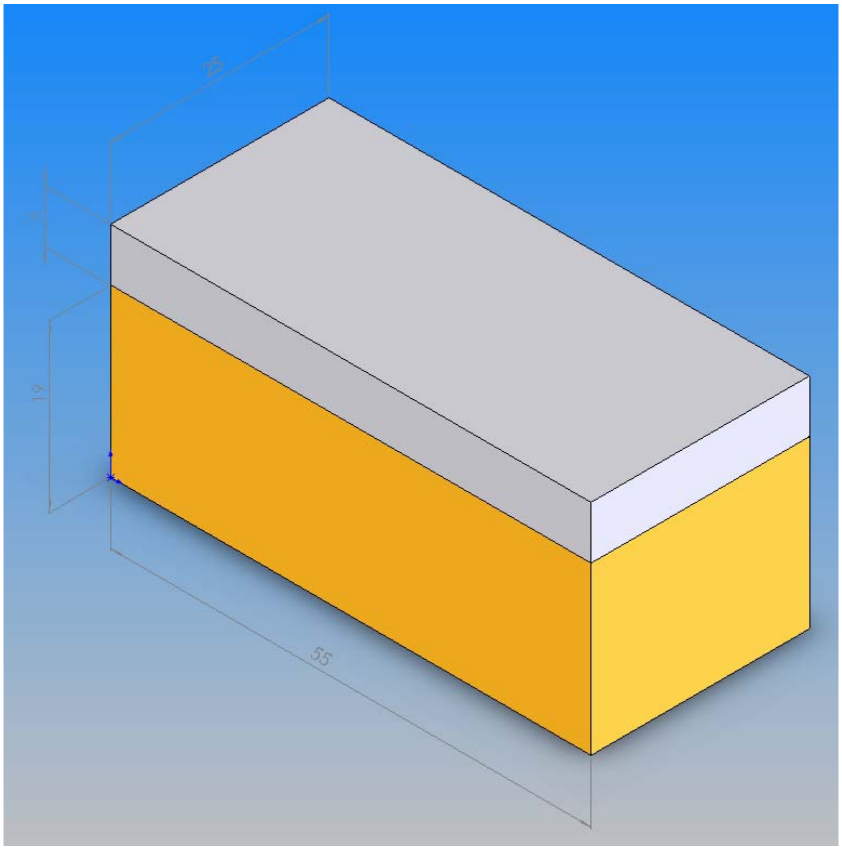


Figure 3.1 Shape of part used in the study

The part was cut into six tabs 5 mm (0.197 inch) apart and 6 mm (0.24 inch) in height as shown in Figure 3.2. Tab thickness varied using six different web thicknesses from 0.05mm (0.02 inch) to 0.30mm (0.12 inch).

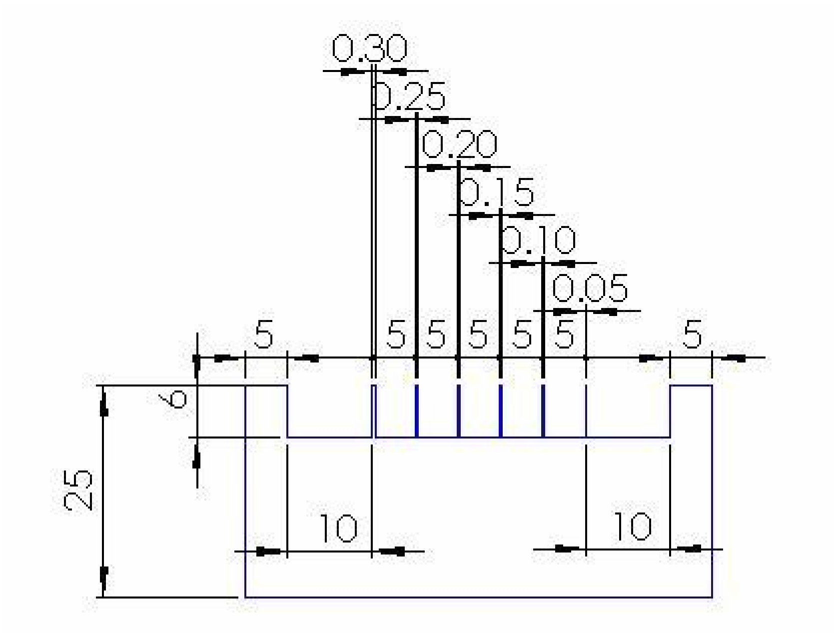


Figure 3.2 The designed web thickness

After the part was cut on the WEDM machine to the desired thickness, it was similar to what is shown in Figure 3.3. Three samples were tested for each web. The web height and thickness were measured for each sample.

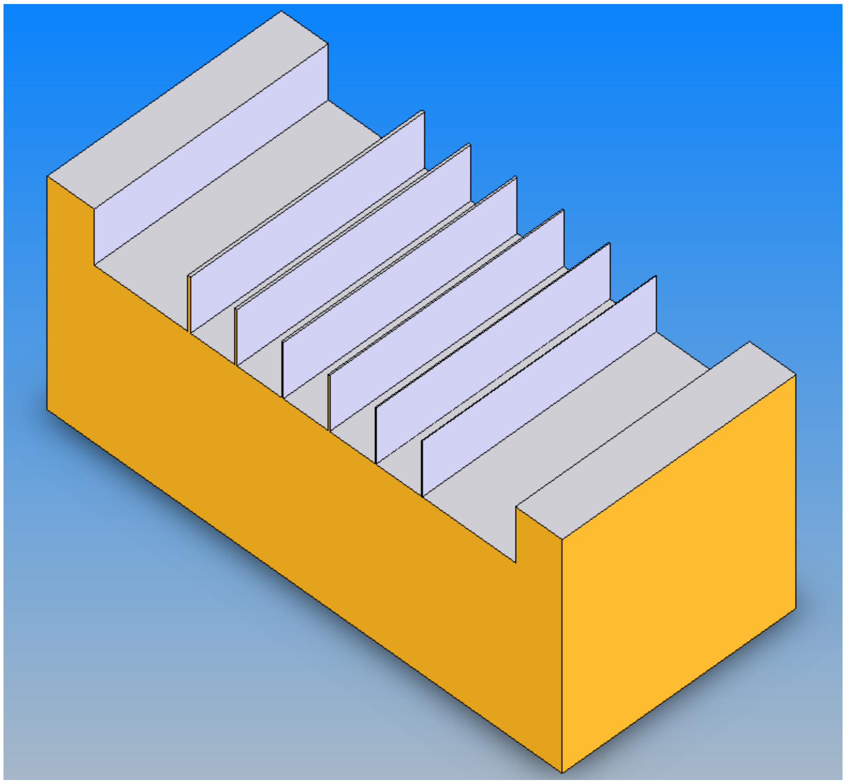


Figure 3.3 The finished test piece cut on a WEDM machine

3.2 TESTED METALS

Five different metals were tested: Aluminum 6061 T6, Yellow Brass 360, 420 Stainless Steel, D2 unheat-treated tool steel 25-30 Rockwell, and D2 heat-treated tool steel 60-65 Rockwell. All of the metals are commonly cut on WEDM machines.

3.2.1 Thermal Conductivity

Thermal conductivities of the materials were found using Internet searches and hand books. The following Table 3.1 shows the thermal conductivity of each material.

Table 3.1 Thermal conductivity of each material

Materials	Thermal conductivity	
D2 heat-treated tool steel	18.8W/m-k	130btu-in/ft^{2}hr^{0}F
D2 un-heat-treated tool steel	18.8W/m-k	130btu-in/ft^{2}hr^{0}F
Aluminum 6061 T6	167W/m-k	1159btu-in/ft^{2}hr^{0}F
Yellow Brass SS360	123W/m-k	853btu-in/ft^{2}hr^{0}F
420 Stainless Steel	24.9W/m-k	173btu-in/ft^{2}hr^{0}F

3.2.2 Melting Temperature

Melting temperatures of the materials were found using Internet searches and handbooks. Generally, these materials were alloys, and even though the same elements were used, different percentages of these elements were found in the materials received from different manufacturers. Most of the elements have a range of values for the percentages. The following Table 3.2 shows an example of the material element percentages for the chemical composition of Aluminum 6061.

Table 3.2 The chemical composition percentages for Aluminum 6061
(Maryland Metrics, 2002)

eight%	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Others total
Minimum	0.4	-	0.15	-	0.8	0.04	-	-	-
Maximum	0.8	0.7	0.4	0.15	1.2	0.35	0.25	0.15	0.15

As shown in the above table, all the elements have a range of values. These different percentages affect the melting temperatures slightly. For this thesis, we will take the median value of the melting temperature for each material. The following Table 3.3 shows the melting temperatures of the materials which were used.

Table 3.3 The median value of the melting temperatures of the materials

Materials	Melting Temperature	
Aluminum 6061 T6	615^0C	1139^0F
Yellow Brass SS360	888^0C	1630^0F
420 Stainless Steel	1480^0C	2696^0F
D2 unheat-treated Tool Steel	1450^0C	2650^0F
D2 heat-treated Tool Steel	1450^0C	2650^0F

3.2.3 Hardness

Material hardness was measured using a Rockwell hardness tester. A 1.524mm (0.06 inch) Brale diamond cone indenter was used to measure the hardness of D2 heat-treated tool steel in HRC with 980.7 N (1000 Kgf). A 1.587mm (0.0625 inch) tungsten carbide ball was used to measure the hardness of the other materials in HRB with 147.1 N (150 Kgf). Each material was tested five times, and the three median values were averaged for each (See appendix E).

Table 3.4 The conversion of HRC and HRB to Brinell Hardness
(Hardness conversion, 1999)

Materials	Average	Brinell Hardness
D2 heat-treated tool steel	HRC 60.7	658
D2 un-heat-treated tool steel	HRB 96.6	221.0
Aluminum 6061 T6	HRB 59.5	95.0
Yellow Brass SS360	HRB 71.3	123.0
420 Stainless Steel	HRB 97.0	223.0

Table 3.4 shows the conversion of HRC and HRB to Brinell hardness. The Aluminum 6061 T6 value (103.0) was too low for the reference table, but for convenience we converted it.

3.2.4 Coefficient of Thermal Expansion (CTE)

The CTE of each material was found using the same method as we used to find the melting temperatures. The following Table 3.5 shows the CTE of each material we used.

Table 3.5 Coefficient of thermal expansion of each material

Materials	CTE
D2 heat-treated tool steel	10.4μm/m.^{0}C
D2 unheat-treated tool steel	10.4μm/m.^{0}C
Aluminum 6061 T6	23.6μm/m.^{0}C
Yellow Brass SS360	20.5μm/m.^{0}C
420 Stainless Steel	10.3μm/m.^{0}C

3.3 MACHINE SETTING AND CUTTING PROGRAMS

The Sodick AQ325L Power settings were used for each different material cut for the study. These settings are shown in Appendix A. It was important to set the cutting parameters before the cuts were made on each part. Detailed parameters are shown in Appendix B.

The CNC part program was made for each particular cutting sequence, and all are shown in Appendix C. The programs were compiled by assembling both machine commands and X Y cut paths.

3.4 CUTTING CONDITION AND OFFSET

To find the cutting conditions, we used the condition search option from the preset condition of the SODICK AQ325L. Table 3.6 indicates the condition of the machine.

Table 3.6 The cutting condition of the machine

Machine Fluid	Water
Wire Diameter	0.254 mm (0.0098 inch)
Wire Method	Brass
Work	Al, Cu(for Brass), Steel (for D2 Tool Steel and Stainless Steel)
Thickness	30 mm (1.18 inch)
Machine	Punch
Nozzle Position	Open-U
Number of passes	1, 2, 4

The three experiments consisted of the following cutting steps.

A. Rough Cut only (0 skim cut)

B. Rough & one Skim Cut (1 Skim Cut)

C. Rough & three Skim Cut (3 Skim Cut)

When the webs were cut, the different heights of each web were shown depending on the different cutting conditions and the offset. Table 3.7 below shows the offset amounts of each cut. Offset measurements had to be converted from inches into mm because the Sodick AQ 325L preset machine conditions are in English units.

Table 3.7 The offset amounts of each cut unit: mm

Materials	**Rough Cut (RH only)** mm	**1 Skim Cut (RH + 1 skim)** mm	**3 Skim Cut (RH + 3 skims)** mm
Aluminum 6061	rough 0.1930	rough 0.2360 1 skim 0.1461	rough 0.2570 1 skim 0.1669 2 skim 0.1369 3 skim 0.1321
Yellow Brass 360	rough 0.1971	rough 0.2339 1 skim 0.1491	rough 0.2451 1 skim 0.1600 2 skim 0.1349 3 skim 0.1331
420 Stainless Steel	rough 0.1661	rough 0.2009 1 skim 0.1359	rough 0.2179 1 skim 0.1529 2 skim 0.1331 3 skim 0.1311
D2 Unheat-treated Tool Steel	rough 0.1661	rough 0.2009 1 skim 0.1359	rough 0.2179 1 skim 0.1529 2 skim 0.1331 3 skim 0.1311
D2 Heat-treated Tool Steel	rough 0.1661	rough 0.2009 1 skim 0.1359	rough 0.2179 1 skim 0.1529 2 skim 0.1331 3 skim 0.1311

Wire offset is the distance from the desired finished dimension to the wire center plus an arc gap. The arc gap is the distance between the edge of the material and the wire circumference. The wire radius is 0.127 mm which is half the size of the 0.254 mm (0.01 inch) diameter brass wire for the machine. As shown in the Table 3.7, the 420 Stainless Steel, D2 unheat-treated tool steel, and D2 heat-treated tool steel rough cut (RH) offsets are 0.1661mm, and the arc gap is 0.0391 mm. D2 heat-treated tool steel, D2 unheat-treated tool steel, and Stainless were all machined under the same working conditions as steel.

The offset for Rough & three Skim Cuts (RH + 3 skims) for Aluminum 6061 was 0.2179 mm with an arc gap of 0.0909 mm. Rough & three skim cuts (RH + 3 skims) were run under the same conditions as the single Rough Cut (RH) with an arc gap of 0.0391 mm. This resulted in web thickness increase of 0.0518 mm to be removed by the three skim passes.

The offset for the Rough Cut of the Rough & three Skim Cuts (RH + 3 skims) for each material was greater than the offset of the Rough Cut (RH) shown in Table 3.7. For example, when Aluminum 6061 is cut, the offset of the Rough Cut (RH) is 0.1930 mm, but the offset for the Rough & one Skim Cut(RH + 1 skim) was 0.2360 mm, and the offset of the Rough & three Skim Cuts (RH + 3 skims) was 0.2570mm. The Rough Cut for the Rough & three Skim Cuts under the same cutting conditions produced a thicker web than the rough pass of the Rough Cut and the Rough & one Skim Cut because of the offset. This will be important to note because of the differences in measured heights of the web between the Rough & three Skim Cuts (RH + 3 skim) and the other cuts.

