The effects of the processing parameters on the laser machining of a green china ceramic

Sam Nerone Ramrattan
Iowa State University

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The effects of the processing parameters on the laser machining of a green china ceramic

Ramrattan, Sam Nerone, Ph.D.

Iowa State University, 1989
The effects of the processing parameters on the laser machining of a green china ceramic

by

Sam Nerone Ramrattan

A Dissertation Submitted to the Graduate Faculty in Partial Fulfillment of the Requirements for the Degree of

DOCTOR OF PHILOSOPHY

Department: Industrial Education and Technology
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Signature was redacted for privacy.

In Charge of Major Work

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For the Major Department

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For the Graduate College

Iowa State University
Ames, Iowa
1989

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CHAPTER 1. INTRODUCTION

The earliest use of ceramics was in making pottery and bricks. This practice dates back to as early as 2000 B.C. Ceramics play an important role in today's high tech society, where they have a tremendous range of application. Typical examples of the ceramics used in manufacturing and building construction are: building materials such as cement, bricks, and tiles; optical equipment such as glass ware, eye glasses, microscopes, and windows; sanitary ware such as sinks and toilets; earthenware such as china, stoneware, and porcelain for ornamental objects; and tools in the form of abrasives like sandpaper, grinding wheels, and cutting tools. The electronic circuitry industry is a major consumer of ceramic materials used in capacitors, thermistors, varistors, piezoelectric devices, and magnet cores. Ceramic chips allow computers to continually increase in computing power as their sizes shrink dramatically.

Other examples such as electrical and thermal insulators, as seen in the spark plug, and corrosion resistant containers used in the chemical industry indicate the wide range of uses for ceramics as engineering materials.

Common methods of processing ceramics include wet plastic forming, dry powder pressing, hot pressing, and slip casting. After any of these processes, the desired shape is given strength by firing.

Slip casting has made possible elaborate and complex castings not achievable with other ceramic processing techniques. The main advantage
of slip casting is that it can produce much thinner sections and much finer details than press molding. Slip cast molds can be much deeper than press molds.

Some typical products made by slip casting china would be: table ware, sanitary ware (sinks, bath tubs, and toilet tanks), ornamental figurines, and industrial components.

There are three main disadvantages of using slip casting. Firstly, a considerable amount of water is absorbed by the plaster mold during each casting, so that the saturated mold has to be dried out between each casting. Secondly, the part shrinks considerably during the process. Thirdly, there is the labor intensive nature of the process and, consequently, a high rate of defect while punching and trimming greenware.

High shrinkage and wet molds reduce cycle time, which affects the efficiency and productivity of the slip casting industry, but the discovery of deflocculants and their later improvements has lessened these problems. This discovery has made slip casting the viable mass production process it is today. How is the third problem solved? How can the slip casting process be fully automated, and how can the human problems be eliminated or reduced, while improving the cut quality of the greenware?

Lasers are used in some machining operations. The focused, high-energy density beam melts and vaporizes material. The laser provides a means of material processing without any mechanical stresses.

This study will investigate a technique of laser cutting slip cast china greenware. The process will be automated to help eliminate the problems due to manual punching and trimming of the greenware. The study
will provide details of the processing parameters relating to the laser cutting one type of china greenware.

Statement of the Problem

The problem of this study is threefold:

1. To investigate the quality of cut as affected by the power, moisture content, and feed rate.
2. To investigate the thickness of the heat-affected zone as affected by the power, moisture content, and feed rate.
3. To investigate the weight of dross as affected by the power, moisture content, and feed rate.

The Purpose of the Study

The purpose of the study is to investigate the quality of the cut, the thickness of the heat-affected zone, and the amount of dross produced by laser cutting green china ceramics. This study seeks an alternative method to cut greenware, which will reduce the high rate of defect found in conventional punching and trimming. The information gathered will be important in the development of a new laser cutting process for green china ceramics.

This new cutting process will afford greater:

1. Reliability - this will minimize the human errors that are normally found in the conventional methods.
2. Repeatability - being a controlled automated process, quality parts can be produced repeatedly.
3. Flexibility - this means that there is a wider range at which
the green ware can be cut.

4. Efficiency - the process will minimize defects which would normally be caused by the inability to flexibly schedule the cuts. This method will give a greater lead time for cutting operations. Larger batches could, therefore, be processed at lower cost.

5. Effectiveness - this process produces the desired effect in cutting.

With all these considerations, the laser cutting of green china ceramics would result in reduced costs, increased productivity, and improved quality over the conventional process.

Need for the Study

Ceramics have many desirable properties, but there are some problems preventing their widespread use. This fact is noted by Jacobs and Kilduff (1985) who state:

Ceramics offer advantages for engine materials but pose some serious challenges because of their strength, ductility, and fracture-resistant properties and the available processing technology (p. 306).

New ceramic materials continue to be developed, yet processing technologies continue to lag. In making particular reference to ceramics, Jacobs and Kilduff further say:

The key to broader acceptance lies in processing that will ensure highly reliable parts to fit into material systems (p. 323).
The ceramic raw materials may be less expensive than other materials but the limited processing technologies make product cost high. Processing problems should be given the research priority in this field.

There is a need to study the processing of ceramics in more detail than to study the processing of other common industrial materials such as woods, metals, and plastics. The reason is that ceramics are not as machinable as these other materials. Most fired ceramics are hard and not easily machined; brittle, eliminating cold working (there are a few exceptions, such as the machining of pressed ceramic before firing in the "leather hard" condition and soft materials such as graphite, boron nitride, and macor); and very little can be done to change the properties of the material. In relation to the machining of post fired ceramics, Kalpakjian (1985) states:

After firing, additional machining may be performed to remove flaws and to improve surface finish and tolerances. The processes that can be used are grinding, lapping, ultrasonic, chemical, and electrodischarge machining. The choice of process is important in view of the brittle nature of most ceramics and the additional costs involved in material removal (pp. 677-678).

Many problems exist with the conventional processing techniques, for example the labor intensive tasks of trimming and punching of greenware which always require subsequent smoothing of the cut edges with a wet sponge. These are costly and time consuming steps in the process and it is necessary to investigate ways of alleviating these problems.

Bearing in mind the fact that in many cases it is impractical or uneconomical to attempt to change dimensions after firing, it may be
practical to process ceramics with a tool which does not come in contact with the work. The laser is such a tool and with its use no mechanical stresses are left on the work since there is lack of physical contact. It may be advantageous to laser cut ceramics in their green state since laser cutting fired ceramics require larger power output and thermal shock may leave jagged edges.

Control of the quality of the ceramic material along with the processing parameters is essential in improving the process. Improvement of processes in needed with the intent of making a more productive and efficient world.

Research Questions and Hypotheses of the Study

Questions

The questions to be investigated are:

1. Is the quality of cut in the greenware affected by one of, or a combination of variables:
   a. the power of the laser beam,
   b. the moisture content of the greenware, and
   c. the feed rate at which it is cut?

2. Is the thickness of the heat-affected zone in the greenware affected by one of, or a combination of, the following:
   a. the power of the laser beam,
   b. the moisture content of the greenware, and
   c. the feed rate at which it is cut?
3. Is the weight of dross on the greenware affected by one of, or a combination of, the following:
   a. the power of the laser beam,
   b. the moisture content of the greenware, and
   c. the feed rate at which it is cut?

   The following hypotheses will be used to test these questions.

The hypotheses are based on the three-way ANOVA model:

\[ Y_{i,j,k} = \mu + \alpha_i + \beta_j + \gamma_k + \alpha\beta_i,j + \alpha\gamma_i,k + \beta\gamma_j,k + \alpha\beta\gamma_i,j,k + \epsilon \]

**Research hypothesis I**

There is no difference among the mean quality of cut, mean thickness of heat-affected zone, and mean weight of dross of the samples cut at high power, medium power, and low power.

**Statistical hypothesis I**

There is no difference among the power population mean.

\[ H_0: \mu_1 = \mu_2 = \mu_3 \]

\[ H_a: \text{There is at least one inequality.} \]

Where \( \mu_1, \mu_2, \) and \( \mu_3 \) are the mean quality of cut or mean thickness of heat-affected zone or mean weight of dross.

**Research hypothesis II**

There is no difference among the mean quality of cut, mean thickness of heat-affected zone, and mean weight of dross of the samples cut at high moisture content, medium moisture content, and low moisture content.
Statistical hypothesis II

There is no difference among the moisture content population means.
Ho: $\mu_1 = \mu_2 = \mu_3$
Ha: There is at least one inequality.
Where $\mu_1$, $\mu_2$, and $\mu_3$ are the mean quality of cut or mean thickness of heat-affected zone or mean weight of dross.

Research hypothesis III

There is no difference among the mean quality of cut, mean thickness of heat-affected zone, and mean weight of dross of the samples cut at high feed rate, medium feed rate, and low feed rate.

Statistical hypothesis III

There is no difference among the feed rate population means.
Ho: $\mu_{..1} = \mu_{..2} = \mu_{..3}$
Ha: There is at least one inequality.
Where $\mu_{..1}$, $\mu_{..2}$, and $\mu_{..3}$ are the mean quality of cut or mean thickness of heat-affected zone or mean weight of dross.

Research hypothesis IV

There is no difference among the interaction effects of power and moisture content on the population means of quality of cut, heat-affected zone, and weight of dross; where population is defined by combinations of power and moisture content.
Statistical hypothesis IV

There is no difference among the interaction effect of power and moisture content.

\[ H_0: \alpha\beta_{11} = \alpha\beta_{12} = \alpha\beta_{13} = \alpha\beta_{21} = \alpha\beta_{22} = \alpha\beta_{31} = \alpha\beta_{32} = \alpha\beta_{33} \]

\[ H_a: \text{There is at least one inequality.} \]

Where \( \alpha\beta_{11}, \alpha\beta_{12}, \alpha\beta_{13}, \alpha\beta_{21}, \alpha\beta_{22}, \alpha\beta_{23}, \alpha\beta_{31}, \alpha\beta_{32}, \text{ and } \alpha\beta_{33} \) are the mean quality of cut or mean thickness of heat-affected zone or mean weight of dross.

Research hypothesis V

There is no difference among the interaction effects of power and feed rate on the population means of quality of cut, heat-affected zone, and weight of dross; where population is defined by combinations of power and feed rate.

Statistical hypothesis V

There is no difference among the interaction effect of power and feed rate.

\[ H_0: \alpha\gamma_{11} = \alpha\gamma_{12} = \alpha\gamma_{13} = \alpha\gamma_{21} = \alpha\gamma_{22} = \alpha\gamma_{31} = \alpha\gamma_{32} = \alpha\gamma_{33} \]

\[ H_a: \text{There is at least one inequality.} \]

Where \( \alpha\gamma_{11}, \alpha\gamma_{12}, \alpha\gamma_{13}, \alpha\gamma_{21}, \alpha\gamma_{22}, \alpha\gamma_{23}, \alpha\gamma_{31}, \alpha\gamma_{32}, \text{ and } \alpha\gamma_{33} \) are the mean quality of cut or mean thickness of heat-affected zone or mean weight of dross.
Research hypothesis VI

There is no difference among the interaction effects of moisture content and feed rate on the population means of quality of cut, heat-affected zone, and weight of dross; where population is defined by combinations of moisture content and feed rate.

Statistical hypothesis VI

There is no difference among the interaction effect of moisture content and feed rate.

Ho: \( \beta_{Y_{11}} = \beta_{Y_{12}} = \beta_{Y_{13}} = \beta_{Y_{21}} = \beta_{Y_{22}} = \beta_{Y_{23}} = \beta_{Y_{31}} = \beta_{Y_{32}} = \beta_{Y_{33}} \)

Ha: There is at least one inequality.

Where \( \beta_{Y_{11}}, \beta_{Y_{12}}, \beta_{Y_{13}}, \beta_{Y_{21}}, \beta_{Y_{22}}, \beta_{Y_{23}}, \beta_{Y_{31}}, \beta_{Y_{32}}, \) and \( \beta_{Y_{33}} \) are the mean quality of cut or mean thickness of heat-affected zone or mean weight of dross.

Research hypothesis VII

There is no difference among the interaction effects of power, moisture content, and feed rate on the population means of quality of cut, heat-affected zone, and weight of dross; where population is defined by combinations of power, moisture content, and feed rate.

Statistical hypothesis VII

There is no difference among the interaction effect of power, moisture content, and feed rate.