3.5 DATA COLLECTION

Each type of material was used for the rough cut, rough & one skim cut, and rough & three skim cuts programs. Geometric measurements were obtained using a Starret HB 400 Optical Comparator for each of the 45 test parts. The eroded webs were measured and the center height of the web was used because the ends were either eroded or were not straight. Each web height was averaged between the three test times. The full size of the web should have been 6 mm according to the CNC machine program. The thickness of each web was measured with an inch Vernier Digital Caliper and measurements were then converted into mm.

3.6 WEB BENDING DIRECTION

Pre-test cuts were taken on the materials to check for bending during the cutting. Two different bending tests were performed to check for bending. Figure 3.4 and Figure 3.5 illustrate how the cuts were performed on each of the materials.

Figure 3.4 shows the design of the vertical and horizontal direction cuts for bending. The thickness and the height of the webs were the same, but the direction of the cut is vertical and horizontal to compare the bending directions of the webs.

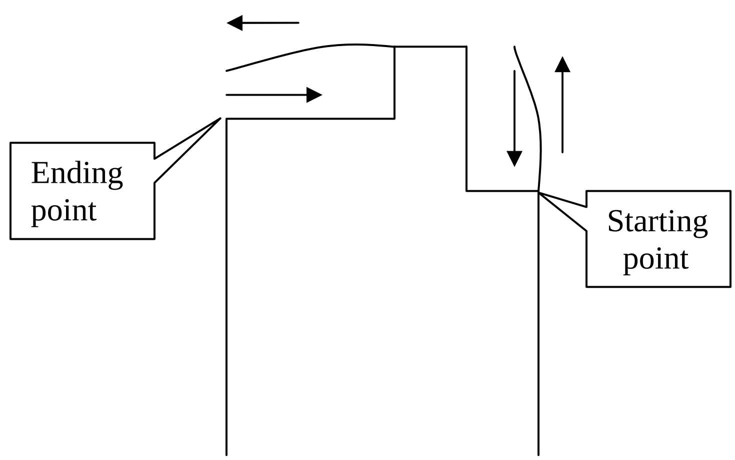


Figure 3.4 Vertical and horizontal direction cuts for bending

In this case, the thickness was 0.20 mm (0.008 inch) and the height of the web was 12.7 mm (0.5 inch). The cutting directions are indicated by arrows. The complete cutting program can be found in Appendix B.

Figure 3.5 shows left and right direction cuts for bending. The thickness and the height of the webs are the same, but the direction of the cut is left-to-right from start point 1 and right-to-left from start point two. The thickness of the web and the full height of the web are the same as those in the vertical and horizontal tests. The complete cutting program can be found in Appendix C.

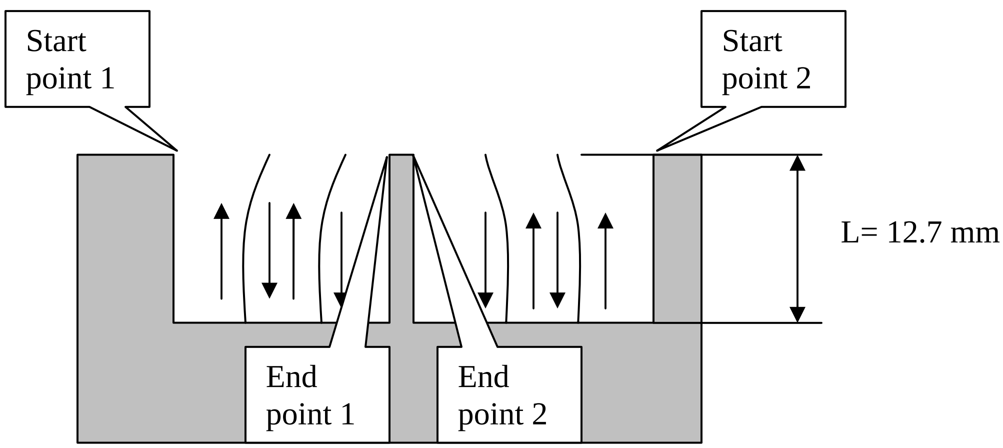


Figure 3.5 Left and right direction cuts for bending

CHAPTER 4

RESULT AND ANALYSIS

The results of this research are focused in two principle areas for WEDM machining of thin webs: a) differences in the height of the resulting webs as the web thickness is reduced, b) and differences in the height of the webs for different materials. The results of the experiments discussed in Chapter 3 will be reviewed in this chapter.

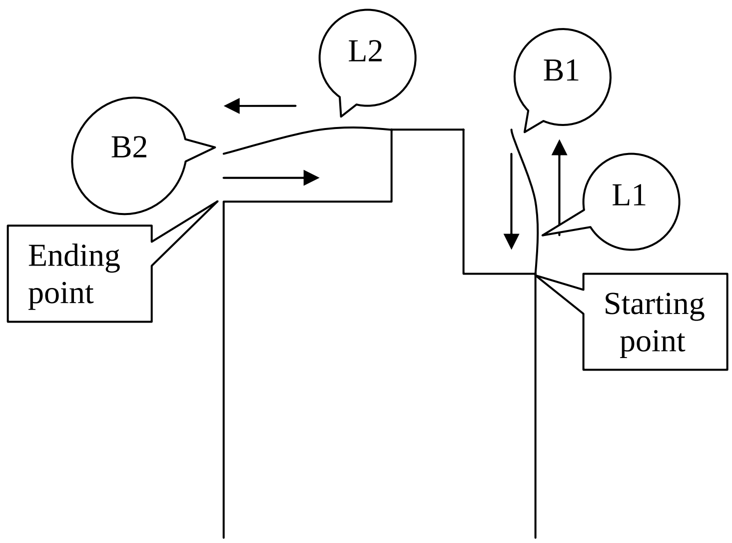
The procedure for Wire EDM machining of thin walled parts was programmed and followed according to the preset conditions of the machine. The full height of the web was 6 mm and the thickness of the web varied from 0.05 mm to 0.30 mm (6 webs). The web height and web thickness were cut and measured in 5 different materials common to the manufacturing field: Aluminum 6061, Yellow brass 360, 420 stainless steel, D2 unheat-treated tool steel, and D2 heat-treated tool steel.

4.1 PRE-BENDING TEST

Test cuts were made on each material to check for bending in the web after the first rough pass. Two different pre-test cuts were taken on each material to check for bending during the rough cut.

4.1.1 Bending in Vertical and Horizontal Directions

Figure 4.1 shows that bending occurred in the vertical and horizontal directions towards the second cut side of the web as predicted. The vertical direction (L2) is the parallel shorter direction of the material and the horizontal direction (L1) is the perpendicular direction of the material. The thickness and the height of the webs were kept the same to compare the bending directions of the webs. Table 4.1 shows the bending measurements for each type of material.



L1 = L2 = 12.7 mm (0.5 inch), Web thickness = 0.2 mm (0.008 inch)

Figure 4.1 Schematic for vertical and horizontal bending tests

Table 4.1 The bending measurements for each material Unit: mm

	B1(vertical bending)	B2(horizontal bending)	B1-B2(bending difference)
Aluminum 6061 T6	0.523	0.437	0.086
Yellow Brass 360	0.480	0.747	- 0.267
420 Stainless Steel	0.262	0.371	- 0.109
D2 unheat-treated tool steel	0.236	0.368	- 0.132
D2 heat-treated tool steel	0.048	0.025	0.023

As shown in Table 4.1, all materials have the same direction of bending with slight variations in magnitude. The largest bending difference (0.267 mm) between the horizontal and vertical cuts occurred in Yellow Brass 360. The smallest bending difference (0.023 mm) occurred in D2 heat-treated Tool steel. The wire paths were programmed and used for each material to maintain the same height for each of the pretest cuts.

4.1.2 Bending in the Left and Right Directions

Figure 4.2 shows the design for the left and right direction cuts for bending and Table 4.2 indicates the left and right direction bending amounts for each material.

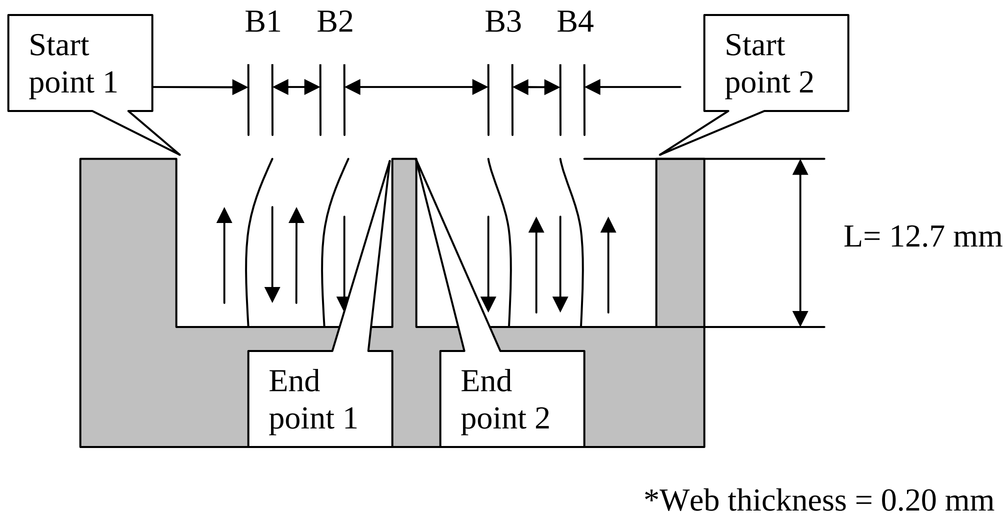


Figure 4.2 Schematic for left and right bending tests

Table 4.2 Left and right bending results for each material

	B1	B2	B3	B4	B1 + B4 (bending difference)	B2 + B3 (bending difference)
Aluminum 6061 T6	0.538	0.503	-0.538	-0.599	-0.061	-0.035
Yellow Brass 360	0.399	0.518	-0.445	-0.488	-0.089	0.073
420 Stainless Steel	1.034	1.003	-1.144	-1.095	-0.061	-0.141
D2 un-heat-treated tool steel	0.541	0.582	-0.574	-0.574	-0.033	-0.008

The thickness of the webs was 0.20 mm and the height was 12.7 mm similar to the dimensions for the vertical and horizontal bending test. The left two webs were cut from left to right and the right two webs were cut from right to left.

According to the data shown, the right side of Stainless Steel 420 was bent more than the left side. But the other materials (Aluminum 6061, Yellow Brass 360, D2 Tool Steel) showed more consistent bending for both sides. Measurement B1 was compared with B4 and B2 with B3. As mentioned above, the bending difference of the horizontal and vertical on Aluminum 6061 was larger than other materials and the bending of Yellow Brass 360 was similar on both the right and left sides as shown in the Table 4.2. From this experiment, the bending always occurs toward the wire on the second cut side of the web. The largest bending difference (0.141 mm) occurred between the left and right cuts in 420 Stainless steel. The smallest bending different (0.008 mm) occurred in D2 unheat-treated tool steel.

Figure 4.3 shows left and right direction cuts for bending on Aluminum 6061.

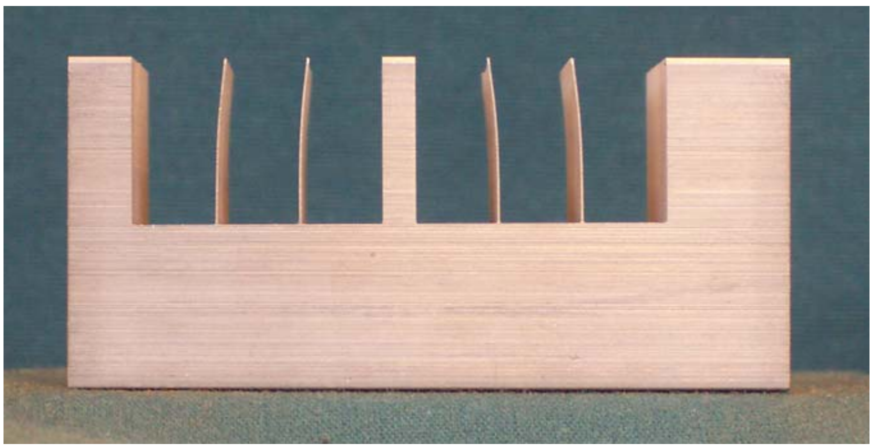


Figure 4.3 Left and right bending experiment for the Aluminum 6061 test piece

One can see from Figure 4.3 that there was no loss in web height due to bending in the Aluminum 6061 test piece. In the Aluminum block shown above, all bending occurred towards the last cut side of each web.

Through these pretest experiments all materials showed some bending of the webs toward the latter pass of the wire. Bending in the vertical and horizontal directions as quantified in Table 4.1, had negligible differences when compared to the length of the web. There were similar differences for bending in the left and right directions. If significant differences in bending from one direction to the other (i.e. from right and left or from vertical or horizontal) existed, then residual stresses would also be significant. However, because web bending was similar for all pretest conditions, residual stresses may be ignored. The thickness of each of the webs for pretest experiments was 0.20 mm. Bending occurred in all webs for each pretest material as shown in Tables 4.1 and 4.2. This bending phenomenon will affect the height of the web for each test when skim passes are used.

4.1.3 Part Thickness Test Result

The web heights were measured three times for each material and the average recorded. Web thickness was for the most part uniform for all materials with the exception of aluminum. Raw data for all measurements can be seen in Appendix D. Table 4.3 and Figure 4.4 show the thickness of each web for each of the five materials.