Ho: \( \alpha \beta_{Y_{111}} = \alpha \beta_{Y_{112}} = \alpha \beta_{Y_{113}} = \alpha \beta_{Y_{121}} = \alpha \beta_{Y_{122}} = \alpha \beta_{Y_{123}} = \alpha \beta_{Y_{131}} = \alpha \beta_{Y_{132}} = \alpha \beta_{Y_{133}} = \alpha \beta_{Y_{211}} = \alpha \beta_{Y_{212}} = \alpha \beta_{Y_{213}} = \alpha \beta_{Y_{221}} = \alpha \beta_{Y_{222}} = \alpha \beta_{Y_{223}} = \alpha \beta_{Y_{231}} = \alpha \beta_{Y_{232}} = \alpha \beta_{Y_{233}} \)
\[a_{232} = a_{y_{233}} = a_{y_{311}} = a_{y_{312}} = a_{y_{313}} = a_{y_{321}} = a_{y_{322}} = a_{y_{323}} = a_{y_{331}} = a_{y_{332}} = a_{y_{333}}\]

Ha: There is at least one inequality.

Where \(a_{y_{111}}, a_{y_{112}}, a_{y_{113}}, a_{y_{121}}, a_{y_{122}}, a_{y_{123}}, a_{y_{131}}, a_{y_{132}}, a_{y_{133}}, a_{y_{211}}, a_{y_{212}}, a_{y_{213}}, a_{y_{221}}, a_{y_{222}}, a_{y_{223}}, a_{y_{231}}, a_{y_{232}}, a_{y_{233}}, a_{y_{311}}, a_{y_{312}}, a_{y_{313}}, a_{y_{321}}, a_{y_{322}}, a_{y_{323}}, a_{y_{331}}, a_{y_{332}},\) and \(a_{y_{333}}\) are the mean quality of cut or mean thickness of heat-affected zone or mean weight of dross.

**Assumptions of the Study**

1. It is assumed that the material used to make samples is taken from one randomized source of supply.
2. It is assumed that the slip is homogeneous and will not behave in an anisotropic manner.
3. It is assumed that the flow patterns in the mold cavity is consistent and will not affect the final properties of the product.
4. It is assumed that possible fluctuations and inaccuracies in the machine parameters will not cause any variations in the results obtained.

**Limitations of the Study**

1. The study is limited to the use of an industrially used slip.
2. The green samples produced in this study will be limited to a rectangular shape with a predetermined thickness.
3. The study is limited to the variables of power, moisture content and feed rate. The many other variables which can affect the process of laser cutting green china ceramic are held constant and are not considered factors of the experiment.

Procedure

1. Review literature in order to identify the parameters of the study.
2. Build pattern and case mold from plastic and wood.
3. Cast a plaster of paris mold.
4. Identify a company that slip casts china ware.
5. Obtain slip from a company.
6. Determine sample size with the use of a pilot study and the power test. This sample size will be determined based on selection of Type I Error $\alpha = 0.10$ and Type II Error $\beta = 0.05$. Variance from these Type II Error rates may be necessary if the sample size required exceeds the cost, time, and/or resources of the investigator.
7. Cast samples to desired moisture content. The moisture level of the greenware will vary with the length of time the samples are left to dry.
8. Punch samples to desired dimensions.
9. Identify a carbon dioxide industrial laser.
10. Set the parameters of the laser.
11. Laser cut samples.
12. Measure roughness of cut surface with a profilometer and record the data.
13. Measure thickness of heat-affected zone with a filocular microscope and record the data.
14. Weigh the dross produced by cutting with a sensitive scale and record the data.
15. Statistically analyze the data using three-way ANOVA techniques.
16. Report findings.
17. Make conclusions based on findings.
18. Make recommendations relevant to the study.

Definition of Terms

Abrasive: A hard material capable of scratching or removing material from a surface.

Anisotropic: Exhibiting different properties when tested in different directions.

Automation: Process of following a predetermined sequence of operations with little or no human labor.

Average Roughness: Ra -- The arithmetic average height deviation of the measured surface profile from the profile centerline.

Ball Clay: Fine-grained, highly plastic clays chiefly used in white-ware and electrical porcelain.

Beam Diameter (1/e^2): The diameter of that particular irradiance contour in a laser beam at which the irradiance has fallen to 1/e^2 (13.5%) of the peak or axial irradiance.
Bisque: Porcelain or ceramic ware that has been fired once to maturity without glaze.

Bisque Fire: The first firing without a glaze.

Boron Nitride: A soft ceramic with a hexagonal structure similar to graphite. Like graphite, it is relatively easy to machine because of its structure. However, it is an electrical insulator and more oxidation-resistant.

Brittle: Material behavior where fracture takes place with little or no plastic deformation. Opposite of tough, fractures with little energy absorption.

Capacitor: Two conductors separated by an insulator or dielectric used to store an electrical charge.

Case Mold: A mold used to cast plaster molds for casting china.

Casting: The process of pouring a liquid or suspension into a mold, or the object produced by this process.

Cavity: An optical resonator formed by two coaxial mirrors positioned so that it is possible for photons to be multiply reflected between them.

Ceramic: A hard and brittle material consisting of compounds of metallic and nonmetallic elements.

China: A ware consisting of a translucent body of low or zero porosity with a glaze applied and matured in a second fire at the same or at a lower temperature than the bisque fire, or it may be once fired.

Clay: A fine-grained natural material that can be shaped when moist, usually composed of alumina silicates and other materials; it becomes
hard and brittle when fired.

Coherence: Describes the spatial and temporal relations at different points in a beam of light.

Cold Work: The deformation of material below its recrystallization temperature.

Continuous Wave: Abbreviated to CW, continuous output.

Cutoff: The electrical response characteristic of the roughness averaging instrument, selected to limit the spacing of the surface irregularities to be included in the roughness average measurement.

Deflocculant: Chemicals like sodium silicate, sodium carbonate, or sodium phosphate when mixed with slip break up agglomerates called flocs.

Depth of Focus: The axial distance over which a spot is clearly focused according to some criterion. Depth of focus is proportional to the square of the f-number.

Divergence: Characteristic property of light beams resulting in increase in cross sectional area with distance from source.

Dried Greenware: Ware that has dried bone dry.

Dross: The scum that forms at the base of a cut.

Dry Powder Pressing: A process in which ceramic powder plus lubricant and binder are pressed into a die.

Earthenware: A glazed or unglazed ware having a medium to high porosity.

Effectiveness: Producing a desired result.

Efficiency: The power or capacity to produce a desired result.
without loss or waste.

Extrusion: Shaping by pushing the material through a die.

Feldspar: An alkali-aluminum silicate rock, not a clay. It is an ingredient of many industrial clay mixtures, however, serving as a flux.

Firing: Sintering process for ceramics at elevated temperatures in a furnace.

Flaws: The unintentional irregularities which occur at relatively infrequent or widely varying intervals, such as cracks, checks, ridges, and scratches.

Flexibility: Systems incorporating many individual automation concepts and technologies into a single production system.

Flint: These are hard clays almost devoid of plasticity, which are added to more plastic clays. The flint clay may be likened to the skeleton of the clay structure, with the plastic clay acting as cementing binder.

Fundamental Mode: The zero order transverse mode of laser resonance. For this mode the output irradiance profile of the beam is Gaussian, and the beam angular radius is minimized.

f-Number: For a lens or mirror, the ratio of focal length to clear aperture. Also known as focal ratio.

Gas Laser: Laser in which the active medium is a gas, normally excited by an electric discharge.

Graphite: A layered (hexagonally) crystalline structure of carbon.

Green: Unsintered as in damp or wet clay.

Greenware: Unfired bone-dry ware.
Heat-Affected Zone: The portion of the base material that has not vaporized, but whose properties have been affected by heat.

Homogeneous: Involving only one phase.

Hot Pressing: A method similar to dry pressing, except that the heated die causes sintering of the part.

Hydroplastic: Formable when mixed with water, as in clay.

Infrared: Region of the optical spectrum extending from .077 μm.

Kaolin: A white clay, nearly pure kaolinite. Kaolins are used for china, electrical porcelain bodies, and sanitary ware.

Kiln: A firing oven.


Laser Head: Used to describe the laser as distinct from other associated optical components or power supply.

Lay: The direction of the predominant surface pattern, determined by the production method.

Machining: Removal of material by mechanical, electrical, chemical, or other means.

Macor: Trade name for one polycrystalline glass ceramic consisting of mica crystals in an opal glass matrix.

Maturity: The temperature at which a clay body attains maximum hardness.

Mode: A three-dimensional configuration of electric and magnetic fields which is exactly reproduced by reflections from the cavity end mirrors.

Negative Impression: The shape inside a mold for casting.
Notch Sensitivity: Reduction in mechanical properties due to the presence of notches, scratches, and other stress raisers.

Piezoelectric: The ability of same types of crystals to produce a voltage when put under certain types of stress.

Porcelain: A hard translucent nonporous ware consisting mostly of kaolin, flint, and feldspar. Biscuit fired at a low temperature, or it may be once fired. The body is nonporous.

Power Output: The rate of radiation emission from a laser, normally expressed in watts. One watt equals one joule per second.

Profilometer: An instrument used to measure surface roughness.

Pumping Source: Method of exciting laser transition, for example, flash tubes or gas discharge.

Quality of Cut: Measurable quantities of surface finish or texture. For example, waviness, roughness, lay, and flaws.

Quartz: The mineral SiO₂, commonly colorless, and transparent.

Reliability: The ability of a product to serve its intended function for a specified period of time.

Repeatability: The ability of a machine to position at the same programmed position under the same conditions.

Roughness: The finer irregularities, usually including those which result from the production process. Includes traverse feed marks and other irregularities within the limits of the instrument cutoff setting.

Roughness Spacing: The average spacing between adjacent roughness peaks within the instrument cutoff setting.
Scab: A defect on the surface of a casting in the shape of a raised surface blemish.

Seam: Protruding area of clay that appears from mold joints on greenware.

Shrinkage: The contraction of porcelain when fired. The piece actually shrinks in size.

Sintering: Bonding of adjacent particles in a pressed powdered material or in a matrix by heating.

Slip: A slurry or suspension for casting into porous mold of the desired product shape. The mold absorbs the liquid.

Slip Casting: A shape-forming method in which a suspension of a solid, such as clay in water, is poured into a porous mold. The water diffuses from the layers next to the mold surface leaving a solid shape. The liquid is poured out of the interior of the mold.

Slurry: A suspension of particles in a liquid.

Solid-State Laser: Laser in which the active material is a crystal-line host.

Stimulated Emission of Radiation: The mechanism by which excited atoms are stimulated to emit radiation by photons from other atoms. The stimulating photons must have a wavelength identical to that of an allowed transition of the excited atoms. In this effect the stimulating and emitted radiations are perfectly coherent (colinear, identical phase, identical wavelength, and identical polarization state).

Stoneware: A glazed or unglazed ware made largely of stoneware clays fired to low porosity, but with no translucency.
Stress Raisers: Changes in the contour of a structure or discontinuities that cause local increases in stress.

Surface Texture: The random deviations from the nominal surface which form the three-dimensional topography of the surface. Includes roughness, waviness, lay, and flaws.

Thermistor: Semiconductor device with a high resistance dependence on temperature. It may be calibrated as a thermometer.

Trimming: Removal of excess material from a formed part.

Varistor: A two electrode semiconductor device that drops in resistance as the voltage is increased.

Viscosity: The bulk property of a fluid, semi-fluid, or semi-solid substance that causes it to resist flow. The ratio of shear stress to velocity gradient.

Vitreous: Glassy or glass-like.

Waviness: The more widely spaced component of the surface texture. Includes all irregularities spaced more widely than the instrument cutoff setting.

Waviness Spacing: The average spacing between adjacent peaks of the waviness component.

Wet Plastic Forming: A method in which a wet plastic refractory mix is shaped by extrusion or other forming.

YAG Laser: Yttrium Aluminum Garnet, one of the hosts used for neodymium-doped lasers.
CHAPTER 2. LITERATURE REVIEW

This review of literature is organized into two areas, material and process. The literature reviewed under material is organized into eight sections. Section one reviews the general properties of ceramics. Section two looks at the plaster mold. Section three deals with the development of china slip. Section four covers the various steps in the slip casting process. Section five covers cleaning greenware. Section six gives details of drying and the various problems associated with it. Section seven cites information on the reasons for clay cracks, and section eight provides an overview of the firing process.

The literature reviewed under process is organized into five sections. Section one provides a background on the laser with an emphasis on characteristics and uses. Section two gives details on the carbon dioxide lasers, their classification, and reasons for their selection and justification. Section three deals with laser cutting emphasizing the various methods of cutting and, more specifically, the cutting of ceramics. Section four covers laser processing parameters, and finally, section five looks at the important concerns of laser safety.

Material

General properties of ceramics

Typically, ceramics are crystalline compounds (glasses have an amorphous structure). Most ceramics contain both metallic and nonmetallic elements with ionic or covalent bonds. This makes it difficult to make generalizations about their properties. Normally, they are very hard
and brittle and withstand high temperatures, but they may sometimes be weak and melt at low temperatures, depending on the specific ceramic material.

Ceramics are among the hardest industrial materials processed. Hardness is a measure of the resistance of a material to indentation. It is this property that makes ceramics important in products requiring a wear resistant application. In addition, it has been experimentally verified that hard ceramics are generally strong.

A brittle fracture in ceramics is promoted by stress concentrations, which develop from sharp corners, porosity from trapped air, and micro-cracks that develop as the ceramic is processed in the green state. Tensile strength of a ceramic is usually difficult to determine because of the sensitivity of the material to microcracks, which are almost always present in specimens. Ceramics are generally brittle and fracture without plastic deformation, however, they generally have high compressive strength. For this reason ceramic materials are often selected for use in structures and products requiring high compressive strength.

A number of ceramics are used as refractories, meaning in general that these are materials with good resistance to heat. The very low thermal conductivity of some ceramics makes them ideal for use as thermal insulators at elevated temperatures. Some ceramics have virtually no thermal expansion over a wide temperature range. Kalpakjian (1985) states in addition that:

The thermal properties of expansion and conductivity are important in inducing thermal stresses, which can lead to thermal
shock or thermal fatigue. The tendency for thermal cracking or spalling is reduced with low expansion and high thermal conductivity (p. 686).

There are numerous examples which indicate that ceramics have a variety of characteristics. Jacobs and Kilduff (1985) cite two examples showing why ceramics are indispensible for current-day technological and societal needs:

NASA's use of silica tiles as part of the Space Shuttle thermal protection system marks a significant advance in ceramic high technology (p. 309).

Jacobs and Kilduff continue:

Nickel, being expensive, has not been considered for low-cost turbine automobile engines. Instead, ceramics materials are being developed for use in turbine engines operating at 2500°F with fewer polluting emissions than in the present internal combustion engine (p. 11).

Besides having desirable high temperature properties, there are a few other properties worth mentioning. Ceramics are generally lighter than their metallic counterparts. The push for higher temperatures and lighter weights makes ceramics excellent candidates for material process research. Ceramic materials are usually good electrical insulators. At elevated temperatures, ceramics do conduct electricity but poorly when compared with metals. Most ceramic materials are transparent, at least in thin sections, and finally, ceramics are resistant to chemical alteration.
The mold

Ironically, a slip casting mold is made by casting in a case mold. The case mold is a negative impression of the positive shape made out of plaster of paris. When the slip is poured into the mold, the impression inside makes a copy of the original shape from which the mold is made. Mold making is an art in itself.

When molds are newly wet or saturated from pouring, they cannot be poured. The wetness of the mold will not let the slip build up to make the thickness needed for casting.

A fan blowing directly on a mold is an effective and desirable way of drying plaster molds. For a two piece mold, always dry them banded together, or they may dry out of shape and become warped. Cowley (1978) has an interesting observation concerning a mold:

When using a plaster mould for the first time, the first few casts seldom prove to be successful. Satisfactory casts only come after two or three castings when the inside casting surface of the mould has received a slightly greasy, oily surface covering from the casting slip. The surface seems to help the easy separation of cast from mould, preventing sticking and subsequent cracks appearing, consequently it is important not to sponge the inside of a mould (p. 94).

China slip

China ware was first produced by the Chinese thousands of years ago from mixtures of special clays and minerals. Their formula was a safely guarded secret. As years went by, other countries mastered their own mixtures. Ball clay, feldspar, china clay, and flint are mixed in water to make china slips. Today, everyone has their own recipe.
Because there are many types of china mixes, it is up to the cer­
amist to select the right type. There are many manufacturers who produce
slips by the gallon, they are all good for certain purposes.

Stored slip will become thick and lumpy. It is important to thor­
roughly blunge slip and strain before casting. In industry, agitators
are employed, rotating slowly to keep the slip in suspension and at the
same time allowing air bubbles to escape. At the end of the blunging
period the pint weight, viscosity, and thixotropy should be checked and
recorded. This can serve as data in statistical process control. Casting
slip should also be maintained at room temperature. Cowley (1978) sug­
gests:

The good casting slip needs to maintain clay particles in sus­
pension, produce good definition from a mould, shrink as little
as possible, have a good strength when dry, and not excessively
saturate the mould (p. 91).

China slips have a high water content which results in the molds
quickly becoming saturated. This leads to long mold drying times and,
consequently, lower china ware production rates, unless very many addi­
tional molds (at greater cost) are used for compensation.

With the addition of a chemical deflocculant to the clay it is pos­
sible to produce a slip with the same fluidity as that of a clay-water
slip, but with a much lower water content. Cowley (1978) explains:

Individual clay particles have a static electrical charge which
makes them stick, draw together in groups or flock. So in
order to make a clay fluid, the particles have to be separated
from one another, or dispersed, in other words, break up the
flock. This can be done by adding a great deal of water to
make them a liquid suspension, or by adding to a clay a substance known as an electrolyte. An electrolyte usually an alkali, such as sodium silicate or soda ash, changes the electrical charge on the clay particles, which now repel one another and float individually rather than flocking together. The clay is now said to be de-flocculated (p. 91).

Deflocculated slips have become the norm for slip casting because much lower volumes of slip have to be made, saving in space, and a reduced number of molds in use are obtained.

Casting

Slip is poured continuously till the mold is filled, a stop may cause a separation line or lamination. The mold absorbs a high proportion of water from the casting slip and a layer of stiff clay is gradually formed on the inside of the mold.

The casting's thickness is determined by the length of time the casting slip is allowed to sit in the mold. When the part is of desired thickness, the excess casting slip is poured off. Pouring out the slip will make hollow casting; otherwise the slip remaining inside the mold would cause the object to become solid. See Figure 1 showing the slip casting process.

As the clay in the mold dries, it shrinks and pulls away from the sides of the mold. The cast or greenware is now firm enough to retain its shape when handled. Trimming, punching of holes, and removal of forming marks or seams must be performed before the greenware is allowed to dry off.
Figure 1. Slip casting of ceramic shapes

Cleaning greenware

After the casting is set up to desired thickness, the excess slip needs to be trimmed and required holes punched. This should be done while the cast is still in the mold in order to prevent distortion of the green casting.

Trimming and punching done too quickly often result in a defective part. Always trim towards the mold and not away from it. Serfass (1979) states, "Cut the area so the hole is perfectly smooth. If it has jagged edges, it will cause cracking when drying" (p. 27).
When removing the greenware, hold the ware lightly so as not to push it out of shape. Serfass adds: "Once it has dropped and fallen out of shape there is nothing you can do to make it right again" (p. 26).

Once a piece is dried completely the greenware is so brittle and fragile that slight mishandling could fracture the part. After cleaning seam lines, drag a wet sponge across the cleaned area to remove any residue. Any holes in the greenware can be filled at this stage. Drip water into the hole. Grind some dry greenware scraps into powder and fill the hole. The water will make the particles of clay moist, filling the gap and forcing air out.

**Drying**

Water is dried from clay ware by the process of evaporation. Water surrounding clay particles or "free water" moves to the surface of the casting to replace water loss from evaporation at the surface. Initially, this moisture will be evaporated only from the surface of the casting, but as drying continues the "wet surface" moves back from the surface of the part, and vapor diffuses to the surface. As water between the clay particles is continually removed the part shrinks. Clay with particles in contact and "chemical water" present is referred to as "leather hard" greenware.

In theory, no further shrinkage should take place after the "free water" is removed, but slight shrinkage does occur for reasons which are not fully understood. Clay shapes do not shrink evenly, shrinkage
depends on the way in which they have been dried and the shape of the design. An article is not likely to crack during further drying if it has survived to the "leather hard" state. Figure 2 shows the shrinkage and moisture content of a ceramic body during drying.

![Graph showing shrinkage and moisture content during drying](image)

**Figure 2.** Typical shrinkage and moisture content of a ceramic body during drying.

Drying is not an even process and moisture evaporates from some surfaces sooner than others. Walls of vessels dry faster than their bases, and thin sections dry before thick sections. Upper surfaces of tiles will shrink sooner than the lower surfaces which are in contact with the plaster mold. The tile may, therefore, warp; the upper surface may become concave. Faster drying makes this defect more obvious.
Drying speed is constant up to a certain point and then diminishes with time. Increasing the drying temperature, increasing the air flow through the drying area, or decreasing the humidity will lower the drying time. Drying should be controlled with the aim of drying pieces evenly.

Clay cracks

Cracks in greenware are caused by stresses. Cracks do not suddenly arise; they begin from some defect and then grow. Common causes of greenware cracking are:

1. Uneven drying temperatures, very low humidity, and draughts must be avoided at all cost. Fraser (1986) explains:

   Maintaining high drying temperature under high atmospheric humidity to prevent excess drying speed, reduces risk of cracking and distortion since the ware dried much more evenly (p. 10).

   If draughts blow across drying parts they may cause rapid drying of one section of the part while another area of the same part dries at the normal rate. Shrinkage will be uneven and cracks may form due to tension stresses.

2. Uneven thickness of section and poor design of articles.

3. Poor handling of greenware.

4. Poor trimming and/or punching.

With respect to trimming, Fraser (1986) states:

   Trimming and fettling tools should always be very sharp and any cutting or paring should be done when the clay is leather hard. If trimming or fettling is carried out when the clay is too dry the clay is much weaker and will be more easily
torn by the action of the tool. The minute cracks in the trimmed surface then act as stress multipliers (p. 14).

Smoothing cut edges of greenware with a wet sponge may resolve the problem.

A further cause of cracking is due to thermal stresses in firing. Cracks are caused by very fast removal of pore water due to rapid firing. Fine hairline cracks may result, and, in extreme cases, the part may explode. These cracks are not jagged but cut cleanly through the biscuit ware and are called dunts.

Firing

Dried greenware must be fired to achieve maximum strength and hardness. Jacobs and Kilduff (1985) have provided a definition:

Firing (sintering) is a process that uses high temperatures to cause ample atomic movement of the solids so surface tension will bring the material together and reduce the openings (pores) between the constituents. The high temperature may cause melting of some elements, which forms a glassy substance (vitreous) that seals to pores and cements the crystals together in a ceramic bond. This process is known as vitrification; vitreous materials are glasslike (p. 311).

Greenwares are fired in an oven kiln which is made from light weight fire brick. Kilns come in different sizes but they all fire to temperatures as high as 2,300 degrees Fahrenheit.

When greenware is fired at high temperatures it becomes soft and shrinks, therefore, support is needed. Materials used in supports and for making shelves are called kiln furniture. All kiln furniture are coated with flint wash which keeps them from adhering to the product.
being fired.

An object called a cone (because of its shape) indicates the time for kiln shut down. The cone is made of a substance that will melt and bend at a desired temperature, and different cones will melt at different firing temperatures. In addition, a pyrometer is used to measure the exact temperature inside the kiln.

Glazing is a firing process where glass is melted onto the surface of the ceramic body and allowed to adhere to that surface during cooling. Glasses are prepared by grinding various metal oxides and frit. The mixture is applied in a thin layer to greenware, bisque-fired ceramics, or to completely vitrified ceramics by spraying, dipping, or painting. The purpose of glazing is to seal the ceramic surface of pores, add special colors, and provide decoration.