Table 4.3 The thickness of each material web Unit: mm

Cuts	Thickness	Aluminum	Yellow Brass	Stainless Steel	D2 Unheat-treated	D2 Heat-treated
RH	RH:0.30	0.305	0.296	0.292	0.292	0.292
	RH:0.25	0.254	0.241	0.241	0.241	0.241
	RH:0.20	0.199	0.195	0.191	0.191	0.191
	RH:0.15	0.152	0.144	0.140	0.140	0.140
	RH:0.10			0.089		
	RH:0.05					
RH + 1S	1S:0.30	0.292	0.279	0.292	0.292	0.292
	1S:0.25	0.241	0.229	0.241	0.241	0.241
	1S:0.20	0.191	0.178	0.191	0.191	0.191
	1S:0.15	0.140	0.127	0.140	0.140	0.140
	1S:0.10	0.102	0.089	0.089	0.076	0.089
	1S:0.05					
RH + 3S	3S:0.30	0.288	0.279	0.279	0.279	0.279
	3S:0.25	0.241	0.229	0.229	0.229	0.229
	3S:0.20	0.191	0.178	0.178	0.178	0.178
	3S:0.15	0.140	0.127	0.127	0.127	0.127
	3S:0.10	0.089	0.076	0.076	0.076	0.076
	3S:0.05					

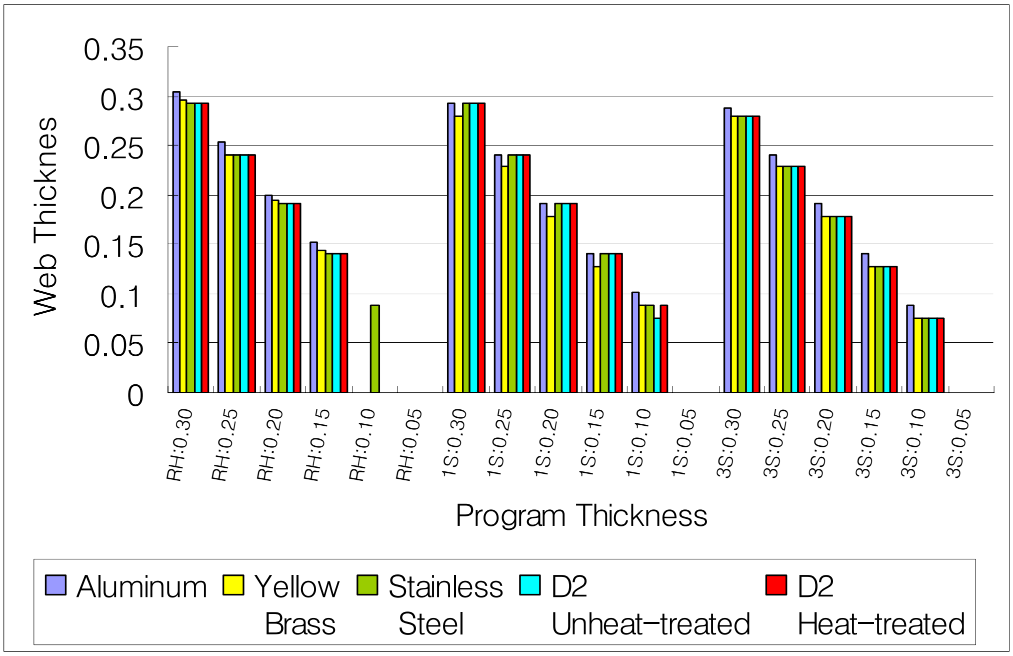


Figure 4.4 The thickness of each material web

As shown in Figure 4.4, the 0.30 and 0.20 mm web thicknesses for Aluminum 6061 were a little larger at 0.305 and 0.254 mm. The cause of this increase in the aluminum web thickness is not known but may be an area for future research. Other webs for the aluminum were equal to or less than the nominal.

Also in Table 4.3, the Rough & one Skim Cut web thicknesses for Brass 360 were almost all under the nominal values (0.279, 0.229, 0.178, and 0.127). The cause for this trend is not known.

Stainless steel results for the Rough Cut and the Rough & one Skim Cut were all under the nominal by 0.01 mm. For the Rough & three Skim Cut experiment, web thicknesses were all under the nominal by 0.02 mm. For 0.10 mm experiments all webs were lost with the exception of stainless steel during the rough cut experiment.

D2 tool steel results for the Rough Cut and the Rough & one Skim Cut experiments were all under the nominal by 0.01 mm with the exception of D2 unheat-treated at a web thickness of 0.15 mm for the Rough & one Skim Cut experiment which was under the nominal by 0.02 mm. For the Rough & three Skim Cuts web thicknesses were consistently under the nominal by 0.02 mm.

Even though the thickness is smaller than what was programmed, the web thickness was consistent throughout the part. The reduction in thickness should not affect the height of the webs with any significance for the larger webs but may have for the smaller ones.

4.2 WEB HEIGHT RESULTS FOR INDIVIDUAL WEB THICKNESS

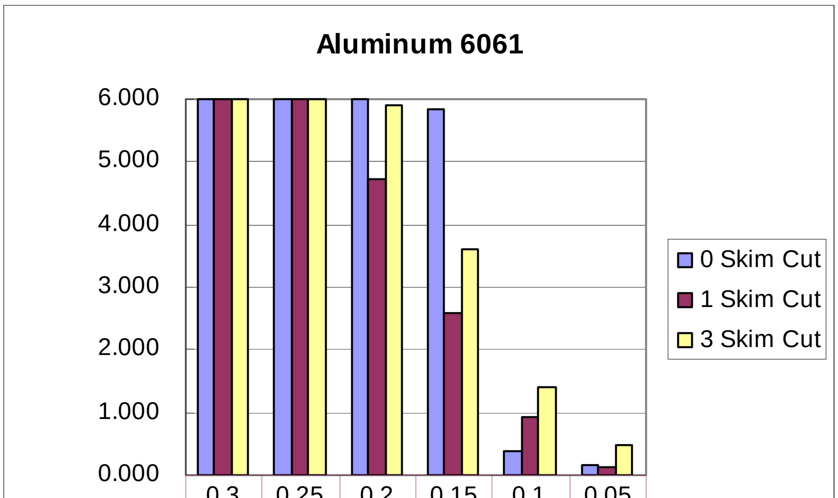
Each material was cut with 6 different web thicknesses according to the Rough Cut program, the Rough & one Skim Cut program, and the Rough & three Skim Cut program. Each web was cut three times and the average of the cuts was recorded.

4.2.1 Cutting Results for each Web Thickness

4.2.1.1 Aluminum 6061

Table 4.4 shows web heights of Aluminum 6061 with Rough Cut, Rough & one Skim Cut, and Rough & three Skim Cuts.

Table 4.4 The heights of each web for Aluminum 6061



Height(mm)	0.3	0.25	0.2	0.15	0.1	0.05
0 Skim Cut	6.000	6.000	6.000	5.851	0.373	0.164
1 Skim Cut	6.000	6.000	4.728	2.600	0.938	0.128
3 Skim Cut	6.000	6.000	5.908	3.614	1.416	0.465

There was no height decrease for the 0.30 and 0.25 mm webs. However, for the 0.20 mm thickness web, there was 0 % decrease for the Rough Cut, 21.1%(1.272 mm) for the Rough & one Skim Cut, and 1.5% (0.092 mm) for the Rough & three Skim Cuts. A 0.15 mm thick web resulted in a 2.5% (0.149 mm) for decrease for the Rough Cut, a 56.7%(3.4 mm) for the Rough & one Skim Cut, and 39.7% (2.386 mm) for the Rough & three Skim Cuts. These reductions or decreases in web height were caused by bending of the webs during each rough pass. The 0.10 mm thick webs had the most significant reduction with a 93.8% (5.627 mm) decrease for the rough cut, a 56.7%(3.4 mm) for the Rough & one Skim Cut, and a 39.7% (2.386 mm) for the Rough & three Skim Cuts.

The aluminum results for 0.20 and 0.15 mm web thicknesses were different between the Rough Cut and the Rough & one Skim Cut because bending occurred during the rough pass and a portion of the web was cut off on the skim pass. The 0.10 mm results were also different for the Rough Cut. During the rough pass a high heat arc was used. If there was a single Rough Cut used to get the finished dimensions then the possibility of the losing the web due to the generated heat increased. This is precisely the reason there was no web left for a single rough pass yet there was some height remaining after a skim pass. With skim passes, the rough pass was done with a larger offset and so it was less likely that the web would be lost due to the high heat arc. Any skim passes performed after would have smaller offsets than a rough cut but the web was not as likely to be melted away because a lower heat arc was used during the skim cuts. It is also less likely they will be lost when the web gets a little thinner. The results from the aluminum demonstrate this phenomenon.

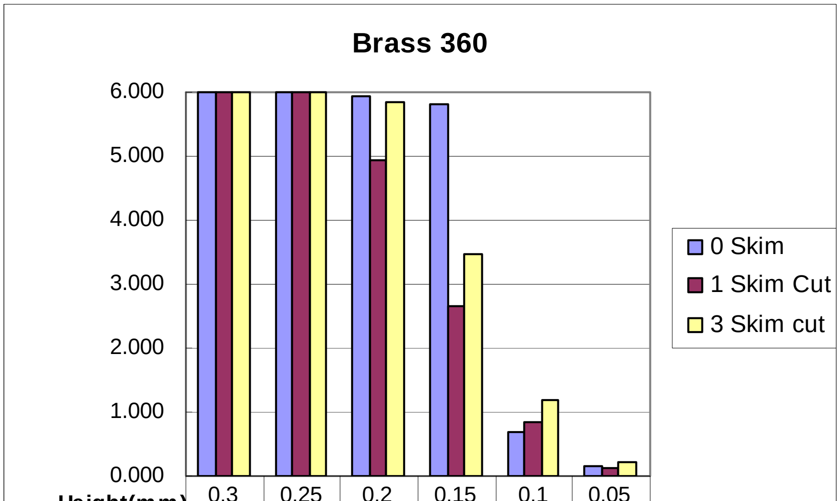
For the 0.05 mm thick webs, there is a 97.3% (5.836 mm) height decrease for a single Rough Cut, 97.9%(5.872 mm) for Rough & one Skim Cut, and 92.3% (5.535 mm) for Rough & three Skim Cuts.

The same type of phenomena with high/low arc heat for the rough/skim cuts can be seen in the 0.10 mm experiment for brass 360. There may be some threshold between the 0.15 mm and 0.10 mm web thicknesses where a high heat arc can not be used or the web will be melted away.

4.2.1.2 Yellow Brass 360

Table 4.5 shows web heights of Yellow Brass 360 with Rough Cut, Rough & one Skim Cut, and Rough & three Skim Cuts.

Table 4.5 The heights of each web for Yellow Brass 360



Height(mm)	0.3	0.25	0.2	0.15	0.1	0.05
0 Skim	6.000	6.000	5.941	5.821	0.676	0.142
1 Skim Cut	6.000	6.000	4.930	2.642	0.840	0.120
3 Skim cut	6.000	6.000	5.855	3.475	1.192	0.223

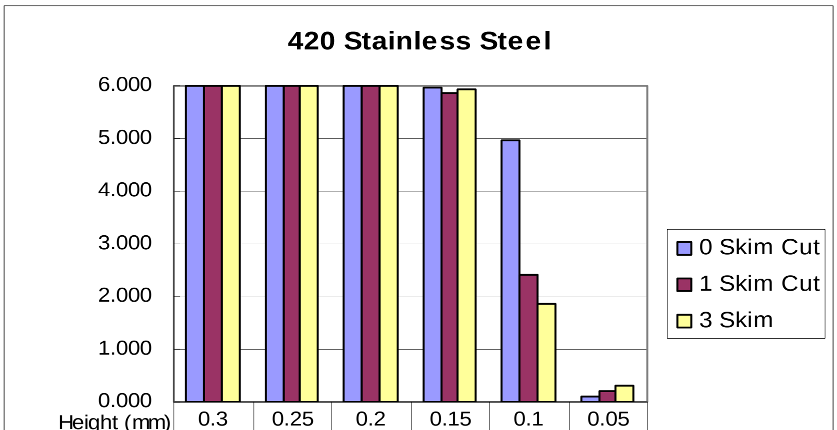
The same type of phenomena with high/low arc heat for the rough/skim cuts can be seen in the 0.10 mm experiment for brass 360. Yellow Brass 360 mechanical properties are very similar to Aluminum 6061. At 0.20, 0.15, 0.10.and 0.05 mm, the web heights for the Rough & one Skim Cut and Rough & three Skim Cuts decreased proportionally. For the 0.05 mm thick webs, there was a 97.6% (5.858 mm) height decrease for a single Rough Cut, 98.0%(5.880 mm) for a Rough & one Skim Cut, and 96.3% (5.777 mm) for Rough & three Skim Cuts.

Again, there may be some threshold between the 0.15 mm and 0.10 mm web thicknesses where a high heat arc can be used or the web will be melted off.

4.2.1.3 420 Stainless Steel

Figure 4.6 shows web heights of Stainless Steel with Rough Cut, Rough & one Skim Cut, and Rough & three Skim Cuts.

Table 4.6 The heights of each web for 420 Stainless Steel



Height (mm)	0.3	0.25	0.2	0.15	0.1	0.05
0 Skim Cut	6.000	6.000	6.000	5.955	4.959	0.111
1 Skim Cut	6.000	6.000	6.000	5.848	2.421	0.210
3 Skim	6.000	6.000	6.000	5.935	1.866	0.305

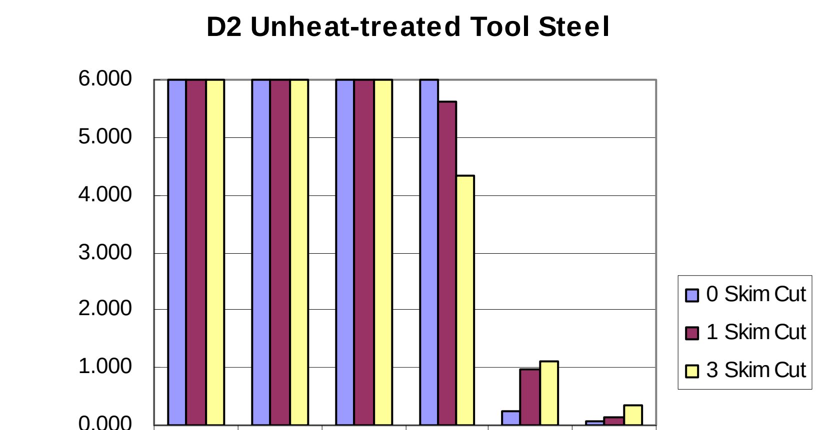
For the first four web thicknesses, the height remained fairly constant in 420 Stainless Steel. With a web thickness of 0.10 mm, there was a significant difference in height due to bending. During the 0.05 mm experiments all three of the webs were almost completely removed. For the 0.05 mm thick webs, there was a 98.2% (5.889 mm) decrease in height for a single Rough Cut, 96.5%(5.790 mm) for a Rough & one Skim Cut, and 94.9% (5.648 mm) for Rough & three Skim Cuts.

For a 0.05 mm web, web heights with skim passes were larger than without skim passes because of the increase in the wire offset during the first rough pass. The high heat arc was not as close to the center of the web during the second two experiments, hence more of the height of the web was left. Again, there is some threshold between 0.10 and 0.05 mm that the high heat arc for the rough cut may not be used.