Firing and glazing are both important and complicated stages in ceramic processing, and many defects can occur during these stages. However, this study is not interested in the research of firing and glazing, and only an outline concerning the stages in firing is presented for review. Fraser (1986) outlines the stages in firing as:

<table>
<thead>
<tr>
<th>Temperature</th>
<th>What Happens</th>
</tr>
</thead>
<tbody>
<tr>
<td>20-200°C</td>
<td>Remaining pore water is evaporated from clay ware. Should be less than 1% content. Risk of explosion or fine cracking if firing speed too rapid and ware not dry. Kiln must be ventilated.</td>
</tr>
<tr>
<td>200-500°C</td>
<td>Ware can be fired more quickly but maintain ventilation.</td>
</tr>
<tr>
<td>Temperature Range</td>
<td>Description</td>
</tr>
<tr>
<td>-------------------</td>
<td>-------------</td>
</tr>
<tr>
<td>470-700°C</td>
<td>Most of chemically combined water driven out. Carbonates begin to dissociate. Gas evolution is no problem because of permeability of extremely porous body but once-fired ware may crawl if firing too quickly. Quartz inversion at 573°C. Endothermic reactions.</td>
</tr>
<tr>
<td>650-1000°C</td>
<td>Carbon burns out. Highly carbonaceous clays and especially once-fire ware must be slowly fired to avoid later bloating. Vent hole closed. Glaze sinters.</td>
</tr>
<tr>
<td>880-1100°C</td>
<td>Body shrinkage under way. Temperature differences across each piece must be reduced before firing contraction becomes pronounced. Sulphates in body decompose and must be driven out before glaze-body interface seals. Vents should be closed.</td>
</tr>
<tr>
<td>1100°C- top temp.</td>
<td>If interface sealed, gases escape through unglazed areas. As glaze melts and matures firing rate should be slowed or maturing temperature held to facilitate clearing of bubbles, etc. which escape through glaze melt. Reaction layer formed. Body contraction and vitrification continues with increasing risk of ware distortion if unevenly made or supported.</td>
</tr>
<tr>
<td>top temp.- 750°C</td>
<td>Molten glaze cools towards liquidus point. Shiny transparent glazes can be rapidly cooled. Ware is pyroplastic and little risk of damage. Crystalline glazes however may need to be cooled slowly to 900°C to ensure crystal development.</td>
</tr>
<tr>
<td>750-600°C</td>
<td>Cooling must be reasonably slow to promote temperature uniformity before passing through quartz inversion at 573°C. Vents must be closed. The glaze solidifies and begins to be compressed by the cooling body.</td>
</tr>
<tr>
<td>600-500°C</td>
<td>Slow cooling needed to prevent cooling dunts due to quartz inversion at 573°C.</td>
</tr>
</tbody>
</table>
Allow to cool slowly to avoid risk of denting around cristobalite inversion at 225°C although little risk of damage between 500-300°C. Cristobalite free bodies can be cooled more quickly if desired (p. 47).

Process

Laser background

The first laser was invented by Th. Maiman, Ph.D., in 1960. The word laser is defined by its acronym as Light Amplification by Stimulated Emission of Radiation. The important characteristics of laser light are established in the fact that laser light differs from ordinary or incandescent light. Laser light is directional, coherent, collimated, intense, and monochromatic. These properties that have afforded the laser use in a variety of applications.

Lasers are used in industry, medicine, and science. They also play a big role in military defense. The following are some commercial uses for lasers:

1. Material Processing—cutting, drilling, welding, heat treating, surface modification, and engraving.
3. Printing.
5. Optical Memories—compact disc.
6. Communications—fiber optics.
7. Barcode Scanners
8. Alignment Control—suspended ceilings, leveling devices, and safety.
10. Entertainment—disco lights
11. Military—tactical-range finding, target designators, and weapons.

Laser material processing has been investigated since 1963 with numerous papers and books published by several authors, yet this is still a strongly developing field. The laser as a tool offers new technologies, new products, and new applications. High-power lasers are being used in numerous applications in many industries with the hope of finding the solutions for processing problems unsolved by conventional processing techniques. Kales (1988) states, "Worldwide sales of commercial lasers reached $570 million in 1987" (p. 88).

There are different types of laser systems that are designed to meet specific demands. These systems are usually either continuous power (usually referred to as continuous wave or CW lasers; for example, the CW CO₂ laser) or pulsed systems (usually referred to as solid state lasers; for example, the neodymium yttrium aluminum garnet, YAG, lasers).

The most versatile industrial laser is the carbon dioxide laser. This is because of its continuous wave output, ease and stability of operation, compatibility with industrial environments, and cost-effective performance. Referring to information gathered in 1987, Kales (1988) further states:
CO₂ lasers are used in nearly every laser application. Last year sales of CO₂ lasers in the commercial market reached nearly $120 million, just slightly better than the year-earlier level (p. 89).

For the present work, CO₂ laser is used because it is the only laser available in continuous mode at high powers. For this reason the review of literature is limited to a discussion about the CO₂ laser.

**Carbon dioxide lasers, classification, selection and justification**

All lasers require three mediums:

1. An active medium—laser material that generates the light,
2. a power supply—a source of energy to excite the active medium, and
3. a resonant cavity—an optical resonator (two parallel mirrors which amplify light).

Figure 3 shows a typical carbon dioxide laser configuration.

In the carbon dioxide laser an active medium is typically a mixture of gasses such as carbon dioxide, nitrogen, and helium. A typical composition might be 10% of carbon dioxide, 10% of nitrogen, and 80% of helium. This gas mixture is kept in an excited state with a power supply which produces a high voltage supply.

The resonant cavity consists of a discharge tube containing the excited gas mixture between two end mirrors. One of the mirrors is made totally reflective, the other partially reflective so that a proportion of the incident light is transmitted.
Various mirror configurations can be used in the resonant cavity. The choice of configuration depends on beam stability, acceptable beam divergence, and efficiency. Figure 4 shows the sequential phases from nonlasing to lasing in the resonant cavity.

1. Molecules in the lasing medium exist in the ground state without excitation.
2. They emit photons spontaneously when excited to higher energy levels.
3. An emitted photon collides with an excited molecule which also emits a photon.
Figure 4. Nonlasing to Lasing

4. Stimulated emission proceeds, with some photons striking a mirror in a direction parallel to the resonator axis.

5. The photons are reflected back and forth between mirrors, stimulating the emission of more photons in a cascading effect.
6. Some pass through the partially transmissive mirror, emerging as a coherent beam. Others remain, continuing to generate photons.

The wavelength of the beam emitted by this type of laser is usually in the range of 9-11 microns, with 10.6 microns being common. The power output of industrial carbon dioxide lasers can be anywhere from 100 W to 10 kW.

Classification of carbon dioxide lasers

The following discussion relating to the subject of carbon dioxide laser classification was presented in a class room lecture at Iowa State University, by Dr. P. A. Molian, Department of Mechanical Engineering, 1988:

Carbon dioxide lasers can be classified according to their tube design as sealed-tube lasers and flowing-gas lasers. The flowing-gas laser is more common than the sealed-tube laser.

Sealed-tube lasers

The gas mixture is trapped in a sealed tube across which is applied the electric discharge. The principal disadvantage of this type of laser is that the carbon dioxide gas breaks down rapidly. This can be prevented to some extent by the addition of water which reacts with carbon monoxide to produce carbon dioxide. The power output is of the order of 100 W and only 50 Wats per meter length of the tube can be produced. The cooling requirements of this type of laser are also very high. For all these reasons, the sealed-tube laser is not a popular type of laser.

Flowing-gas lasers

Flowing-gas lasers are what their name implies, the gasses instead of being sealed in a tube are made to flow through the tube. The direction of the gas flow subdivides this type of laser into two classes. They are the parallel or axial flowing-gas lasers and the transverse flowing-gas lasers.

1) Axial flowing-gas lasers

In this type of laser the gas flows along the axis of the tube. The electric discharge is also applied along the tube's axis. A maximum power output of 0.7 kiloWatt per meter length of the tube can be produced.
The laser operates at very low pressures and, therefore, a vacuum pump is needed. The beam can be folded through multiple tube segments with the aid of mirrors. Commercial units of this type will deliver up to 2 kW of power.

ii) Transverse flowing-gas lasers

This type of laser can produce more than 10 kilowatt per meter length. The gas flow is perpendicular to the axis of the laser cavity and the electrical discharge is also applied transverse to the axis. This type of arrangement provides for efficient cooling of the gas. The gas mixture is circulated through the system after regeneration of the carbon dioxide gas. The compact design of the transverse flowing-gas laser makes it the most popular type of laser manufactured today.

See Figure 5 on the basic structures of sealed-tube and flowing-gas lasers.

Selection and justification of carbon dioxide lasers

The continued development of the industrial CO2 laser has resulted in more powerful systems. In the selection of a CO2 laser for material processing one must be concerned with:

1. the power that will be required,
2. the gas handling requirements and gas usage,
3. the cooling provisions for the cavity optics, discharge chamber, and electrodes, and
4. the choice of beam handling optics.

These concerns involve the choice of which type of gas flow geometry one will use and the selection of either transmissive or reflective beam optics.

A bit further along this review of literature identifies how laser cutting can compete with the conventional cutting process. However,
the initial capital cost of laser equipment makes it difficult to justify the replacement of conventional equipment and machine tools with lasers. Lasers can only be introduced if they offer improvements in productivity and quality. With regard to productivity of laser cutting, Walker (1984) states:
For low volume (less than 500 parts), the versatility and flexibility of the laser are clearly reflected in a lower cost per part. For high volume (over 1,000 parts), the conventional machining methods clearly yield a lower cost per part. For high volume of a single item, even with the initial high tooling costs, a conventional cutting/stamping system has considerable economic advantages over a laser system. For low volume of a large number of different parts, the flexibility of the laser causes the roles to be reversed, with the laser becoming the most economical (p. 62).

Every application must be assessed on its individual merits and requirements. Determining the typical cost per piece part for various cutting systems is one type of assessment. Another way may be to determine cutting speed versus thickness for various power levels, when cutting the material on various cutting systems.

**Spectra-820 carbon dioxide laser** The Spectra-820 carbon dioxide laser is an industrial laser manufactured by the Spectra Physics Corporation. This is a transverse flowing-gas type of laser. Figure 6 shows a block diagram of the Spectra-820 carbon dioxide laser, Figure 7 shows the Spectra-820 laser optics, and Figure 8 shows the Spectra-820 laser head components.

**Blower** The blower circulates the carbon dioxide gas mixture through an electrode structure that causes an electrical excitation of the mixture. The photons of energy that are produced as a result of the lasing action are amplified by the mirrors on either side of the cavity.

**Mirrors** There are several mirrors in the discharge region of the laser. The highly reflective rear mirror reflects all but a small portion of the beam incident upon it. The front mirror is only partially
Figure 6. Block diagram of the Spectra-820 carbon dioxide laser

Figure 7. Spectra-820 laser optics
reflective and it is through this mirror that the laser beam finally emerges. There are two fold mirrors that increase the number of passes of the beam through the discharge region, thus increasing the amplification. A polarizing mirror linearly polarizes the beam. Linearly polarized beam is required in cutting materials. The beam emerging through the front mirror passes out of the vacuum shell through the output window.

**Shutter** This device is located between the front mirror and the output window. The shutter closes the optical path when needed. When the shutter is closed, the beam energy is absorbed in a cone in the shutter. The shutter, therefore, has to be cooled by circulating water.
**Power meter**  A small portion of the laser beam gets transmitted through the rear mirror and is absorbed by the power meter. The power of the laser beam is output continuously by the power meter.

**Power supply**  The power supply conditions the three-phase AC power to DC output required by the electrodes.

**Microprocessor**  The microprocessor controls all functions by analyzing the signals from the different parts of the laser. External commands for power adjustment, shutter opening, interlock status, etc., are fed to the microprocessor. The microprocessor, in turn, directs the appropriate components to perform the functions.

**Gas controller**  This device fills the discharge cavity with the gases in the right proportion and pressure. When the laser is in operation, the hot gases are fed through a gas-to-water heat exchanger and are fed back to the laser head. The gas controller also monitors the quality of the gas mixture and replenishes the mixture continuously.

**Vacuum pump**  The vacuum pump assists the gas controller in maintaining the pressure in the laser cavity. The pump also evacuates the cavity at shut-down.

**Cooling system**  The carbon dioxide laser is only about 10% efficient. A great amount of energy is, therefore, wasted as heat which is absorbed by the gases and the electrodes. Besides the gases, different parts of the system such as the cabinet, power supply, blower motor, shutter and the optics require cooling. The cooling system in this laser uses water from an external source to remove the unwanted heat. The gas temperature, for example, is reduced from 200°C to 25°C by the
gas-to-water heat exchanger. Interlocks are provided to prevent the laser from being operated without water supply.

Closed-loop cooling system The electrode structure is cooled by circulating deionized water in a closed-loop. Deionized water is used to prevent damage as the water comes in contact with the electrodes. The heat energy from the deionized water is removed by the external water supply through a water-to-water heat exchanger. See Figures 6, 7, and 8 showing the internal components of the Spectra-820 carbon dioxide laser.

Laser cutting

There are a number of reasons for specifying a cutting process in a manufacturing operation:

1. Closer tolerances may be required which are unavailable from casting or forming processes.
2. The part may have external and internal geometric features that cannot be produced by other processes.
3. It may be more economical to cut the part than to obtain the finished product by other manufacturing processes.

However, there are certain limitations in the cutting process:

1. Waste of material is inevitable with cutting.
2. Cutting a product generally takes a longer time than other processes like forming.
3. The process of cutting can have adverse effects on the surface quality and properties of the product.
In spite of these limitations, the cutting processes of drilling, milling, planing, and turning are indispensable to manufacturing technology. Still there are many situations in manufacturing where material is either too hard, too brittle, or its shape is not achievable by conventional cutting techniques. The high-energy densities of laser beams can be put to use in these cutting operations.

Methods of laser cutting

Steen and Kamalu (1983) identify five ways in which a laser can be used to cut material:

(i) Vapourisation. The beam energy heats the substrate to above its boiling point and material leaves as vapour and eject—requires around 10 times the energy of (ii).
(ii) Melting and Blowing. The beam energy melts the substrate and a jet of inert gas blows the melt out of the cut region—requires around twice the laser energy of (iii).
(iii) Burning in reactive gas. The beam energy heats the material to the kindling temperature which then burns in a reactive gas jet, as in (ii) the jet also clears the dross away—requires around 10 times the energy of (iv) for some materials.
(iv) Thermal stress cracking or controlled fracturing. The beam energy sets up a thermal field in a brittle material, e.g., glass such that it can guide a crack in any direction.
(v) Scribing. A variant on (i) whereby a blind cut is used as a stress raiser allowing mechanical snapping along the scribed lines (p. 19).

In the present study, the cutting method of melting and blowing, commonly referred to as fusion cutting is used, and because of this it is the only laser cutting method discussed in detail.

In explaining the physical mechanism involved in the phases of fusion cutting, Steen and Kamalu continue:

In fusion cutting, the laser beam is of sufficient power to evaporate a hole (known as a "keyhole") into the work piece, as noted before, for vaporization cutting, but instead of
removing the material as vapour and eject it is here removed as a molten product by an auxiliary jet, usually mounted co-axially with the laser beam. The result is a clean cut made with around one tenth of the power density required for vaporization cutting. The physical mechanism involved in fusion cutting can be summarized as follows.

(a) The laser beam strikes the work piece surface, some of its energy is reflected while the rest is absorbed, evaporating a small hole.

(b) The small hole (keyhole) acts as a blackbody and absorbs all the laser energy. The hole is surrounded by molten walls which are held in place by the fast flow of vapour eject.

(c) The melting isotherm penetrates the work piece, and pressure from the auxiliary gas jet blows the molten material away.

(d) The work piece moves and so the "hole" is traversed leaving a slot. The laser beam now strikes only the leading edge of this slot from which a steady or pulsing flow of molten material is blown.

There is little vapour interference with the laser beam since it is blown clear. At very slow cutting speeds (of thin material), most of the laser beam will pass straight through the kerf (Duley and Gonsalves, 1972). Increasing the speed causes more of the beam to strike the material, thus automatically increasing the coupled power to the material and explaining the fairly wide operating region for good quality cuts obtainable with the laser. Arata et al. (1979) measured the temperature of the cutting face and showed that it increased with cutting speed, a natural result of this mechanism. In thicker materials the laser evaporating action is not fast enough or the molten product does not move fast enough and so the beam may be reflected within the kerf on the cutting face. A cut will then be achieved if the molten product can escape before it is frozen by the cold gas jet. All laser cut edges show a striation pattern since:

(i) The cutting process is initiated at one power level with the resultant oxygen burning being stopped at a lower power level.

(ii) The slope of the cutting face is so steep the power density on it cannot sustain the melting process so a step in the cutting face forms, causing intermittent advance of the cutting face.

(iii) As cutting proceeds absorbing or reflecting plasma or smoke may cause an intermittent action (pp. 24-26).

A typical fusion cutting system with nozzle outlet for a gas jet is shown in Figure 9.
There are some considerations which should be followed, whatever the method of laser cutting used. The primary considerations determine whether the laser is suitable for the cutting process. The secondary considerations involve processing parameters, economic, and safety considerations of the laser cutting process. Table 1 provides a list of preliminary and secondary considerations for laser material processing.
Table 1. Considerations for laser material processing

<table>
<thead>
<tr>
<th>Primary Considerations:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorption energy of the material</td>
</tr>
<tr>
<td>Thermal diffusivity of the material</td>
</tr>
<tr>
<td>Reaction temperature</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Secondary Considerations:</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Heat-affected zone</td>
</tr>
<tr>
<td>Burr on the edge</td>
</tr>
<tr>
<td>Tolerances</td>
</tr>
<tr>
<td>Thermal expansion</td>
</tr>
<tr>
<td>Smoke or debris</td>
</tr>
<tr>
<td>Assist gases</td>
</tr>
<tr>
<td>Material</td>
</tr>
<tr>
<td>Personal safety—burns, electrical shock, eye protection, reaction products</td>
</tr>
</tbody>
</table>

The advantages of laser cutting

Laser cutting offers many advantages over conventional machining techniques:

1. The cut can have a narrow kerf resulting in material savings.
2. Precise control over the total heat input results in minimum thermal distortion and heat-affected zone (HAZ).
3. The cut edges can be smoother than edges cut by conventional machining techniques.
4. The cut has square edges.
5. There is no mechanical stress on the cut edge since there is lack of physical contact with the work.
6. There is no tool wear.
7. It is possible to cut through brittle, soft, or hard materials.
8. The cut can be made equally easily in all directions, and it
can start anywhere affording selective material removal.

9. The work piece does not need to be held by any work holding mechanism.

10. The cutting speed is fast compared with speeds for conventional machining techniques.

11. The process is easily automated by numerical control.

12. Low operating noise.


Its major weaknesses are the limited cutting depth which is a function of power and the capital cost which is also a function of power. With respect to laser set-up, the setting-up and alignment of an optical guidance system require time and manual positioning. Table 2 compares laser cutting with other conventional cutting processes.

The laser cutting rates are high enough to have practical application. The reason for this is noted by Walker (1984):

Significant improvements in quality and speed of cutting have been achieved during the past few years. This advance has been driven by the product demands of industrial laser users (p. 63).

A laser cut has high precision and reproducibility. The precision of a laser cut has been quoted at +0.10 mm for a numerically-controlled table. Walker continued by explaining that:

Most laser cutting systems in industry employ lasers with maximum output powers of approximately 1 kW. Kerf widths of the order of 0.01 in. and accompanying HAZs of around 0.008 in. are common with laser cutting systems (p. 63).
Table 2. Comparison of laser and conventional cutting

<table>
<thead>
<tr>
<th>Process</th>
<th>Laser's advantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxy-Acetylene</td>
<td>Narrow kerf, minimal heat-affected zone, cuts sharp profiles, minimal part distortion.</td>
</tr>
<tr>
<td>Plasma Arc</td>
<td>Narrow kerf, minimal heat-affected zone, cuts sharp profiles, minimal part distortion.</td>
</tr>
<tr>
<td>Band Saw</td>
<td>Narrow kerf, no burrs, minimal distortion, sharp profiles, faster rates.</td>
</tr>
<tr>
<td>Nibbling</td>
<td>Smooth edges, no burrs, narrow kerf, no part distortion.</td>
</tr>
<tr>
<td>Punching</td>
<td>No dies necessary, complex profiles processed, adaptable to short runs.</td>
</tr>
<tr>
<td>Shearing</td>
<td>No dies necessary, complex profiles processed, adaptable to short runs.</td>
</tr>
</tbody>
</table>

Many three-axis CO$_2$ lasers have been integrated successfully into the production line environment. Today, five-axis laser systems are common place in many industries. Other advances taking place are combinations of laser plus robot which result in a tool of even greater versatility.

**Laser cutting of ceramics** Lasers can be used to cut any metal or nonmetal. The interest in the present study focuses on the fusion cutting of a certain china ceramic. Since there is a lack of literature relating to laser cutting china, the review of literature focuses on laser cutting of related ceramics.

Scribing (defined in the section entitled Methods of Laser Cutting) is one of the more common methods used to cut ceramics. Ready (1978)
notes that:

Scribing is an important method of cutting and shaping without vaporizing all the way through the work piece. It can be applied to brittle materials such as ceramics, silicon, and glass. Scribing may be performed either by cutting a continuous groove into the surface or by drilling a series of closely spaced holes. The material will then snap easily along the path of the scribed line (p. 421).

There is a disadvantage to scribing. If the fracture is not properly controlled, then surface stresses give rise to chipping in brittle ceramics. A badly chipped surface inevitably decreases the quality of cut.

Fusion cutting has also been used to successfully cut certain ceramics. In reference to fusion cutting, Ready (1978) states:

A continuous CO₂ laser emitting 100 W is adequate for many cutting applications. Cutting has been demonstrated on a variety of materials such as paper, rubber, ceramics, glass, cloth, and wood (p. 408).

In addition, "The Industrial Laser Annual Handbook" 1986 Edition has suggested that 0.25 inch ceramic tiles can be cut with a CO₂ laser at the rate of 24 in./min. using 500 W power.

The most common ceramic being fusion cut using a CO₂ laser is Alumina (Al₂O₃). Alumina with a thickness of 0.027 in. is separated at rates over 60 in./min. Separations are made along any desired path, not necessarily only straight lines. No material is lost and the surface remains undamaged. The technique is applicable in separating small, brittle chips for microcircuits.

This technical ceramic substrate is of major significance to the
computer industry. A metal paste such as gold or silver is printed by silk screening circuitry pattern onto an alumina substrate which is either greenware or bisque.

Computer-controlled lasers may trim resistors to exact dimension. The substrates with metal paste are stacked and sintered (fired) around 1600°C. After sintering the ceramic circuits require no further finishing and are referred to as thick-film. The same process of laser trimming is followed for thin-film production. The only difference is that the metal is vacuum deposited onto thinner ceramic substrate.

The push for higher temperature and lighter weight materials makes engineering ceramics such as alumina, beryllia, porcelain, china, silicon carbide, and zirconia excellent candidates. Before these ceramics can gain wider use processing will require newer technologies. Advanced techniques like laser machining complementing processes like hot isostatic pressing, extruding, and slip casting will be the ceramic processing industry of the future.

**Processing parameters**

The interaction of a laser beam with the work piece depends mainly on the material parameters and the laser beam parameters.

**Material parameters** The material parameters that affect laser processing include: reflectance, absorption, specific heat, thermal conductivity, thermal diffusivity, latent heat, and transformation temperatures. These material parameters are discussed by Luxon and Parker (1985):
1. Reflectance $R$ is the ratio of the power reflected from a surface to the power incident on it. In chapter 1 it was pointed out that $R$, for normal incidence, is related to the refractive index by

$$R = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2 \quad \text{Eq. (11-1)}$$

where $n_2$ and $n_1$ are the refractive indices of the substrate material and incident medium, respectively. For conducting or absorbing dielectric materials, $n_2$ is a complex number and the square in Eq. (11-1) is an absolute square. The magnitude of the refractive index for good conductors (metals) is proportional to $[\sigma/(2\pi f)]/2$, where $\sigma$ is electrical conductivity, $\mu$ is magnetic permeability, and $f$ is the frequency of the light. Consequently, metals like copper and silver have high reflectances that increase with decreasing frequency (increasing wavelength). It is found that the reflectance of metals substantially decreases as the temperature nears the melting point.

2. Absorption coefficient $\alpha$ is the fractional loss of light power per unit distance for light traveling in a nonmetallic material. Beer's (Lambert's) law relates power to absorption by

$$P = P_0e^{-\alpha z}$$

where $P_0$ is the power entering the surface and $P$ is the power at depth $z$. The absorption coefficient can also be interpreted as the penetration depth or distance at which the power has dropped to one over $e$ (37%) of the value entering the surface.

3. Specific heat $C$ is the energy required to raise the temperature of unit mass one degree. The SI unit are joules per kilogram-Celsius degree but calories per gram-Celsius and BTU (British thermal unit) per pound-Fahrenheit degrees are also common. A frequently useful variation is the volume specific heat $C_v$ given by $\rho C$, where $\rho$ is the mass density of the material. $C_v$ is the energy required to raise the temperature of unit volume one degree, or energy per unit volume-degree.

4. Thermal conductivity $k$ is the heat flow per unit area per unit thermal gradient. The units are presented in a variety of ways, but a look at the one-dimensional heat conduction equation, which relates rate of heat flow $Q$ to thermal gradient $dT/dz$,

$$Q = -kA\frac{dT}{dz}$$

indicates that the SI units for $k$ are watt/m.$^{\circ}$C, but watt/cm.$^{\circ}$C are frequently used.