4.2.1.4 D2 unheat-treated Tool Steel

Table 4.7 shows web heights of D2 unheat-treated Tool Steel with Rough Cut, Rough & one Skim Cut, and Rough & three Skim Cuts.

Table 4.7 The heights of each web for D2 unheat-treated Tool Steel



Height(mm)	0.3	0.25	0.2	0.15	0.1	0.05
0 Skim Cut	6.000	6.000	6.000	5.986	0.248	0.086
1 Skim Cut	6.000	6.000	6.000	5.617	0.966	0.154
3 Skim Cut	6.000	6.000	6.000	4.330	1.126	0.352

D2 unheat-treated Tool Steel differs from 420 Stainless Steel because the web heights start to drop significantly due to bending at a 0.15 mm web instead of at the 0.10 mm web.

For the 0.05 mm thick webs, there was a 98.6% (5.914 mm) reduction in height for a single rough cut, 97.4%(5.846 mm) for a Rough & one Skim Cut, and 91.2% (5.470 mm) for Rough & three Skim Cuts.

Again, experiments with the skim cuts produced taller webs due to the larger offset during the Rough Cut in both the 0.10 mm and 0.05 mm experiments. The threshold between the 0.15 mm and 0.10 mm web thicknesses where a high heat arc can not be used exists.

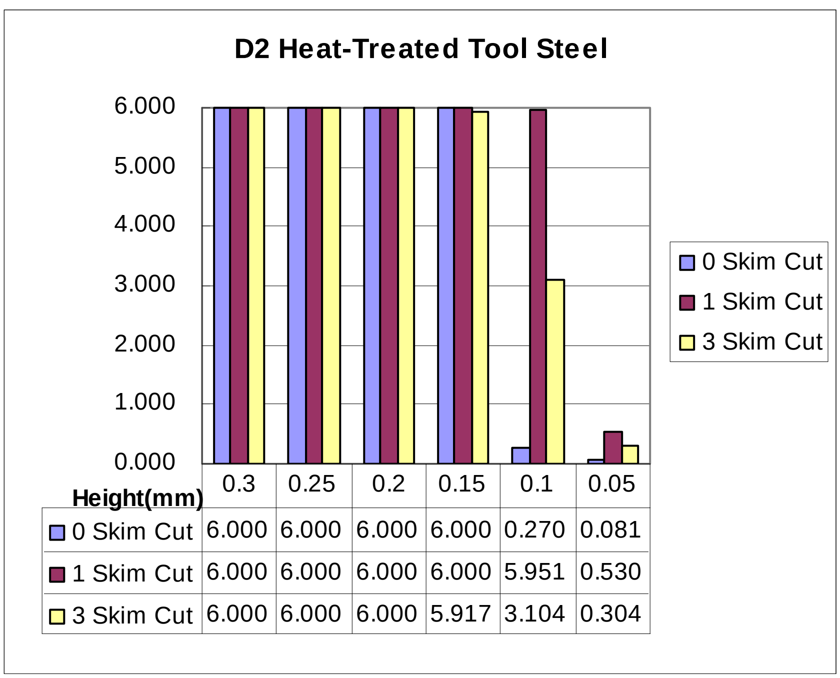
4.2.1.5 D2 heat-treated Tool Steel

Table 4.8 shows web heights of D2 unheat-treated Tool Steel with Rough Cut, Rough & one Skim Cut, and Rough & three Skim Cuts.

D2 heat-treated Tool Steel produced the best results for maintaining web height while cutting thin webs. There was no change in height until the web reached a thickness of 0.15 mm. Even then it was a minor change only in the Rough & three Skim Cut experiment.

For a web thickness of 0.10 mm, there were a few unique changes because the rough pass was very short with a decrease in height of 95.5% (5.730mm), yet those with skim passes experienced less of a decrease in height. There was only a 0.8% (0.049mm) decrease for the Rough & one Skim Cut.

Table 4.8 The heights of each web for D2 heat-treated tool steel



For materials with a hardness of Brinell 658 (HRC 62), the threshold for thin web survival of the high heat arc may be around 0.10 mm. It is important to note that the very small increase in the wire offset during the rough pass between the Rough Cut and the Rough & one Skim Cut experiment was significant enough for the web to keep from being melted off.

For the 0.05 mm thick webs, there was a 98.7% (5.919 mm) height decrease for a single Rough Cut, 91.2% (5.470 mm) for a Rough & one Skim Cut, and 94.9% (5.696 mm) for Rough & three Skim Cuts. There may be some threshold between the 0.15 mm and 0.10 mm web thicknesses for the Rough Cut and between the 0.10 mm and 0.05 mm for the Rough & one Skim Cut.

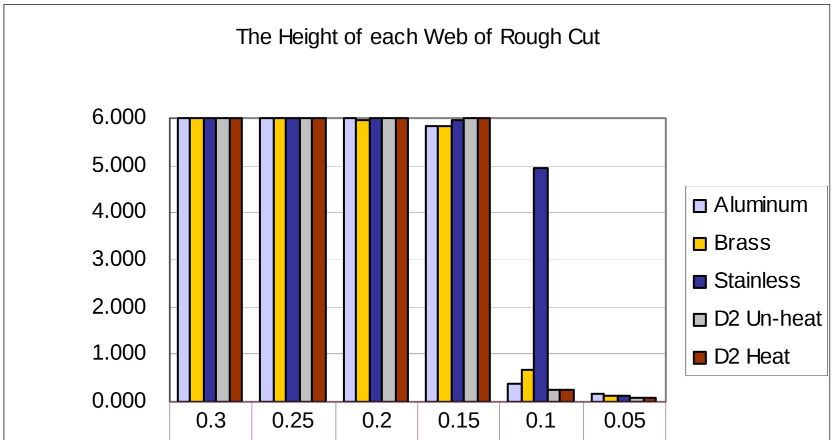
A clear pattern was established in the 0.10 mm and 0.05 mm experiments for D2 Heat treated steel. Rough & one Skim Cut heights were taller than Rough & three Skim Cuts because they may have experienced more bending or rather more opportunities to be bent. There may have also been some losses in height due to the low heat arc during the skim passes.

4.3 WEB EHIGHT RESULTS FOR EACH MATERIAL

4.3.1 Rough Cut (rough cut only)

For general purposes a single rough cut produces a reasonably good surface finish and good dimensional tolerances. Table 4.9 shows the height of each web for a single Rough Cut.

Table 4.9 The height of each web for a single Rough Cut



	0.3	0.25	0.2	0.15	0.1	0.05
Aluminum	6.000	6.000	6.000	5.851	0.373	0.164
Brass	6.000	6.000	5.941	5.821	0.676	0.142
Stainless	6.000	6.000	6.000	5.955	4.959	0.111
D2 Un-heat	6.000	6.000	6.000	5.986	0.248	0.086
D2 Heat	6.000	6.000	6.000	6.000	0.270	0.081

As shown in Table 4.9, there were height differences for the 0.15 mm webs with the exception of D2 heat-treated tool steel. The heights of Aluminum 6061 and Yellow Brass 360 were more affected than the other metals. Both showed a decrease in height for the 0.20 mm thickness web because of bending. The height was dramatically reduced for all materials when the web thickness was 0.10 mm with the exception of stainless steel.

Table 4.10 shows the percentage of height loss for each web of rough cut.

Table 4.10 The percentage of height loss for each web of Rough Cut
Unit: loss %(lost height mm)

	Web Thickness	Aluminum	Brass	Stainless	D2 Un-heat treated	D2 Heat Treated
RH	0.300	0.0% (0)	0.0% (0)	0.0% (0)	0.0% (0)	0.0% (0)
	0.250	0.0% (0)	0.0% (0)	0.0% (0)	0.0% (0)	0.0% (0)
	0.200	0.0% (0)	1.0% (0.059)	0.0% (0)	0.0% (0)	0.0% (0)
	0.150	2.5% (0.149)	3.0% (0.179)	0.7% (0.045)	0.2% (0.014)	0.0% (0)
	0.100	93.8% (5.627)	88.7% (5.324)	17.4% (1.041)	95.9% (5.752)	95.5% (5.730)
	0.050	97.3% (5.836)	97.6% (5.858)	98.2% (5.889)	98.6% (5.914)	98.7% (5.919)

For 0.10 mm thick webs, there was a 93.8% (5.627 mm) reduction in web height for Aluminum 6061, 88.7% (5.324 mm) for Yellow brass 360, 17.4% (1.041 mm) for 420 Stainless Steel, 95.9% (5.752) for D2 unheat-treated Tool Steel, and 95.5% (5.730 mm) for D2 heat-treated Tool Steel. For a web thickness of 0.05 mm, the heights were significantly reduced. Figure 4.5 shows the side view of these defects for the rough cut.

A: Aluminum 6061

B: Yellow Brass 360

Figure 4.5 The side view of Aluminum 6061 and Yellow Brass 360

One can see that most height reduction occurred for web thicknesses of 0.10 and 0.05 mm. This may indicate that the webs in Aluminum 6061 and Yellow Brass 360 were lost due to a high heat arc temperature for the 0.15 mm thick webs. This may also mean that metal webs with a thickness less than 0.10 mm are difficult to cut without some type of degradation of the web. Figure 4.5 A shows the serious damage to the web in a 0.15 mm web in Aluminum 6061, even though it has almost retained its full height. A similar phenomenon happened on the 0.10 mm web in 420 Stainless steel.

Figure 4.6 shows the side view of 420 stainless steel, D2 unheat-treated tool steel, and D2 heat-treated tool steel for a single rough cut.

A: Stainless steel B: D2 unheat-treated tool steel C: D2 heat-treated tool steel

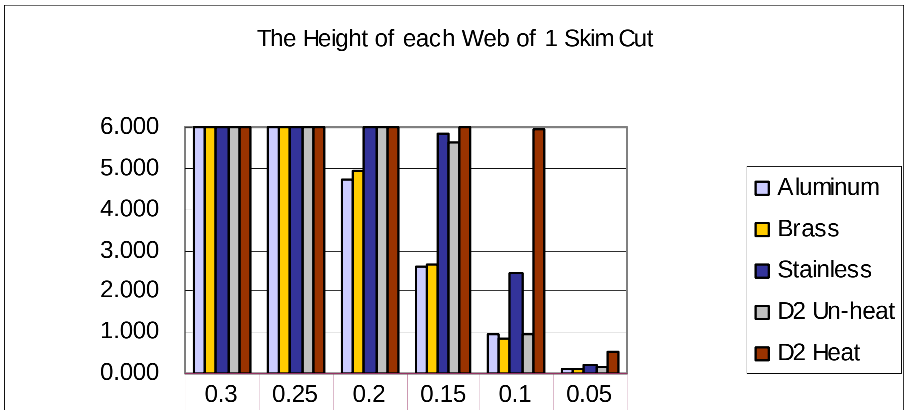
Figure 4.6 Side view of Stainless steel, D2 unheat-treated steel, D2 heat-treated steel for Rough cut only

As shown in the Figure 4.6, some damage occurred on the web of D2 tool steel for a thickness of 0.15 mm. For a 0.20 mm thick web in the D2 unheat-treated steel, the damage occurred from a wire short cut. It would have had a full height if not for the short cut. There was a serious damage to the 0.10 mm web of Stainless steel.

4.3.2 Rough & one Skim Cut (rough cut and one skim pass)

Table 4.11 shows the height of individual web of Rough & one Skim Cut.

Table 4.11 The height of each web of Rough & one Skim Cut



	0.3	0.25	0.2	0.15	0.1	0.05
Aluminum	6.000	6.000	4.728	2.600	0.938	0.128
Brass	6.000	6.000	4.930	2.642	0.840	0.120
Stainless	6.000	6.000	6.000	5.848	2.421	0.210
D2 Un-heat	6.000	6.000	6.000	5.617	0.966	0.154
D2 Heat	6.000	6.000	6.000	6.000	5.951	0.530

As shown in Table 4.11, the web heights of Aluminum 6061 and Yellow Brass 360 saw more and more degradation as the thickness decreased below 0.20 mm. For the 0.15 mm web, a slight reduction in height occurred for 420 stainless steel, D2 unheat-treated tool steel, and D2 heat-treated tool steel. The 0.10 mm web for D2 heat-treated tool steel height was not affected, but it was slightly damaged on the corners.

When Table 4.11 data was compared to that of a single Rough Cut in Table 4.9, a significant reduction in web height occurred for thicknesses that were less than 0.20 mm. This means that for a single Rough Cut the top portion of the webs were not removed even though bending occurred. In the case of the Rough & one Skim Cut, the bending occurring in the rough cut set the webs up to be removed during the skim pass

As the high or low heat arcing begins and the heat is localized, there may be more expansion in aluminum and brass than the other three materials. This expansion of the material may increase the web bending and increase the possibilities of the web being melted off.

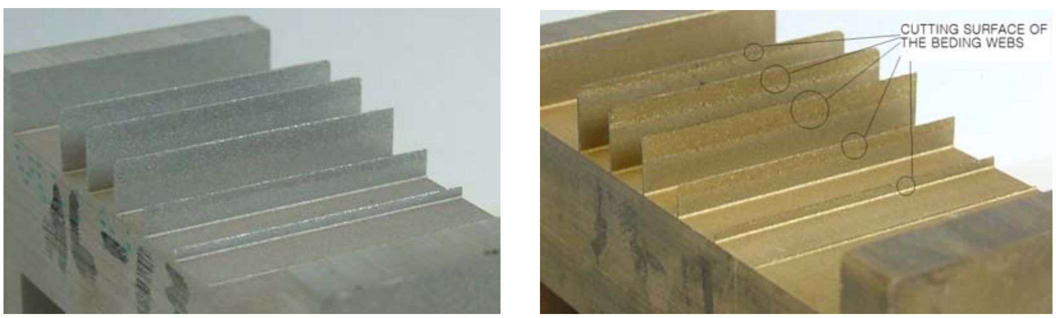
Table 4.12 below shows the mechanical properties for each material.

Table 4.12 Physical properties of the five materials.

	Thermal conductivity	**Melting temperature**	**Hardness**	**CTE**
Aluminum 6061 T6	167W/m-k	615^0C	Brinell 95	23.6μm/m.^{0}C
Yellow Brass SS360	123W/m-k	888^0C	Brinell 123	20.5μm/m.^{0}C
420 Stainless Steel	24.9W/m-k	1480^0C	Brinell 223	10.3μm/m.^{0}C
D2 un-heat-treated tool steel	18.8W/m-k	1450^0C	Brinell 221	10.4μm/m.^{0}C
D2 heat-treated tool steel	18.8W/m-k	1450^0C	Brinell 658	10.4μm/m.^{0}C

As shown in the Table 4.12, Aluminum and Brass have both a low melting temperature and hardness while Stainless and D2 steels have high melting temperatures and hardness's. The CTE and thermal conductivities of the materials have an inverse relationship to those of the melting temperature and hardness. They are high for Aluminum and Brass and low for Steel. It can be said that the resulting web height when machined in these five materials is proportional to the hardness and melting temperature and inversely proportional to the CTE and thermal conductivity. These physical properties influence the amount of bending in thin webs during the rough cuts.

Once bending has occurred during a rough pass, the bent part will be cut off by the next skim pass. As shown in Table 4.11, as the thickness of Aluminum 6061 and Yellow Brass 360 decreased for the Rough & one Skim Cut, the heights also decreased proportionally. This was caused by bending during the rough cut. One can see the cut surfaces where the bent webs have been cutoff in Figure 4.7 B as indicated by the circles.



A. Aluminum 6061 B. Yellow Brass 360

Figure 4.7 Rough & one skim cut for Aluminum 6061 and Brass 360

Figure 4.7 B shows a second facet of cutting for each web due to web bending after a Rough & one Skim Cut. One can see in Figure 4.7 that after the thickness is less than 0.15 mm, the portion of the removed web gets larger.

Figure 4.8 shows the side view of D2 heat-treated tool steel after Rough & one Skim Cut was performed. There was only a slight amount of damage on the corner of the 0.10 mm web.

Figure 4.8 The side view of D2 heat-treated tool steel for the Rough & one skim cut

Through this experiment for the Rough & one Skim Cut, one can see that bending during the rough pass significantly affected the reduction in web height during the skim pass. Table 4.13 shows the percent decrease in height for each web of the Rough & one Skim Cut.

Table 4.13 The percentage of height loss for each web of Rough & one Skim Cut

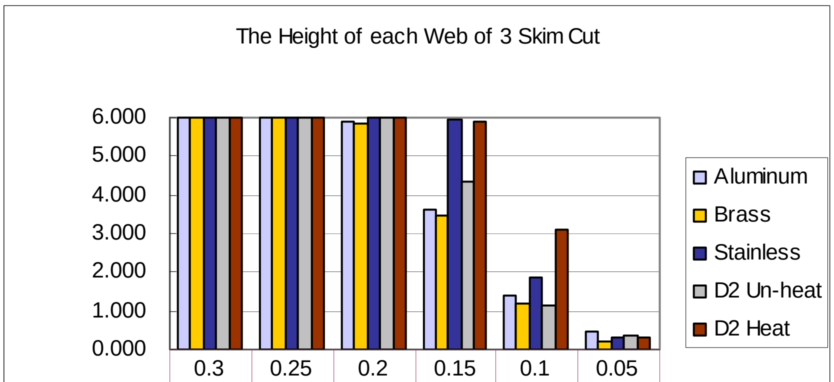
Unit: loss %(lost height mm)

	Web Thickness	Aluminum	Brass	Stainless	D2 Un-heat treated	D2 Heat Treated
RH + 1S	0.300	0.0% (0)	0.0% (0)	0.0% (0)	0.0% (0)	0.0% (0)
	0.250	0.0% (0)	0.0% (0)	0.0% (0)	0.0% (0)	0.0% (0)
	0.200	21.2% (1.272)	17.8% (1.070)	0.0% (0)	0.0% (0)	0.0% (0)
	0.150	56.7% (3.400)	56.0% (3.358)	2.5% (0.152)	6.4% (0.383)	0.0% (0)
	0.100	84.4% (5.062)	86.0% (5.160)	59.7% (3.579)	83.9% (5.034)	0.8% (0.049)
	0.050	97.9% (5.872)	98.0% (5.880)	96.5% (5.790)	97.4% (5.846)	91.2% (5.470)

4.3.3 Rough & three Skim Cuts

For precision cutting and a fine surface finish one rough pass with three skim passes is recommended. Table 4.14 shows the height of each web for the Rough & three Skim Cuts experiment.

Table 4.14 The height of each web of Rough & three Skim Cuts



	0.3	0.25	0.2	0.15	0.1	0.05
Aluminum	6.000	6.000	5.908	3.614	1.416	0.465
Brass	6.000	6.000	5.855	3.475	1.192	0.223
Stainless	6.000	6.000	6.000	5.935	1.866	0.305
D2 Un-heat	6.000	6.000	6.000	4.330	1.126	0.352
D2 Heat	6.000	6.000	6.000	5.917	3.104	0.304

In Table 4.14, the height of each web decreased starting with a 0.20 mm thickness and was significantly reduced at 0.05 mm. After the rough pass and first skim pass, the offset became less and the cut became more precise for a second and third skim pass. Even the hard metals such as 420 stainless steel and D2 heat-treated tool steel became significantly reduced for 0.10 and 0.05 mm thick webs. There was not much bending in these hard materials at 0.15 mm and so the heights were not reduced as much when compared with the other metals. The hardness of each metal is shown in Appendix

E. Holding all properties the same and changing only the hardness for D2, it is important to note that the hardness does have an effect on the web height. The reason for this is that it was less likely to bend and be cut off by a skim pass. Table 4.15 shows the percentage of height loss for each web of Rough & three Skim Cuts.

Table 4.15 The percentage of height loss for each web of Rough & three Skim Cut
Unit: loss %(lost height mm)

	Web Thickness	Aluminum	Brass	Stainless	D2 Un-heat treated	D2 Heat Treated
RH + 3S	0.300	0.0% (0)	0.0% (0)	0.0% (0)	0.0% (0)	0.0% (0)
	0.250	0.0% (0)	0.0% (0)	0.0% (0)	0.0% (0)	0.0% (0)
	0.200	1.5% (0.092)	2.4% (0.145)	0.0% (0)	0.0% (0)	0.0% (0)
	0.150	39.8% (2.386)	42.1% (2.525)	1.1% (0.065)	27.8% (1.670)	1.4% (0.083)
	0.100	76.4% (4.584)	80.1% (4.808)	68.9% (4.134)	81.2% (4.874)	48.3% (2.896)
	0.050	92.3% (5.535)	96.3% (5.777)	94.9% (5.695)	94.1% (5.648)	94.9% (5.696)

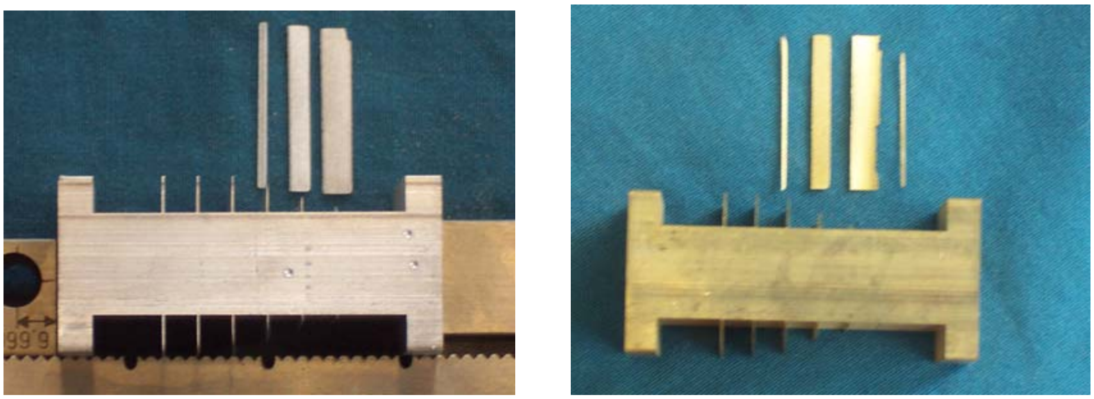
As in the cases of D2 un-heat treated and D2 heat treated steels, the Brinell hardness is 221 and 658 respectively. Comparing the heights of the two steels at a thickness of 0.15mm, they are 4.330 mm (27.8% decrease) and 5.917 mm (1.4 % decrease) respectively. Furthermore, at a thickness of 0.10mm, the heights are 1.126 mm (81.2 % decrease) and 3.104 mm (48.3 % decrease). This means that the web height is proportional to the hardness. However, as the thickness reaches 0.05 mm, both heights of the two steels were reduced to 0.352 mm (94.1 % decrease) and 0.304 mm (94.9 % decrease) respectively and the difference between them was not as significant. Hardness does not seem to matter when the web becomes extremely thin as in the case of the 0.05 mm thick web. For this instance, the arc heat may have annealed the heat treated D2 and changed its physical properties to those of the un-heat treated D2.

4.4 COMPLEMENTARY ANALYSIS

4.4.1 Bending Cutoff

For this test, the Rough & one Skim Cut experiment was performed on Aluminum 6061 and Yellow Brass 360. There was bending after the rough pass and the bent parts were cut off during a skim pass.

Figure 4.9 shows the three remnant pieces of cutoff parts for Aluminum 6061 with 0.15, 0.10, and 0.05 mm webs and for Yellow Brass 360 with 0.20, 0.15, 0.10 and 0.05 mm webs. These remnant pieces were separated and photographed together.



A. Cutoff parts of Aluminum 6061
Top: one skim pass
Bottom: rough cut

B. Cutoff parts of Yellow Brass 360
Top: one skim pass
Bottom: rough cut

Figure 4.9 The remnant pieces of cutoff after one skim pass

As shown in the Figure 4.9 B, the top webs were cut by a rough pass and one skim pass and the four removed pieces were cutoff during the skim pass. The 0.05 mm web (the last one on the right) in Figure 4.9 B shows some decrease of the web height during the Rough Cut because of the high heat arc.

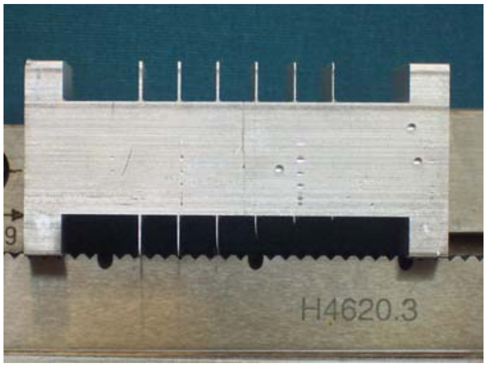
The final outcome for Yellow Brass 360, the bottom webs were Rough Cut (rough pass only) and were missing part of their height from web thicknesses 0.20 mm to 0.05 mm. This means there were some loses in the web because of the high heat arc as the thin web was cut. The bottom part of Figure 4.9 shows that the web height decreased as the webs became thinner.

There are two kinds of material loss when a thin web is cut: one is caused by the arc and the other by bending. As shown in Figure 4.9 the thinner the desired thickness, the less likely the web will survive these two failure modes.

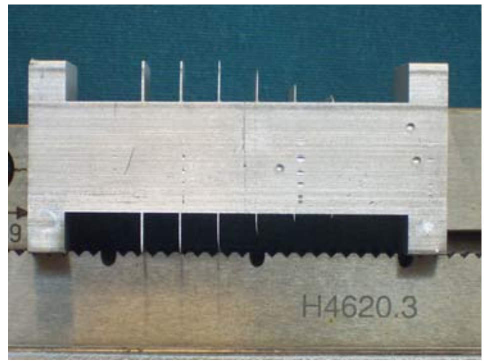
4.4.2 Offset and three skim pass for Aluminum 6061

This experiment demonstrates that web height may decrease during each skim pass. As shown in Table 3.7**,** the offset amounts of each cut differ according to each skim pass. The more skim passes that are taken, the milder the cutting conditions. This makes cutting more precise and results in a smoother surface, but it increases the time it takes to machine the part and for thin webs increases the possibility of undesired removal. Figure 4.10 shows the comparison of the web height for each cutting pass on Aluminum 6061.

A single Rough Cut (rough cut only: bottom) is compared to each step of the Rough & three Skim Cuts (top). A rough cut was performed first on the bottom, and then the Rough & three Skim Cuts were machined on the top of the workpiece. The top shows the difference in height that each skim pass made to the final web dimension. The specimen was left in the machine so there would be no need for realigning the part and to avoid introducing error into the experiment.



A. Top: rough pass
Bottom: rough cut only



B. Top: first skim pass
Bottom: rough cut only

C. Top: second skim pass
Bottom: rough cut only

D. Top: third skim pass
Bottom: rough cut only

Figure 4.10 Comparison of the web heights for a rough cut and a rough & three skim cuts in Aluminum 6061

In Figure 4.10 A there is a noticeable difference in web height and thickness between the rough pass of the Rough & three Skim Cuts and the single Rough Cut. All webs remained their full size during the rough pass. This is because the offset of the rough pass with Rough & three Skim Cuts was larger than the rough pass with a single Rough Cut. (The rough pass offset of the Rough Cut: 0.166 mm, and the rough pass offset with Rough & three Skim Cuts: 0.218 mm).

As shown in Figure 4.10 B, the desired height of the web remains constant during the first three webs (for 0.30, 0.25, and 0.2 mm), but the height of the web for the latter three webs (for 0.15, 0.10, and 0.05 mm) became shorter because of bending. As shown in Figure 4.18 C and D**,** the height and thickness of the web became shorter and thinner with each additional skim pass.

Offsets were made according to machine presets as shown in Table 3.7. There was no difference in the actual heights and thicknesses for the 0.30 mm and 0.25 mm webs even after the third skim pass. However, with the second skim pass for the 0.20 mm web, the height started to decrease slightly. For the 0.15 mm web, the decrease was significant after the first skim pass, and for the 0.10 mm and 0.05 mm webs, the decreases in height was more dramatic after the first skim pass.

All in all, the web heights started to decrease with 0.2 mm thickness and almost disappeared at the 0.05 mm thickness. This experiment shows how offsets affect web height and thickness.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

Wire Electric Discharge Machining (WEDM) uses thermal energy to achieve a high-precision metal removal process from a fine, accurately controlled electrical discharge. It is classified as a non-traditional machining process that has no friction between the material and tool. The spark carries enough energy to melt the work piece and consecutive sparks result in the erosion of the work piece. As the electrode is guided via a computer program with a determined set of design parameters, WEDM can produce the desired dimensions on the work piece within the proper tolerances. It is very difficult to obtain thin webs through conventional machining methods. It is also to be questioned just how thin of a web can be cut on a WEDM machine.

The purpose of this thesis study was to determine if there are significant differences in the height of the webs when the thickness becomes smaller and when different materials are cut on the WEDM machine. To accomplish the purpose of this study the following two hypotheses were established and were followed by their results:

- The null hypothesis 1: There are no significant differences in the height of the webs as the thickness becomes smaller.

This hypothesis was rejected because there are significant differences in web height as the thickness becomes smaller (see section 5.1 for an explanation of the results).

Due to bending and melting, web heights were significantly affected.

- The null hypothesis 2: There are no significant differences in the height of the webs when cutting different metals.