5. Thermal diffusivity $K$ is related to thermal conductivity and volume specific heat by
and is a measure of how much temperature rise will be caused by a pulse of heat applied to the material. It also indicates how rapidly heat will diffuse through the material. Units are generally cm²/s. Materials with high thermal diffusivity will experience a relatively small temperature rise with good heat penetration for a given heat pulse at the surface. A material with a low thermal diffusivity will undergo a relatively large temperature rise at the surface with a low heat penetration into the materials for a given heat pulse.

6. Latent heat \( L \) refers to the amount of heat required to cause a change of phase unit mass of material. \( L_f \) is the latent heat of fusion or the energy required to cause melting of unit mass. Examples of units are cal/g, BTU/lb, and the SI units joule/kg. \( L_v \) is the latent heat of vaporization and has the same meaning and units as \( L_f \). Latent heats of vaporization are much larger than latent heats of fusion and vaporization also requires more energy than that needed to raise unit mass up to the vaporization temperature. Consequently, when vaporization is involved in processing, it is a major factor in determining energy requirements.

7. Transformation temperatures refer to the melting temperature \( T_m \), vaporization temperature \( T_v \), and other phase change temperatures \( T_p \), such as the martensitic transformation temperature on the iron-carbon phase diagram. The last is particularly important in heat treatment of cast iron and steel (pp. 200-202).

Laser beam parameters The characteristics of the laser beam have been widely studies. The characteristics of the laser beam that affect laser cutting are: wavelength, mode structure, divergence, depth of focus, polarization, and power.

Wavelength The output wavelength of a laser is considered monochromatic. The 10.6 micrometer radiation emitted from CO2 laser enables it to cut most materials. Wavelength affects absorption and reflection characteristics of the work piece (also discussed in the section entitled Material Parameters).
Laser safety is an operator's parameter of paramount importance when laser beam wavelength is considered. Depending on the wavelength of light emitted by lasers, specified eye protection is recommended. This point is discussed in greater detail in the section entitled Laser Safety.

**Transverse Electromagnetic Beam Mode**  
An unfocused laser beam does not provide sufficient power density to melt most materials. The diameter of the unfocused beam is too large for cutting operations requiring narrow heat affected zones. For these reasons, concentrating the output beam of the laser is required.

By means of mirrors in the laser cavity and external optics, the laser beam can be made to have different shapes of intensity distributions. Inside the laser cavity the electromagnetic field generated by stimulated emission, is forced to take on certain modes, such as the Gaussian mode, also called TEM (TEM for transverse electromagnetic), ring mode, also called "donut" mode or TEM01*, multimode, and square mode. The shape of the transverse modes can be seen by looking at the shape of the output beam, see Figure 10.

The Gaussian beam has many advantages over the output beam of ring mode, multimode, or square mode. The Gaussian beam has a circular cross section with a maximum intensity in the center and decreasing in intensity radially out from the center.

The Gaussian mode produces the smallest diameter and lowest divergence laser beam. The Gaussian beam can be thought of as the sharp tool, while the ring mode, multimode, or square mode can be thought of as dull
tools in conventional machining techniques. Figure 11 shows the likeness of laser modes to a sharp or blunt tool.

In relation to the advantages of a Gaussian beam, Walker (1984) states:

First, the Gaussian energy distribution gives the maximum focused spot and hence the maximum energy density. Second, the energy profile across the beam is the same on all axes (p. 62).
It is the quality of the beam profile rather than the total power which determines the ultimate material processing performance for most applications.

The Gaussian mode is suitable for drilling, welding, and cutting operations, while the ring mode, multimode, and square mode are used for surface treatment applications. In the present work, only the Gaussian mode will be used.

**Divergence** All light beams spread out, or diverge, as they travel away from their sources. Lasers are the most directional light sources available, but even their beams diverge with distance. Only when the beam reaches a point of maximum diameter called a beam waist...
does it begin to diverge, as seen in Figure 12.

Figure 12. A Gaussian beam with a simple lens

Where:  
\[ f = \text{lens focal length.} \]
\[ \text{dm} = \text{beam diameter at waist.} \]
\[ \lambda = \text{laser wavelength.} \]
\[ \theta = \text{half-angle beam divergence.} \]
\[ z = \text{depth of focus.} \]
\[ d = \text{focused spot diameter.} \]

The divergence of ring mode, multimode, and square mode exceeds that of the Gaussian mode. The beam diameter of a Gaussian beam is defined as the distance across the center of the beam dm, for which the
irradiance equals $1/e^2 = 0.135$ of the maximum irradiance.

**Depth of focus** The depth of focus, $z$, is significant for material processing applications since it determines the focusing accuracy and, hence, work piece surface uniformity that is required. The depth of focus varies directly with the square of spot size and inversely with wavelength, $\lambda$. The depth of focus $z$, is given by

$$z = \frac{2\lambda}{\pi}(f/dm)^2$$

Where:
- $f =$ lens focal length.
- $dm =$ beam diameter at waist.
- $\lambda =$ laser wavelength.

Focused spot size $d$, is the radial distance from the point of maximum irradiance to the $1/e^2$ point. Focused spot size is typically accepted as one-half the beam diameter $dm$. The focus spot size $d$ is given by

$$d = \frac{4f\lambda}{\pi dm} = f\theta$$

Where:
- $f =$ lens focal length.
- $dm =$ beam diameter at waist.
- $\lambda =$ laser wavelength.

From this equation, the following observations can be made:

1. The focused spot size is directly proportional to the lens focal length, $f$, and laser wavelength, $\lambda$, and inversely proportional to beam diameter, $dm$, at the waist.

2. For radiation at a given wavelength, the focused spot size is minimized by reducing the ratio, $f/dm$, which is the working $f$ number of the lens.
Polarization According to Harry (1974):

The behavior of a light ray can be described in terms of an electric vibration and a magnetic vibration at right angles to each other and perpendicular to the direction of propagation of the ray. The ray is said to be plane polarized since the electric vibration is only in one plane. By superimposing other rays with polarization planes in different directions a randomly polarized beam may result. Alternatively if the direction of polarization is ordered more complex forms of polarization such as elliptical and circular polarization can be obtained (pp. 18-19).

If a work piece is moved in the direction of polarization, the processing speed would be increased. When cutting with plane polarization, the laser beam digs a cone shaped hole into the work piece. Therefore, polarization has an effect on processing, but Welch (1986) suggests, "Circular polarization is a convenient, comfortable way to preserve processing homogeneity" (p. 71).

Power Power is expressed in Watts. The amount of output power is dependent on the method of excitation and the length of the laser (both these points are discussed in detail in the section entitled, Classification of Carbon Dioxide Lasers).

Power is independent of time for continuous wave lasers. A focused 2 kW laser beam can produce energy densities at the work surface well in excess of 10 E7 Watts per square inch. Although this energy density is sufficient to vaporize most materials, Walker (1984) states:

The maximum power level readily accepted at the present time appears to be 5 to 6 kW. Frequently, 1 to 5 kW CO2 lasers work alongside conventional machine tools in normal production environments (p. 61).
The more difficult a material is to cut the greater the required power density. The peak power density, $I_0$, is found from the total incident power, $P_0$, and the area of the focused spot size and is given by:

$$I_0 = \frac{2P_0}{\pi(d/2)^2}$$

Material and the laser beam are the two major process parameters that determine material removal rate. There are still three other process parameters worth mentioning: cutting speed, type of reactive gas, and thickness of material. These three parameters are all interrelated.

The thicker a given piece of material the greater the amount of time and power required for cutting. The effectiveness of the laser for cutting can be increased by the use of an assist gas jet emitting a reactive gas.

The depth of cut (thickness of material) increases as the pressure of the gas jet is increased, until further increase in pressure has not further effect.

Cutting speed is independent of the gas used and gas pressure applied where the material does not react exothermically with the cutting gas. However, maximum cutting speed increases proportionally with laser power for a given thickness of material.

**Laser safety**

A continuous wave laser causes damage by thermal processes. Eye damage is caused by overheating of eye tissue, and excessive laser radiation cause burns. Winburn (1985) states:
Skin damage from laser radiation is not as great a concern as eye damage, such skin injury can be treated similarly to treatment of a thermal burn or wound. Further, in power or energy densities high enough to cause skin damage, the laser beam is usually enclosed, or some form of physical protection is provided for personnel. If this is not done, laser operators must wear protective clothing (p. 27).

Two parts of the eye, the cornea and the retina, are affected by certain wavelengths emitted by laser. Colored protective eyewear provide protection from wavelength ranges from 0.35 to 1.4 µm which is identified as the "ocular focus" region. Clear glass materials provide excellent protection for all ultraviolet and infrared (CO₂ lasers fall into this range) wavelengths. Colored plastic or glass materials are not needed in these ranges and may even hamper good visibility.

The Fred Reed Optical Company is one of a few firms offering the protective eyewear for the laser industry. Several options of goggles and spectacle frames are available with the primary concern being the comfort and confidence of operators.

The American National Standard Institute (ANSI) has determined "maximum permissible exposure" (MPE) limits for control of laser hazards. The MPE values are given in ANSI Standard No. 136.1, these were determined by a committee studying experimental information on eye and skin. They arrived at values somewhere below known hazardous values. Compliance with ANSI Standard No. 136.1 is not mandatory in the United States but should soon become so.

In addition to radiation hazards, other forms of laser hazards are electrical, bottled gas, combustibles, toxic dust and fumes, and general
safety considerations.

Electrical shock safety rules:
1. Assume that all electrical circuits are energized.
2. Use only one hand when working on circuits.
3. Do not handle electrical equipment when hands, feet, or body are/is wet.
4. Avoid wearing rings.
5. Provide enclosures to prevent accidental contact with electrical circuits.

Bottled gas safety rules:
1. Cap and label cylinders of gas in storage.
2. Support gas cylinders to prevent toppling.
3. Do not subject any part of a cylinder containing a compressed gas to a temperature above 125°F.
4. Keep cylinder valves closed at all times except when actually using gas.
5. Be knowledgeable about properties of gas to be used.

Fire prevention safety rules:
1. Good housekeeping is the best protection against fires.
2. Obvious fire hazards include materials that ignite spontaneously.
3. Be familiar with available fire extinguishers, locations of fire alarms, and exit doors.

Toxic dust and fumes safety rules:
1. Apply exhaust ventilation to remove harmful dust and fumes
at their source.

2. Use respirators when necessary.

General safety rules:

1. Do not try to operate equipment without being familiar with its operation and the location of the panic button.

2. Do not work with powered equipment unless another person is in the work vicinity.

3. Know the material properties.

4. Have emergency medical aid at hand.

5. Obey laser safety signs and symbols. Entrance to doorway of laser room should show sign in Figure 13.

By following the suggested procedures and rules and by exercising safety as an integral part of the operation, accidents with laser processing can be prevented.

Figure 13. Laser warning sign
CHAPTER 3. METHODOLOGY

This study is centered on the laser cutting of green china specimens; data for quality of cut surface, thickness of heat-affected zone, and weight of dross would be collected and analyzed. To achieve this aim, many activities had to be coordinated and performed. This chapter lists these activities showing the order in which they occurred and explains what was involved in each step.

The Material

This experiment was designed so that any slip casted ceramic could be tested. However, a material was selected using the following criteria:

1. The material is in current use in the ceramic industry.
2. The ceramic slip is castable in a plaster of paris mold.
3. The material's expected properties and molding conditions should be well documented so that reference data would be available as needed.

Bearing these conditions in mind, and after careful review of the slip casting industry, a china slip was selected for study. This slip, a product of the Kohler Company, had the following specifications:

- Type of material -- vitreous china
- General composition -- 35% ball clay, 35% feldspar, 15% flint, 15% china
- Specific gravity -- 1.82 (density of water at 20°C)
- Viscosity -- 800-1000 centipoise
- Firing temperature -- 2,350°F
This slip has application in the manufacture of sinks, bathtubs, bidet, toilet bowls, and tanks.

Steps were taken at the time of procuring the slip to insure the quality and grade of the material utilized in this study. This supplier confirmed a delivery date before use in this experiment. Upon delivery, the slip was kept in suspension by continuous mixing using a pneumatic mixer. The slip was kept in a closed container to protect it from evaporation and contamination.

The Mold and Cast Specimen

After deciding on the slip to be tested and the size and shape of the specimen, the mold was designed and built. A plaster of paris mold was cast in a wooden box which was used as the case mold. Figure 14 shows a photograph of the case mold, and Figure 15 shows a photograph of the plaster mold. Detail drawings of these molds are given in Appendix A.