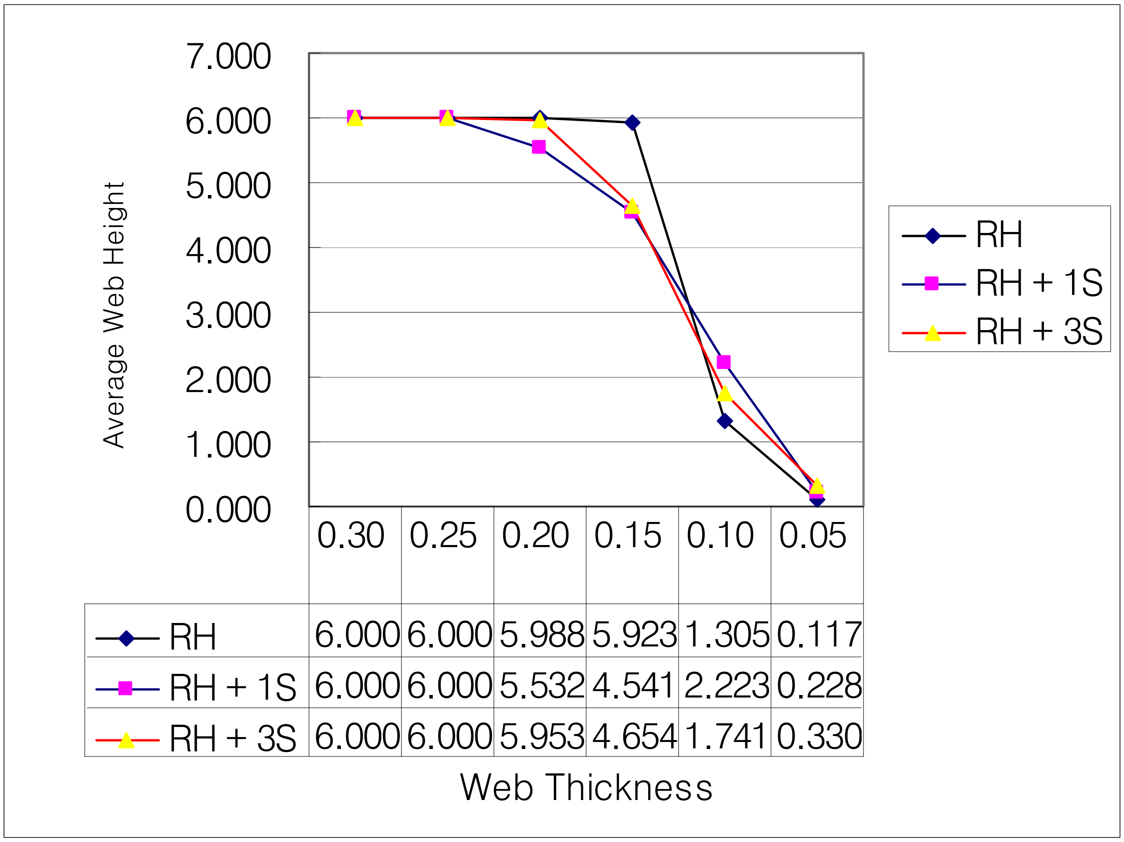
This hypothesis was rejected because there are significant differences in web height when different materials are cut on the WEDM machine (see section 5.2 for an explanation of the results). This is primarily due to the difference in material properties and the interaction with the electric arc.

5.1 CONCLUSION ON THE NULL HYPOTHESIS 1

The null hypothesis 1 states that there are no significant differences in the height of the webs as the thickness becomes smaller. This null hypothesis is rejected because the web thickness affects significantly the web heights across all metals.

Table 5.1 shows the total height of each web of all measured materials.

Table 5.1 The average height of each web of all measured materials



	0.30	0.25	0.20	0.15	0.10	0.05
RH	6.000	6.000	5.988	5.923	1.305	0.117
RH + 1S	6.000	6.000	5.532	4.541	2.223	0.228
RH + 3S	6.000	6.000	5.953	4.654	1.741	0.330

Table 5.1 shows the average height of each web thickness independent of the material. The trends show that as the web thickness decreases so does the height of the surviving portion of the web. As the web thickness became less than 0.15 mm, there was a drastic reduction in height. Some of the observations or insights are gained from this graph are as follows:

Rough Cut (rough pass only)

- For web thicknesses greater than or equal to 0.20 mm, there was no reduction in height. Webs of these sizes or greater can be cut using

WEDM without loss of height. Because there was no loss in height for the experiments using skim passes, it is safe to say that bending did not occur or slightly occurred without of the loss of the height.

- For 0.20 mm thick webs, there was a 0.2 % decrease in height during the Rough Cut. It is at this thickness that damage begins to occur for the softer materials. Brass was the only one that had a decrease in height. This may be due to its physical properties.
- The 0.15 mm thick web resulted in a 1.3% decrease in the average height for the Rough Cut. Aluminum 6061 decreased by 2.5%, Yellow brass 360 by 3.0% , 420 Stainless steel by 0.7%, D2 unheat-treated tool steel 0.2%, and D2 heat-treated tool steel retained its full height.
- A 0.10 mm thick web, the average height resulted in a 78.2% decrease for the Rough Cut. The heights of the webs were dramatically reduced with the exception of 420 Stainless steel. Aluminum 6061 decreased by 93.8%, Yellow brass 360 by 88.7%, 420 Stainless steel by 17.4%, D2 unheat-treated tool steel 95.9%, and D2 heat-treated tool steel by 95.5% During the rough cut the high heat arc burnt off the web. This shows that webs of 0.10 mm or less cannot be cut using the preset conditions of the WEDM machine. For cutting webs of this thickness, machine presets should be changed.
- At a web thickness of 0.05 mm, the average height decrease was

98.1% for the Rough Cut and only small portions were left for each of the tested materials. Aluminum 6061 web height was reduced by 97.3 %, Yellow brass 360 by 97.6 % , 420 Stainless steel by 98.2 %, D2 unheat-treated tool steel by 98.6%, and D2 heat-treated tool steel by 98.7%.

Rough & one Skim Cut (rough pass and one skim pass):

- There was no height decrease for the 0.30 and 0.25 mm webs.
- For 0.20 mm thick webs there was a 7.8 % decrease in height for the rough cut. Aluminum 6061 web height was reduced by 21.2 %, Yellow brass 360 by 17.8 % , 420 Stainless steel by 0 %, D2 unheat-treated tool steel by 0%, and D2 heat-treated tool steel also by 0%. Decreases in height of the aluminum and brass were due to bending.
- A 0.15 mm thick web resulted in a 24.3% decrease in height for the rough cut. Aluminum 6061 web height was reduced by 56.7 %, Yellow brass 360 by 56.0 % , 420 Stainless steel by 2.5 %, D2 unheat-treated tool steel by 6.4%, and D2 heat-treated tool steel by 0.0 %. It is important to note that this web height is proportional to the material hardness.
- A 0.10 mm thick web resulted in a 62.9% decrease for the Rough Cut. Aluminum 6061 web height was reduced by 84.4 %, Yellow brass 360 by 86.0 % , 420 Stainless steel by 59.7 %, D2 unheat-treated tool steel by 83.9%, and D2 heat-treated tool steel by 0.8 %.

- For web thicknesses of 0.05 mm, the average height resulted in a 98.1% decrease for the rough cut and only small portions were left for each of the tested materials. Aluminum 6061 web height was reduced by 97.9 %, Yellow brass 360 by 98.0 % , 420 Stainless steel by 96.5 %, D2 unheat-treated tool steel by 97.4%, and D2 heat-treated tool steel by 91.2%.
- For the Rough & one Skim Cut at thickness of 0.15 mm and 0.10 mm, most materials were significantly reduced, because the bent parts were cut off during the skim pass. However, the height of the D2 heat-treated tool steel was not reduced at the thickness of 0.10 mm because it was hard enough that it resisted bending and the web was not cut off during the skim pass. It can be said that the resulting web height, when machined in these five materials, is proportional to the hardness and melting temperature and inversely proportional to the CTE and thermal conductivity.

Rough & three Skim Cuts (rough pass and three skim passes):

- There was no height decrease for the 0.30 and 0.25 mm webs.
- For 0.20 mm thick webs, there was a 0.8 % decrease for the rough cut. Aluminum 6061 web height was reduced by 1.5 %, Yellow brass 360 by 2.4 % , 420 Stainless steel by 0 %, D2 unheat-treated tool steel by 0%, and D2 heat-treated tool steel by 0%.
- For a 0.15 mm thick web, the average height resulted in a 22.4%

decrease for the Rough Cut. Aluminum 6061 web height was reduced by 39.8 %, Yellow brass 360 by 42.1 % , 420 Stainless steel by 1.1 %, D2 unheat-treated tool steel by 27.8%, and D2 heat-treated tool steel by 1.4 %.

- For a 0.10 mm thick web, the average height resulted in a 71.0% decrease for the Rough Cut. Aluminum 6061 web height was reduced by 76.4 %, Yellow brass 360 by 80.1 % , 420 Stainless steel by 68.9 %, D2 unheat-treated tool steel by 81.2%, and D2 heat-treated tool steel by 48.3 %.
- At a web thickness of 0.05 mm, the average height resulted in a 94.5% decrease for the Rough Cut and again only small portions were left for each of the tested materials. Aluminum 6061 web height was reduced by 92.3 %, Yellow brass 360 by 96.3 % , 420 Stainless steel by 94.9 %, D2 unheat-treated tool steel by 94.1%, and D2 heat-treated tool steel by 94.9%.

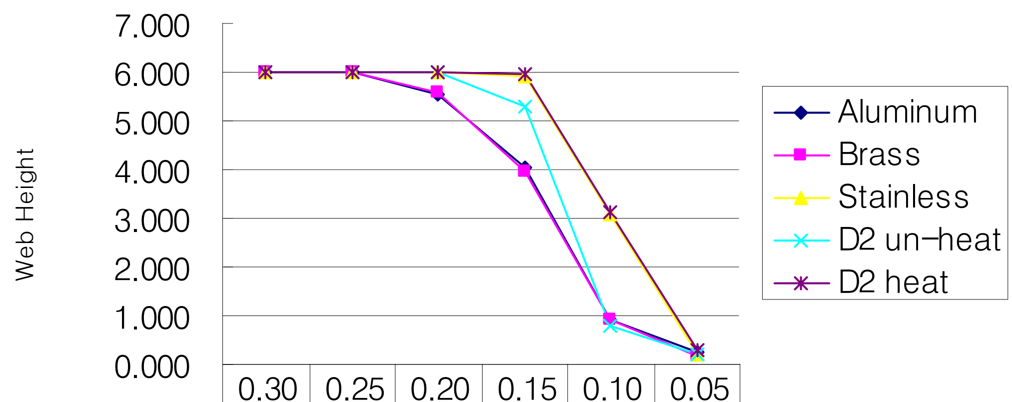
The Rough & three Skim Cut experiment showed similar results to the Rough & one Skim Cut experiment. For the 0.10 mm and 0.05 mm, the first mentioned had web heights that were a little taller than those for the latter. This is because of the small difference in the wire offset for the rough pass. With skim cuts it is less likely that the web will be lost due to the high heat arc and because a lower heat arc is used for the skim pass it is also less likely they will be lost when the web gets a little thinner. The results from the aluminum demonstrate this phenomenon.

5.2 CONCLUSION ON THE NULL HYPOTHESIS 2

The null hypothesis 2 states that there are no significant differences in the height of the cutting webs for different metals. This null hypothesis is rejected because the web thickness affects significantly the web heights of each of the materials.

Table 5.2 shows the average height of each cut of all measured materials

Table 5.2 The average height of each cut of all measured materials



	0.30	0.25	0.20	0.15	0.10	0.05
Aluminum	6.000	6.000	5.545	4.022	0.909	0.252
Brass	6.000	6.000	5.575	3.979	0.903	0.162
Stainless	6.000	6.000	6.000	5.913	3.082	0.209
D2 un-heat	6.000	6.000	6.000	5.311	0.780	0.197
D2 heat	6.000	6.000	6.000	5.972	3.108	0.305

Web Thickness

All materials show a general trend of reduced web height as the thickness of the web decreases. For web thicknesses of 0.10 mm and 0.05 mm the web was almost completely lost for all materials. Table 5.3 shows the percent decrease in average height for each of the materials.

Table 5.3 The percent decrease in the average height.

Web Thickness	Aluminum	Brass	Stainless	D2 Un-heat treated	D2 Heat Treated
0.30	0.00%	0.00%	0.00%	0.00%	0.00%
0.25	0.00%	0.00%	0.00%	0.00%	0.00%
0.20	7.60%	7.10%	0.00%	0.00%	0.00%
0.15	33.00%	33.70%	1.50%	11.50%	0.50%
0.10	84.90%	85.00%	48.60%	87.00%	48.20%
0.05	95.80%	97.30%	96.50%	96.70%	94.90%

Some of the observations and trends between the different metals used in the experiment are as follows.

- For webs equal to or larger than 0.20 mm there was no change in height.
- Materials with similar properties such as aluminum/brass and stainless/D2 steels produced similar results. This may confirm that the survival of thin webs for different materials may be predicted based upon their physical properties. With further research, it may be possible to determine which physical properties are the best predictors. This thesis only considered four properties: thermal conductivity, coefficient of thermal expansion, hardness, and melting temperature.
- Hardness does have an effect on the web height. By changing only the hardness for D2 steel there was a significant difference in the height. The reason for this is that a harder material is less likely to bend and be cut off by skim passes.

- When the web becomes extremely thin as in the case of the 0.05 mm thick web, there may be some property changes in the material due to the arc heat. For instance, the arc heat may have annealed the heat treated D2 and changed its physical properties to those of the un-heat treated D2. Such phenomena would decrease the likelihood of web survival.
- If there was a single rough cut used to get the finished dimensions then the possibility of the web being burnt off due to the high heat arc increased. This is because the finished web dimension may be to thin to handle the high heat. With skim passes the wire offset is larger on the roughing pass and there is more material to absorb the heat.
- Web thicknesses of 0.05 mm had an average web loss of over 90% for all materials.

With the study that was there were some valuable insights and trends that were observed when cutting thin webs in different materials.

5.3 RECOMMENDATIONS FOR FURTHER STUDY

During this study of thin web cutting on a WEDM machine several other opportunities for further study became apparent. This further study would strengthen the understanding of the limits of thin web cutting and the differences in cutting thin webs in materials with different physical properties like melting temperature, thermal conductivity, hardness, and CTE. These ideas for further study are presented below.

- Perform the study in a closed state to determine how thin webs can be cut on WEDM. Bending occurred in the experiment for this thesis because the webs were unconstrained on one side of the material. If the experiment is performed in the closed state or with both sides constrained as shown in the Figure 5.1, bending would be avoided.

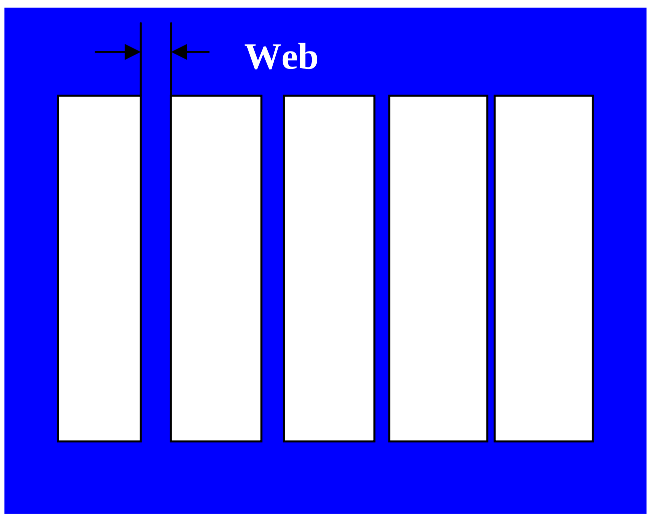


Figure 5.1 Web design with closed state

- Analyze why bending occurs on the web. Most bending occurred with a web thickness of 0.20 mm or less. All bending was inclined toward the last side that was cut. It may have been caused by shrinkage after the rapid cooling from the high water passage. One other thing that may have caused bending is the current in the wire creating a magnetic field around it. This magnetic field may have pulled the heated web towards it.

- What caused the different web height of each material with the different thickness? Were the heights affected by the material hardness, thermal conductivity, melting temperature, or CTE? If an analysis of hardness is performed, different hardness's of the same material will be required with different heat treatments.
- Observations showed that there may have been more significant losses in the web height of aluminum and brass due to a high CTE or melting Temperature. The effects of heat on such thin webs may cause them to expand and contract. This may be an area for future research.
- Corrosion effects may also have caused the surface defects during the WEDM process because water is a chemical solvent. Water trapped inside micro-cracks is not deionized and would be more corrosive. It may have caused different attrition levels for the different materials.

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APPENDIX

APPENDIX A:

WEDM MACHINE SETTING AND PROGRAMS FOR THE TEST

ROUGH CUT

```
"( VER :  2.00A Sodick database 1.2[0]I );"
"(        Search        Data        :Water,BrassƒÓ0.0098,Punch,Open-
U,Al,1.181inch,E=0,20.0ƒÊ,1times,0.00000 );"
"(       ON OFF   IP HRP MAO  SV V   SF C PIK CTRL  WK  WT  WS  WP);"
"C000   =   009 014 2215 000 250 040 8 0047 0 000 0000 025 100 100 045;"
"C001   =   011 014 2215 000 251 035 8 0047 0 000 0000 025 100 100 055;"
"H000   = + 00000.00039 (Aprch.)                  ;"
"H001   = + 00000.00760 (  1ST )                  ;"
"H999   = + 00000.00200 ( Taper Offset )          ;"
"( Other Information );"
"(        UP   DN  !       1st 2nd~ !             );"
"(----------------------!------------------!---------------------);"
"(   Dice  :0.010 0.011 !    PS :15.0  1.0 !       Resi.: 50000 );"
"(   Nozzle: 0.24  0.24 !   UP  :10.0  1.0 !  Taper Offse:0.0020 );"
"( Distance:0.394 0.004 !   DN  : 6.0  1.0 !                    );"
"QAIC(2,1,0.00492,001.0,0.00768,0.00118,006.0,0014,0034,10,035);"
"N0111(1ROUGH);"
"G90;"
"G54;"
"T82;"
"T96;"
"T84;"
"G00X.1968Y.1;"
"G92X.1968Y.3362;"
"G29;"
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"G01G41Y.2362;"
"C001(ROUGH PASS CONDITIONS H&C);"
"G01Y0;"
```

```
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"Y.2362;"
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"T85;"
"T87;"
"T83;"
"M02;"
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ROUGH & ONE SKIM CUT

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U,Al,1.181inch,E=0,20.0ƒÊ,1times,0.00000 );"
"(          ON OFF   IP HRP MAO  SV V   SF C PIK CTRL  WK  WT  WS  WP);"
"C000   =   009 014 2215 000 250 040 8 0047 0 000 0000 025 100 100 045;"
"C001   =   011 014 2215 000 251 035 8 0047 0 000 0000 025 100 100 055;"
"C002   =   002 023 2215 000 750 053 8 6028 0 000 0000 025 100 100 012;"
"H000   = + 00000.00039 (Aprch.)                              ;"
"H001   = + 00000.00929 (  1ST )                              ;"
"H002   = + 00000.00575 (  2ND )                              ;"
"H999   = + 00000.00200 ( Taper Offset )                      ;"
"( Other Information );"
```

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"(            UP   DN  !        1st 2nd~ !                    );"
"(----------------------!-------------------!---------------------);"
"(   Dice  :0.010 0.011 !    PS :15.0  1.0 !        Resi.: 50000 );"
"(   Nozzle: 0.24  0.24 !   UP  :10.0  1.0 !  Taper Offse:0.0020 );"
"( Distance:0.394 0.004 !   DN  : 6.0  1.0 !                    );"
"QAIC(2,1,0.00492,001.0,0.00768,0.00118,006.0,0014,0034,10,035);"
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"G90;"
"G54;"
"G29;"
"T82;"
"T96;"
"T84;"
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"C000H001(LEAD IN CONDITIONS H&C);"
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"C001(ROUGH PASS CONDITIONS H&C);"
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ROUGH & THREE SKIM CUTS

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"(      ON OFF   IP HRP MAO  SV V   SF C PIK CTRL  WK  WT  WS  WP);"
"C000   =   009 014 2215 000 250 040 8 0047 0 000 0000 025 100 100 045;"
"C001   =   011 014 2215 000 251 035 8 0047 0 000 0000 025 100 100 055;"
"C002   =   002 023 2215 000 750 053 8 6028 0 000 0000 025 100 100 012;"
"C003   =   000 001 1015 000 000 030 6 7024 0 008 0000 025 100 100 012;"
"C004   =   000 001 1015 000 000 018 2 7028 0 009 0000 025 100 100 012;"
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"H001   = + 00000.01012 (  1ST )                    ;"
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"H003   = + 00000.00539 (  3RD )                    ;"
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"M02;"
```

APPENDIX B:

WEDM MACHINE SETTING AND PROGRAMS FOR THE VERTICAL AND HORIZONTAL DIRECTION BENDING TEST

VERTICAL AND HORIZONTAL DIRECTION BENDING TEST