The plaster mold contained one cavity which was fed by pouring slip over the top until filled (330 milliliters). This slip was allowed to cure forming a slab \(9\frac{1}{2}\)" x \(8\frac{1}{2}\)" x \(\frac{3}{4}\)". When the slab had dried (one hour) to the green state considered handleable, a flat rigid piece of plastic was placed over the top of the mold and together both were inverted. The cured slab separates from the walls of the plaster mold and, therefore, easily falls away from the mold. At this time a punch made from sheet metal was used to punch rectangular specimens \(1\frac{1}{4}\)" x 1" x \(\frac{3}{4}\)". In Figures 16 and 17, a close up view of the sheetmetal punch and a few
Figure 14. The case mold

Figure 15. The plaster mold
Figure 16. Sheetmetal punch and punched slab of leather-hard greenware

Figure 17. Punched specimens
of the specimens have been shown.

The experimenter had problems building a plaster mold for casting individual specimens. However, the method of punching the specimens from a cast slab works well since uniform specimens were produced.

The Pilot Test and Sample Size

A pilot run of 30 specimens was made varying the process parameters and the specimens tested to determine the variability to be expected in laser cutting. The resulting standard deviation was then used to determine the sample size needed for each cell in the proposed analysis. Once this was determined the specimens required for actual test were then molded.

Results from the pilot test are:

1. Mean roughness of cut surface = 658.33 inch; standard deviation = 1.23.
2. Mean thickness of heat-affected zone = 10.30 \times 10^{-3} \text{ inch}; standard deviation = 0.79.
3. Mean weight of dross = 39.41 \times 10^{-3} \text{ gram}; standard deviation = 0.84.

The sample size was arrived at using calculations based on this standard deviation and a critical difference between the means based on what difference the researcher required the test to be sensitive to. These calculations were made with a Type I error set at the 0.10 level and used as a two-tailed test. The Type II error was set at the 0.05 level but used as a one-tailed test. These values were chosen because
an error in either rejecting or accepting the null hypothesis could cause serious repercussion in the ceramic industry. The Type II error was considered more costly than a type I error, that is, accepting a false null hypothesis could lead to greater losses to the industry than rejecting the null hypothesis in favor of the alternate hypothesis.

The calculations of sample size were based on tables for minimum sample size needed to ensure a given power. Tables of sample sizes used in the analysis of variance are found in the Journal of Quality Technology, 1970, 2, 156-164. Appendix B shows the specific table which was used for the sample size calculation.

With:

\[
\text{Power (1-}\beta\text{)} = .95 \\
\alpha = .10 \\
p \text{ is the number of treatments } = 3 \\
D \text{ is the smallest difference between any pair of means that needs to be detected. } D \text{ is specified as a multiple of C.}
\]

In experimentation, the largest sample size found among the three dependent measures is used as the sample size. For all three dependent variables the difference (D) is equal to three times one standard deviation. With C=3 the sample size for the dependent variables quality of cut, thickness of heat-affected zone, and weight of dross are all equivalent.

From the tables it was determined that a sample size of n=4 samples per cell would be adequate. Figure 18 shows the 3x3x3 statistical design having 27 cells, 4 samples in each cell, and the total number of samples as N=108.
Sample Inspection and Control

Each batch of specimens was inspected after they had been punched. This procedure was utilized to insure there was no warping or visible surface cracking in the greenware. For each treatment group (of varying moisture contents), additional samples were cast to insure that the minimum number required (108) for testing were met.

No major finishing operations were carried out on the greenware. Trimming was avoided since the pieces needed to be identically prepared.
in order to produce meaningful comparisons. Trimming the specimens after punching could only have produced inaccuracies in the comparisons. Most importantly, the test area of the specimen remained in the as casted and as punched condition to ensure that this important section of the specimen received the same treatment for all the specimens throughout the experiment.

The specimens are cast at 75 degrees Fahrenheit and 50% relative humidity, samples are never kept for more than 24 hours. Samples at the same moisture content percent (three levels) are identified and placed in ziplock plastic bags to preserve their moisture content. The moisture content percent is determined by length of curing time and verified by a graphical instrument. Calculations of moisture content percents along with a graph of moisture content percent versus time can be found in Appendix C.

Each specimen was numbered in the order in which it was produced. They were then tested in a random manner to avoid any biases from laser cutting over time. Testing of specimens were done at the same room temperature and relative humidity at which they were casted. The specimens were then resorted into groups according to numbers for data collection.

The Variables

The independent variables that were manipulated in this experiment were:

1. moisture content of the greenware,
2. feed rate at which samples are cut, and
3. power of the laser beam.

Specimens were laser cut at high, medium, and low moisture contents; at high, medium, and low feed rates; and at high, medium, and low powers.

Low moisture content percent was set at relative humidity. High moisture content percent was set at the point where the green specimens were just handleable, and medium moisture content percent was set at the midpoint of high and low moisture content percent.

Cutting feed rates and powers were determined during laboratory trials where separation at the kerf was the discriminate used in selecting levels. From laser cutting samples over a range of feed rate and power combinations, the high and low levels for feed rate and power was determined. Medium feed rate and medium power was set at the midpoint of their respective high and low levels.

The actual settings for moisture content, feed rate, and power levels were:

- Low moisture content = 6%
- Medium moisture content = 13%
- High moisture content = 20%

- Low feed rate = 10 ipm
- Medium feed rate = 25 ipm
- High feed rate = 40 ipm

- Low power = 400 Watts
- Medium power = 600 Watts
- High power = 800 Watts

The investigation was concerned with the effect(s) the independent variations may have on the following dependent variables:

1. quality of cut measured in micro inch (\(\mu\)inch),
2. thickness of the heat-affected zone measured in thousandths of an inch (0.001 inch), and
3. weight of dross measured in thousandths of a gram (0.001 gram).

Laser Cutting

The industrial laser used in this experiment was a Spectra-820 carbon dioxide laser manufactured by Spectra Physics Corporation. Figure 19 shows a photograph of this machine. This transverse flowing gas laser has been described in the Literature Review.

In the process, a high power laser beam interacts with a specimen while a high relative speed is maintained between the two. In order to provide relative motion between the laser beam and the specimen, the laser beam is kept stationary and the specimen is mounted on a work table which is moved in the X and Y directions with stepper motors and controlled numerically. The laser beam emitting head is capable of sliding up and down, and the direction of the beam is always kept perpendicular to the work table.

A 5½ inch focal length lens was used to focus the beam on the surface of the specimen. An assist gas (compressed air) was introduced along with the laser beam and a single-pass melting and blowing method of cutting was employed with all specimens (fusion cutting). The laser was last serviced/calibrated (maintenance performed) January 1988.
Figure 19. Spectra-820 carbon dioxide laser
Measuring Equipment

1. A profilometer was used to measure the quality of cut.
2. A filocular microscope was used to measure the thickness of the heat-affected zone.
3. A sensitive scale was used to measure the weight of dross.

Data was accepted as accurate since each piece of equipment was calibrated prior to its usage. Equipment specification and details are provided in Appendix D.

The Results

Figures 20-22 show examples of the laser cut specimens. Three sets of results were obtained from measurements:

1. quality of cut,
2. thickness of heat-affected zone, and
3. weight of dross.

These results were then used in three separate statistical analyses; three-way analysis of variance (ANOVA) each having 27 cells and containing 108 samples. Figure 18 shows the layout of the statistical design.
Figure 20. Surface finish in laser cutting specimens at A-high, B-medium, and C-low moisture content (magnifications: 250X)
Figure 21. Example of a specimen showing dross at the bottom of the kerf (magnifications: 3½X)
Figure 22. Example of a specimen showing heat-affected zone (magnifications: $4\frac{1}{2}X$)
CHAPTER 4. PRESENTATION OF DATA

The results of this research are presented in this chapter. Each of the null hypotheses listed in chapter one was tested at the 90% confidence level, and the data have been presented in both tabular and graphical forms. The method of analysis chosen was Analysis of Variance (ANOVA) since this method would efficiently test the effects of the three independent variables simultaneously while studying their interactions.

Description of Data, Statistical Analysis, Restating and Testing of the Hypotheses, and Post Hoc Analysis

An ANOVA was performed on each of the three sets of data obtained after laser cutting, using the SPSSX statistical package on Iowa State University's WYLBUR computer system. A three-way ANOVA was performed on the quality of cut data set. Heat-affected zone and weight of dross data could not be obtained from medium and high levels of moisture content. A three-way ANOVA could not be performed where heat-affected zone and weight of dross were the dependent variables and where moisture content was an independent variable. Thus, a two-way ANOVA was performed on both the heat-affected zone and weight of dross data sets.

It was decided from the beginning of this investigation to accept or reject the null hypothesis on the basis of the means of the samples varying by an amount greater than expected by random sampling variation at the 0.10 level. A summary of the hypotheses testing is shown in Table 3.
Table 3. Summary of hypothesis testing

<table>
<thead>
<tr>
<th></th>
<th>Mean Quality of Cut</th>
<th>Mean Thickness of Heat-Affected Zone</th>
<th>Mean Weight of Dross</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MAIN EFFECTS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I. Power</td>
<td>nonsignificant</td>
<td>significant</td>
<td>significant</td>
</tr>
<tr>
<td>II. Moisture Content</td>
<td>significant</td>
<td>significant</td>
<td>significant</td>
</tr>
<tr>
<td>III. Feed Rate</td>
<td>significant</td>
<td>significant</td>
<td>significant</td>
</tr>
<tr>
<td><strong>TWO-WAY INTERACTION</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IV. Power by Moisture Content</td>
<td>nonsignificant</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V. Power by Feed Rate</td>
<td>significant</td>
<td>nonsignificant</td>
<td>significant</td>
</tr>
<tr>
<td>VI. Moisture Content by Feed Rate</td>
<td>significant</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>THREE-WAY INTERACTION</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VII. Power by Moisture Content by</td>
<td>nonsignificant</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed Rate</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

NOTE: Blank cells indicate a two-way ANOVA (power by feed rate) and no hypotheses tests were performed for main effects and interactions containing moisture content.
The statistical analysis was performed on the quality of cut in μinch, the thickness of the heat-affected zone in thousandths of an inch, and the weight of dross in thousandths of a gram to determine how they varied with power, moisture content, and feed rate. The seven hypotheses will be discussed in turn for each dependent variable.

Where there is a significant difference among the means of treatment groups for which the ANOVA yielded a significant F statistic, the Least Significant Difference (LSD) post hoc test was performed. The LSD test identified where the real differences existed in significant interactions and significant main effects. The LSD test has been summarized below with a (*) denoting the pairs of groups with significant differences at the $\alpha = 0.1$ level. In addition, significant interaction plots showing variations due to the interaction effect could also be seen graphically.

Quality of cut: moisture content by feed rate by power

Data description From this analysis, the grand mean of all 27 cells and 108 cases was found to be 581.94 μinch with a standard deviation of 200.78. Table 4 shows graphically the cell means of each main effect, two-way interactions, and the three-way interaction, along with the number of observations in parentheses. The table also shows the manner in which the feed rate, moisture content, and power were labeled from low to high (1-Low, 2-Medium, 3-High). The data were divided into a three row by three column by three slice matrix with each cell containing four samples. Table 5 shows the ANOVA results.
Table 4. Cell means for quality of cut in microinch

<table>
<thead>
<tr>
<th>Main Effects</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture content</td>
<td>814.58</td>
<td>570.83</td>
<td>360.42</td>
</tr>
<tr>
<td></td>
<td>(36)</td>
<td>(36)</td>
<td>(36)</td>
</tr>
<tr>
<td>Feed rate</td>
<td>612.50</td>
<td>572.22</td>
<td>561.11</td>
</tr>
<tr>
<td></td>
<td>(36)</td>
<td>(36)</td>
<td>(36)</td>
</tr>
<tr>
<td>Power</td>
<td>588.19</td>
<td>573.61</td>
<td>584.03</td>
</tr>
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<td></td>
<td>(36)</td>
<td>(36)</td>
<td>(36)</td>
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<table>
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<th>2</th>
<th>3</th>
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</thead>
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<td>2</td>
<td>3</td>
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<tr>
<td></td>
<td></td>
<td>1</td>
<td>789.58</td>
<td>812.50</td>
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<td></td>
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<td>(12)</td>
<td>(12)</td>
<td>(12)</td>
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<tr>
<td></td>
<td>Moisture Content</td>
<td>2</td>
<td>608.33</td>
<td>552.08</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(12)</td>
<td>(12)</td>
<td>(12)</td>
</tr>
<tr>
<td></td>
<td>Moisture Content</td>
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<td>439.58</td>
<td>352.08</td>
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<td></td>
<td>(12)</td>
<td>(12)</td>
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<table>
<thead>
<tr>
<th>Power</th>
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<th>2</th>
<th>3</th>
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</thead>
<tbody>
<tr>
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<td>616.67</td>
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<td>(12)</td>
<td>(12)</td>
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<tr>
<td>Feed Rate</td>
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<td>2</td>
</tr>
<tr>
<td></td>
<td>570.83</td>
<td>566.67</td>
<td>579.17</td>
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<tr>
<td></td>
<td>(12)</td>
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<td>(12)</td>
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<tr>
<td></td>
<td>577.08</td>
<td>579.17</td>
<td>527.08</td>
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<td></td>
<td>(12)</td>
<td>(12)</td>
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</tbody>
</table>