```
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"(          ON OFF   IP HRP MAO  SV V   SF C PIK CTRL  WK  WT  WS  WP);"
"C000   =   007 015 2215 000 260 040 8 0098 0 000 0000 025 160 100 040;"
"C001   =   009 015 2215 000 270 035 8 0098 0 000 0000 025 130 100 045;"
"H000   = + 00000.00039 (Aprch.)                          ;"
"H001   = + 00000.00709 (  1ST )                          ;"
"H999   = + 00000.00000 ( Taper Offset )                  ;"
"( Other Information );"
"(            UP   DN  !       1st 2nd~ !                  );"
"(----------------------!------------------!---------------------);"
"(   Dice  :0.010 0.011 !    PS :10.0  1.0 !        Resi.: 50000 );"
"(   Nozzle: 0.24  0.24 !   UP  : 6.0  1.0 !  Taper Offse:0.0000 );"
"( Distance:0.004 0.004 !   DN  : 6.0  1.0 !                   );"
"QAIC(2,1,0.00492,000.5,0.00728,0.00039,002.0,0054,0092,10,035);"
";"
"G90;"
"G54;"
"G92X-.1Y-3.9;"
"G29;"
"T82;"
"T96;"
"T84;"
"C001;"
"H001;"
"G1 X-.006;"
"Y-2.369;"
"X.361;"
"Y-3.369;"
```

"X.619;"
"Y.006;"
"X3.631;"
"Y-3.881;"
"X.020;"
"T85;"
"T87;"
"T83;"
"T97;"
"T90;"
" M2;"

APPENDIX C:

WEDM MACHINE SETTING AND PROGRAMS FOR THE LEFT AND RIGHT DIRECTION BENDING TEST

LEFT AND RIGHT BENDING TEST

"(VER : 2.00A Sodick database 1.2[0]I);"
"(Search Data :Water,BrassƒÓ0.0098,Punch,Open-U,Al,1.181inch,E=0,20.0ƒÊ,1times,0.00000);"
"(ON OFF IP HRP MAO SV V SF C PIK CTRL WK WT WS WP);"
"C000 = 009 014 2215 000 250 040 8 0047 0 000 0000 025 100 100 045;"
"C001 = 011 014 2215 000 251 035 8 0047 0 000 0000 025 100 100 055;"
"C002 = 002 023 2215 000 750 053 8 6028 0 000 0000 025 100 100 012;"
"H000 = + 00000.00039 (Aprch.) ;"
"H001 = + 00000.00929 (1ST) ;"
"H002 = + 00000.00575 (2ND) ;"
"H999 = + 00000.00200 (Taper Offset) ;"
"(Other Information);"
"(UP DN ! 1st 2nd~ !);"
"(----------------------!------------------!---------------------);"
"(Dice :0.010 0.011 ! PS :15.0 1.0 ! Resi.: 50000);"
"(Nozzle: 0.24 0.24 ! UP :10.0 1.0 ! Taper Offse:0.0020);"
"(Distance:0.394 0.004 ! DN : 6.0 1.0 !);"
"QAIC(2,1,0.00492,001.0,0.00768,0.00118,006.0,0014,0034,10,035);"
";"
"G90;"
"G54;"
"T82;"
"T96;"
"T84;"
"G92X0.0Y0.6;"
"G29;"
"C001H001;"
"G41;"
"G01Y0.5;"
"G01Y0.0;"
"X.25;""Y0.5;"

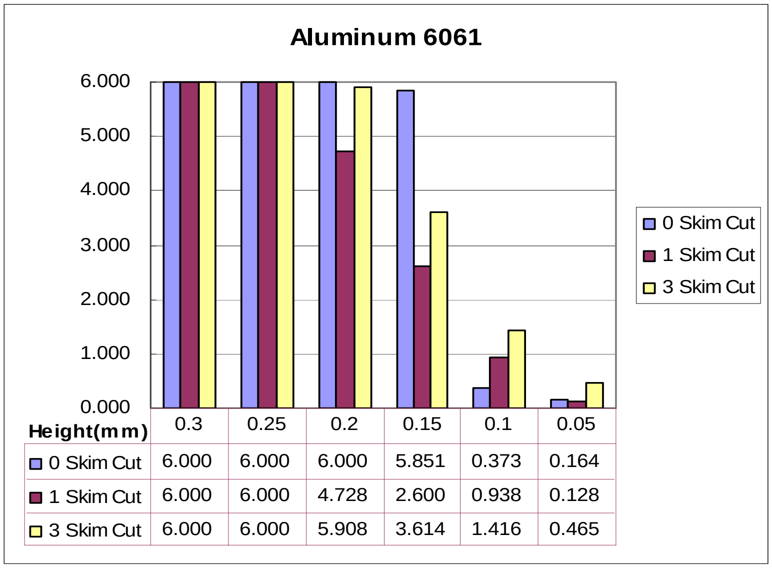
```
"G00Z0;"
"G01X.258;"
"Y0.0;"
"X.50;"
"Y.5;"
"X.508;"
"Y0.0;"
"X.75;"
"Y.5;"
"G00Z0;"
"G40Y.6;"
"G00X1.6;"
"G92X0.0Y0.6;"
"G29;"
"C001H001;"
"G42;"
"G01Y0.5;"
"G01Y0.0;"
"X-.25;"
"Y0.5;"
"G00Z0;"
"G01X-.258;"
"Y0.0;"
"X-.50;"
"Y.5;"
"X-.508;"
"Y0.0;"
"X-.75;"
"Y.5;"
"G40Y.6;"
"T85;"
"T87;"
"T83;"
"T97;"
"M02;"
```

APPENDIX D:

RAW DATA ON HEIGHT, THICKNESS, AND GRAPH

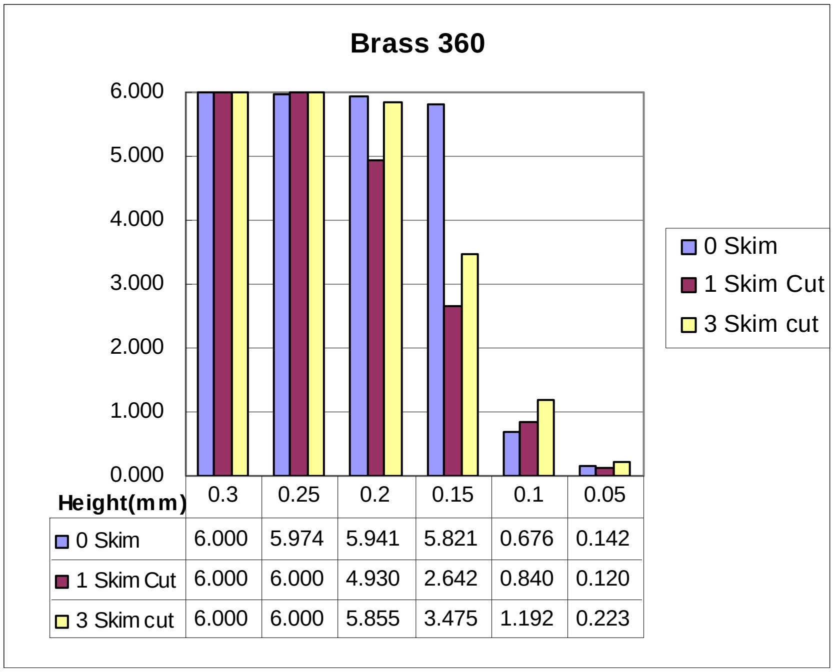
Aluminum 6061

Aluminum		Tab Height unit: mm				Tab Thickness unit: mm			
		First	Second	Third	Avg.	First	Second	Third	Avg.
RH	0.30	6.000	6.000	6.000	6.000	0.305	0.305	0.305	0.305
	0.25	6.000	6.000	6.000	6.000	0.254	0.254	0.254	0.254
	0.20	6.000	6.000	6.000	6.000	0.203	0.203	0.191	0.199
	0.15	5.886	5.801	5.865	5.851	0.165	0.152	0.165	0.161
	0.10	0.413	0.308	0.399	0.373				
	0.05	0.138	0.148	0.205	0.164				
RH + 1S	0.30	6.000	6.000	6.000	6.000	0.292	0.292	0.292	0.292
	0.25	6.000	6.000	6.000	6.000	0.241	0.241	0.241	0.241
	0.20	4.740	4.775	4.669	4.728	0.191	0.191	0.191	0.191
	0.15	2.562	2.654	2.584	2.600	0.141	0.140	0.140	0.140
	0.10	0.904	0.966	0.943	0.938	0.102	0.102	0.102	0.102
	0.05	0.104	0.164	0.117	0.128				
RH + 3S	0.30	6.000	6.000	6.000	6.000	0.279	0.292	0.292	0.288
	0.25	6.000	6.000	6.000	6.000	0.241	0.241	0.241	0.241
	0.20	5.960	5.791	5.972	5.908	0.191	0.191	0.191	0.191
	0.15	3.807	3.231	3.803	3.614	0.140	0.140	0.140	0.140
	0.10	1.534	1.215	1.498	1.416	0.089	0.089	0.089	0.089
	0.05	0.445	0.506	0.443	0.465				



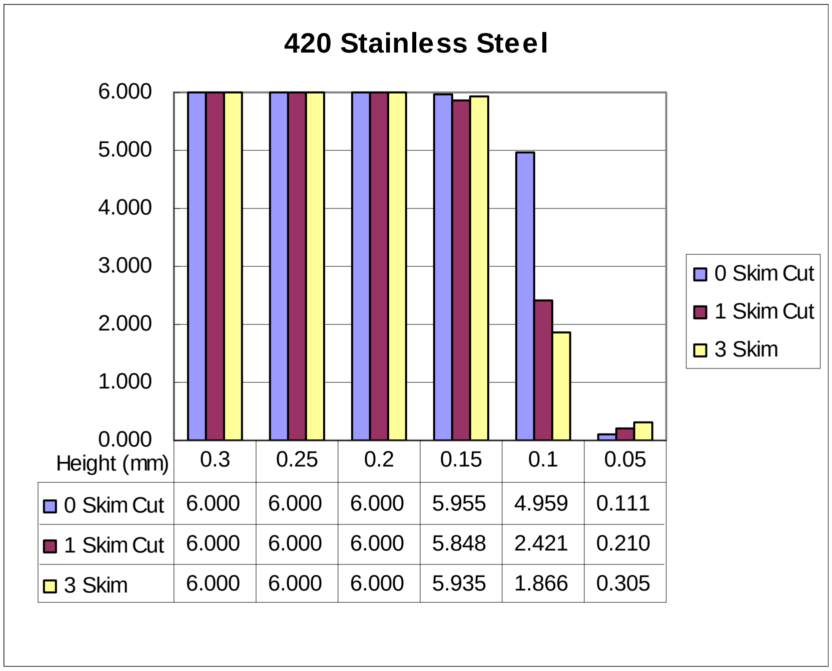
<u>Brass 360</u>

Brass		Tab Height unit: mm				Tab Thickness unit: mm			
		First	Second	Third	Avg.	First	Second	Third	Avg.
RH	0.30	6.000	6.000	6.000	6.000	0.292	0.305	0.292	0.296
	0.25	6.000	5.959	5.962	5.974	0.241	0.241	0.241	0.241
	0.20	6.000	5.900	5.925	5.941	0.191	0.203	0.191	0.195
	0.15	5.894	5.709	5.859	5.821	0.140	0.140	0.152	0.144
	0.10	0.688	1.009	0.330	0.676				
	0.05	0.168	0.126	0.134	0.142				
RH + 1S	0.30	6.000	6.000	6.000	6.000	0.292	0.279	0.279	0.284
	0.25	6.000	6.000	6.000	6.000	0.241	0.229	0.229	0.233
	0.20	5.162	4.782	4.847	4.930	0.191	0.178	0.178	0.182
	0.15	2.771	2.524	2.630	2.642	0.140	0.127	0.127	0.131
	0.10	0.963	0.764	0.794	0.840	0.089	0.089	0.089	0.089
	0.05	0.187	0.070	0.102	0.120				
RH + 3S	0.30	6.000	6.000	6.000	6.000	0.279	0.279	0.279	0.279
	0.25	6.000	6.000	6.000	6.000	0.229	0.229	0.229	0.229
	0.20	5.847	5.887	5.832	5.855	0.178	0.178	0.178	0.178
	0.15	3.498	3.476	3.450	3.475	0.127	0.127	0.127	0.127
	0.10	1.187	1.235	1.152	1.192	0.076	0.076	0.076	0.076
	0.05	0.204	0.215	0.251	0.223				



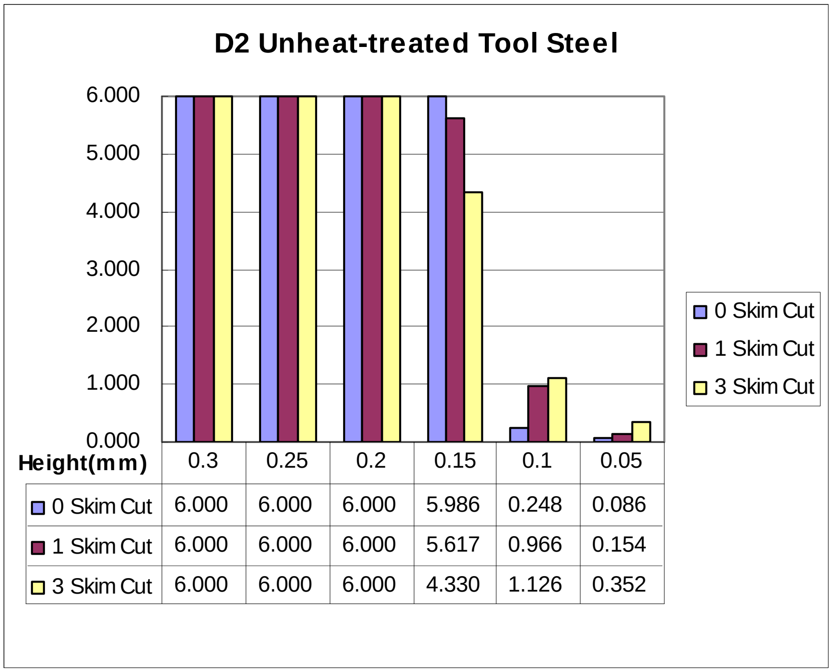
420 Stainless Steel

Stainless		Tab Height unit: mm				Tab Thickness unit: mm			
		First	Second	Third	Avg.	First	Second	Third	Avg.
RH	0.30	6.000	6.000	6.000	6.000	0.292	0.292	0.292	0.292
	0.25	6.000	6.000	6.000	6.000	0.241	0.241	0.241	0.241
	0.20	6.000	6.000	6.000	6.000	0.191	0.191	0.191	0.191
	0.15	5.951	5.964	5.949	5.955	0.140	0.140	0.140	0.140
	0.10	4.378	5.399	5.100	4.959	0.089	0.089	0.089	0.089
	0.05	0.151	0.102	0.081	0.111				
RH + 1S	0.30	6.000	6.000	6.000	6.000	0.292	0.292	0.292	0.292
	0.25	6.000	6.000	6.000	6.000	0.241	0.241	0.241	0.241
	0.20	6.000	6.000	6.000	6.000	0.191	0.191	0.191	0.191
	0.15	5.605	5.981	5.958	5.848	0.140	0.140	0.140	0.140
	0.10	2.640	2.277	2.345	2.421	0.089	0.089	0.089	0.089
	0.05	0.212	0.210	0.208	0.210				
RH + 3S	0.30	6.000	6.000	6.000	6.000	0.279	0.279	0.279	0.279
	0.25	6.000	6.000	6.000	6.000	0.229	0.229	0.229	0.229
	0.20	6.000	6.000	6.000	6.000	0.178	0.178	0.178	0.178
	0.15	6.000	5.952	5.853	5.935	0.127	0.127	0.127	0.127
	0.10	2.040	1.850	1.708	1.866	0.076	0.076	0.076	0.076
	0.05	0.348	0.221	0.345	0.305				



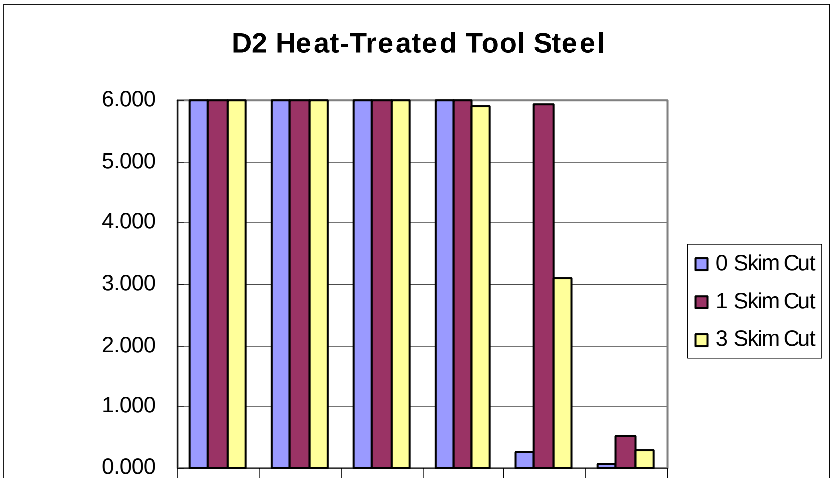
<u>D2 Unheat-treated Steel</u>

D2		Tab Height unit: mm				Tab Thickness unit: mm			
		First	Second	Third	Avg.	First	Second	Third	Avg.
RH	0.30	6.000	6.000	6.000	6.000	0.292	0.292	0.292	0.292
	0.25	6.000	6.000	6.000	6.000	0.241	0.241	0.241	0.241
	0.20	6.000	6.000	6.000	6.000	0.191	0.191	0.191	0.191
	0.15	6.000	6.000	5.957	5.986	0.140	0.140	0.140	0.140
	0.10	0.235	0.257	0.252	0.248				
	0.05	0.089	0.084	0.085	0.086				
RH + 1S	0.30	6.000	6.000	6.000	6.000	0.292	0.292	0.292	0.292
	0.25	6.000	6.000	6.000	6.000	0.241	0.241	0.241	0.241
	0.20	6.000	6.000	6.000	6.000	0.191	0.191	0.191	0.191
	0.15	5.919	5.001	5.931	5.617	0.140	0.140	0.140	0.140
	0.10	0.982	0.987	0.929	0.966	0.076	0.076	0.076	0.076
	0.05	0.165	0.158	0.138	0.154				
RH + 3S	0.30	6.000	6.000	6.000	6.000	0.279	0.279	0.279	0.279
	0.25	6.000	6.000	6.000	6.000	0.229	0.229	0.229	0.229
	0.20	6.000	6.000	6.000	6.000	0.178	0.178	0.178	0.178
	0.15	4.250	4.492	4.247	4.330	0.127	0.127	0.127	0.127
	0.10	1.306	0.856	1.216	1.126	0.076	0.076	0.076	0.076
	0.05	0.319	0.272	0.467	0.352				



D2 heat-treated Steel

D2H		Tab Height unit: mm				Tab Thickness unit: mm			
		First	Second	Third	Avg.	First	Second	Third	Avg.
RH	0.30	6.000	6.000	6.000	6.000	0.292	0.292	0.292	0.292
	0.25	6.000	6.000	6.000	6.000	0.241	0.241	0.241	0.241
	0.20	6.000	6.000	6.000	6.000	0.191	0.191	0.191	0.191
	0.15	6.000	6.000	6.000	6.000	0.140	0.140	0.140	0.140
	0.10	0.324	0.244	0.241	0.270				
	0.05	0.094	0.079	0.071	0.081				
RH + 1S	0.30	6.000	6.000	6.000	6.000	0.292	0.292	0.292	0.292
	0.25	6.000	6.000	6.000	6.000	0.241	0.241	0.241	0.241
	0.20	6.000	6.000	6.000	6.000	0.191	0.191	0.191	0.191
	0.15	6.000	6.000	6.000	6.000	0.140	0.140	0.140	0.140
	0.10	5.965	5.969	5.919	5.951	0.089	0.089	0.089	0.089
	0.05	0.189	0.189	1.213	0.530				
RH + 3S	0.30	6.000	6.000	6.000	6.000	0.279	0.279	0.279	0.279
	0.25	6.000	6.000	6.000	6.000	0.229	0.229	0.229	0.229
	0.20	6.000	6.000	6.000	6.000	0.178	0.178	0.178	0.178
	0.15	5.916	5.939	5.897	5.917	0.127	0.127	0.127	0.127
	0.10	3.709	4.075	1.529	3.104	0.076	0.076	0.076	0.076
	0.05	0.227	0.426	0.258	0.304				



Height(mm)	0.3	0.25	0.2	0.15	0.1	0.05
0 Skim Cut	6.000	6.000	6.000	6.000	0.270	0.081
1 Skim Cut	6.000	6.000	6.000	6.000	5.951	0.530
3 Skim Cut	6.000	6.000	6.000	5.917	3.104	0.304

APPENDIX E:

HARDNESS MEASUREMENT AND BRINELL HARDNESS

NO.	Materials	test1	test2	test3	test4	test5	Average	Brinell Hardness
1	Aluminum 6061 T6	59.9	59	60.7	59.6	58.4	HRB 59.5	95.0
2	Yellow Brass SS360	61.7	69.8	72.2	71.8	72.8	HRB 71.3	123.0
3	420 Stainless Steel	92.9	97.1	97.1	96.9	98.1	HRB 97.0	223.0
4	D2 un-heat-treated tool steel	96.6	96.8	97.1	96.3	96.5	HRB 96.6	221.0
5	D2 heat-treated tool steel	59.1	60.2	61.7	60.9	60.9	HRC 60.7	658.0

APPENDIX F:

THERMAL CONDUCTIVITY, MELTING TEMPERATURE, AND CTE

	Thermal conductivity	Melting temperature	Hardness	CTE
Aluminum 6061 T6	167W/m-k	580-650^{0}C	Brinell 95	23.6μm/m.^{0}C
Yellow Brass SS360	123W/m-k	888^{0}C	Brinell 123	20.5μm/m.^{0}C
420 Stainless Steel	24.9W/m-k	1450-1510^{0}C	Brinell 223	10.3μm/m.^{0}C
D2 un-heat-treated tool steel	18.8W/m-k	1450^{0}C	Brinell 221	10.4μm/m.^{0}C
D2 heat-treated tool steel	18.8W/m-k	1450^{0}C	Brinell 658	10.4μm/m.^{0}C