<table>
<thead>
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<th>2</th>
<th>3</th>
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</thead>
<tbody>
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<td>Power = 1</td>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Moisture Content</td>
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<td>1</td>
<td>781.25</td>
<td>787.50</td>
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<tr>
<td></td>
<td></td>
<td>(4)</td>
<td>(4)</td>
<td>(4)</td>
</tr>
<tr>
<td></td>
<td>Moisture Content</td>
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<td>643.75</td>
<td>568.75</td>
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<td></td>
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<td>(4)</td>
<td>(4)</td>
<td>(4)</td>
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<tr>
<td></td>
<td>Moisture Content</td>
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<td>425.00</td>
<td>356.25</td>
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<td></td>
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Table 4. Continued

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<td>3</td>
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<tr>
<td>Moisture Content</td>
<td>787.50</td>
<td>825.00</td>
<td>837.50</td>
<td></td>
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<tr>
<td></td>
<td>(4)</td>
<td>(4)</td>
<td>(4)</td>
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</tr>
<tr>
<td></td>
<td>537.50</td>
<td>500.00</td>
<td>587.50</td>
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<tr>
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<td>(4)</td>
<td>(4)</td>
<td>(4)</td>
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</tr>
<tr>
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<td>375.00</td>
<td>312.50</td>
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</tr>
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<td>Power = 3</td>
<td></td>
<td></td>
<td>Feed Rate</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moisture Content</td>
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<td>825.00</td>
<td>850.00</td>
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</tr>
<tr>
<td></td>
<td>(4)</td>
<td>(4)</td>
<td>(4)</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>643.75</td>
<td>587.50</td>
<td>475.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(4)</td>
<td>(4)</td>
<td>(4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>493.75</td>
<td>325.00</td>
<td>256.25</td>
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<td></td>
<td>(4)</td>
<td>(4)</td>
<td>(4)</td>
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</tr>
</tbody>
</table>

**Research hypothesis I** There will be no significant difference among the mean quality of cut of the samples cut at high power, medium power, and low power.

For the main effect power, the nonsignificant F-ratio indicated that the differences between the means for quality of cut over all three power levels could only be attributed to random sampling fluctuations. For this reason the null hypothesis has been accepted at the 0.1 level of significance.

**Research hypothesis II** There will be no significant difference among the mean quality of cut of the samples cut at high moisture content, medium moisture content, and low moisture content.

For the main effect moisture content, the significant F-ratio indicated that the differences between the means for quality of cut over
Table 5. Analysis of variance for quality of cut: power by moisture content by feed rate

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>Sum of Squares</th>
<th>DF</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig of F</th>
<th>F Critical</th>
<th>Decision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main effects</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moisture content</td>
<td>3776180.556</td>
<td>6</td>
<td>629363.426</td>
<td>171.356</td>
<td>.000</td>
<td>2.37</td>
<td>S</td>
</tr>
<tr>
<td>Feed rate</td>
<td>3719479.167</td>
<td>2</td>
<td>1859739.583</td>
<td>506.349</td>
<td>.000</td>
<td>2.37</td>
<td>S</td>
</tr>
<tr>
<td>Power</td>
<td>52638.889</td>
<td>2</td>
<td>26319.444</td>
<td>7.166</td>
<td>.001</td>
<td>2.37</td>
<td>S</td>
</tr>
<tr>
<td>Two-way interactions</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moisture content by feed rate</td>
<td>125277.778</td>
<td>4</td>
<td>31319.444</td>
<td>8.527</td>
<td>.000</td>
<td>2.02</td>
<td>S</td>
</tr>
<tr>
<td>Moisture content by power</td>
<td>21250.000</td>
<td>4</td>
<td>5312.500</td>
<td>1.446</td>
<td>.226</td>
<td>2.02</td>
<td>NS</td>
</tr>
<tr>
<td>Feed rate by power</td>
<td>48194.444</td>
<td>4</td>
<td>12048.611</td>
<td>3.280</td>
<td>.015</td>
<td>2.02</td>
<td>S</td>
</tr>
<tr>
<td>Three-way interactions</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moisture content by feed rate by power</td>
<td>45138.889</td>
<td>8</td>
<td>5642.361</td>
<td>1.536</td>
<td>.158</td>
<td>1.75</td>
<td>NS</td>
</tr>
<tr>
<td>Explained</td>
<td>4016041.667</td>
<td>26</td>
<td>154463.141</td>
<td>42.056</td>
<td>.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residual</td>
<td>297500.000</td>
<td>81</td>
<td>3672.840</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>4313541.667</td>
<td>107</td>
<td>40313.474</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

S = Significant, NS = Nonsignificant
all three moisture content levels were too great to attribute these differences to random sampling fluctuations if the null hypothesis was true. For this reason the null hypothesis has been rejected at the 0.1 level of significance and the alternative hypothesis accepted as true.

Research hypothesis III There will be no significant difference among the mean quality of cut of the samples cut at high feed rate, medium feed rate, and low feed rate.

For the main effect feed rate, the significant F-ratio indicated that the differences between the means for quality of cut over all three feed rate levels were too great to attribute these differences to random sampling fluctuations if the null hypothesis was true. For this reason the null hypothesis has been rejected at the 0.1 level of significance and the alternative hypothesis accepted as true.

Research hypothesis IV There will be no significant difference among the interaction effects of power and moisture content on the population means of quality of cut, where population is defined by combinations of power and moisture content.

For the two-way interaction effect power by moisture, the nonsignificant F-ratio indicated that the relationship between quality of cut and power does not change at the different levels of moisture content. For this reason the null hypothesis has been accepted at the 0.1 level of significance.

Research hypothesis V There will be no significant difference among the interaction effects of power and feed rate on the population means of quality of cut, where population is defined by combinations
of power and feed rate.

For the two-way interaction effect power by feed rate, the significant F-ratio indicated that the relationship between quality of cut and power changes at the different levels of feed rate. For this reason the null hypothesis has been rejected at the 0.1 level of significance and the alternative hypothesis accepted as true.

**Research hypothesis VI** There will be no significant difference among the interaction effects of moisture content and feed rate on the population means of quality of cut, where population is defined by combinations of moisture content and feed rate.

For the two-way interaction effect moisture content by feed rate, the significant F-ratio indicated that the relationship between quality of cut and moisture content changes at the different levels of feed rate. For this reason the null hypothesis has been rejected at the 0.1 level of significance and the alternative hypothesis accepted as true.

**Research hypothesis VII** There will be no significant difference among the interaction effects of power, moisture content, and feed rate on the population mean of quality of cut, where population is defined by combinations of power, moisture content, and feed rate.

For the three-way interaction power by moisture content by feed rate, the nonsignificant F-ratio indicated that the relationship between quality of cut, power, and moisture content does not change at the different levels of feed rate. For this reason the null hypothesis has been accepted at the 0.1 level of significance.
**Post hoc test** The three-way interaction of moisture content by feed rate by power and the two-way interaction of moisture content by power are both nonsignificant. However, the two-way interactions of moisture content by feed rate and feed rate by power are both significant. It is not reasonable to use main effects when interaction is present because they compare average effects of the significant interactions.

Nonstatistical conclusions for quality of cut will be made from the significant interaction plots of feed rate versus moisture content, see Figure 23, and power versus feed rate, see Figure 24.

Least significant difference, or LSD, given by:

$$\text{LSD}_\alpha = t_{\alpha/2, \text{Error d.f.}} \cdot S_E \sqrt{2/n}$$

where $\alpha = .1$

Error d.f. = 81

$$S_E = \sqrt{\frac{S_E^2}{\text{Error d.f.}}} = \sqrt{3672.840} = 60.604$$

$n = \text{number of observations in each treatment (cell sample size from two-way interaction)} = 12$

$$\text{LSD}.1 = t_{.05,81} \cdot 60.604 \sqrt{2/12} = (1.664) (60.604) (.408) = 41.170$$

<table>
<thead>
<tr>
<th>Moisture Content</th>
<th>Feed Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>789.58</td>
</tr>
<tr>
<td>2</td>
<td>812.50</td>
</tr>
<tr>
<td>3</td>
<td>841.67</td>
</tr>
</tbody>
</table>

(3) - (2) = 29.17 < 41.17; not significant
(3) - (1) = 52.09 > 41.17; significant
(2) - (1) = 22.92 < 41.17; not significant
Figure 23. Interaction plot of feed rate versus moisture content for quality of cut.
Figure 24. Interaction plot of power versus feed rate for quality of cut
<table>
<thead>
<tr>
<th>Moisture Content 1</th>
<th>Feed Rate</th>
<th>Mean (quality of cut)</th>
<th>GROUP</th>
<th>GRP 1</th>
<th>GRP 2</th>
<th>GRP 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>789.58</td>
<td>GRP 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>812.50</td>
<td>GRP 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>841.67</td>
<td>GRP 3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moisture Content 2</td>
<td>Feed Rate</td>
<td></td>
<td></td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>552.08</td>
<td>GRP 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>552.08</td>
<td>GRP 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>608.33</td>
<td>GRP 3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(1) - (3) = 56.25 > 41.17; significant
(1) - (2) = 56.25 > 41.17; significant
(2) - (1) = 0 < 41.17; not significant

<table>
<thead>
<tr>
<th>Moisture Content 3</th>
<th>Feed Rate</th>
<th>Mean (quality of cut)</th>
<th>GROUP</th>
<th>GRP 1</th>
<th>GRP 2</th>
<th>GRP 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>289.58</td>
<td>GRP 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>352.08</td>
<td>GRP 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>439.58</td>
<td>GRP 3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(1) - (3) = 150.00 > 41.17; significant
(1) - (2) = 87.50 > 41.17; significant
(2) - (3) = 62.50 > 41.17; significant

<table>
<thead>
<tr>
<th>Feed Rate 1</th>
<th>Power</th>
<th>Mean (quality of cut)</th>
<th>GROUP</th>
<th>GRP 1</th>
<th>GRP 2</th>
<th>GRP 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>575.00</td>
<td>GRP 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>616.67</td>
<td>GRP 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>645.83</td>
<td>GRP 3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(3) - (1) = 29.16 < 41.17; not significant
(3) - (2) = 70.83 > 41.17; significant
(1) - (2) = 41.67 > 41.17; significant
### Feed Rate 1

<table>
<thead>
<tr>
<th>Power</th>
<th>Group 1</th>
<th>Group 2</th>
<th>Group 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean (quality of cut)</td>
<td>616.67</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>575.00</td>
<td>GRP 1</td>
<td>GRP 2</td>
<td></td>
</tr>
<tr>
<td>645.83</td>
<td>GRP 3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Feed Rate 2

<table>
<thead>
<tr>
<th>Power</th>
<th>2</th>
<th>1</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean (quality of cut)</td>
<td>566.67</td>
<td>570.83</td>
<td>579.17</td>
</tr>
</tbody>
</table>

(3) - (1) = 8.34 < 41.17; not significant
(3) - (2) = 12.50 < 41.17; not significant
(1) - (2) = 4.16 < 41.17; not significant

### Feed Rate 3

<table>
<thead>
<tr>
<th>Power</th>
<th>3</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean (quality of cut)</td>
<td>527.08</td>
<td>577.08</td>
<td>579.17</td>
</tr>
</tbody>
</table>

(2) - (1) = 2.09 < 41.17; not significant
(2) - (3) = 52.09 > 41.17; significant
(1) - (3) = 50.00 > 41.17; significant

### Heat-affected zone: feed rate by power

Data description From this analysis, the grand mean of all nine cells and 36 cases was found to be 7.58 (x .001) inch with a standard deviation of 2.45. Table 6 shows graphically the cell means of each main effect.
and the two-way interaction, along with the number of observations in parentheses. The table also shows the manner in which the feed rates and powers were labeled from low to high (1-Low, 2-Medium, 3-High). The data were divided into a three row by three column matrix with each cell containing four samples. Table 7 shows the ANOVA results.

**Research hypothesis I** There will be no significant difference among the mean thickness of heat-affected zone of the samples cut at high power, medium power, and low power.

For the main effect power, the significant F-ratio indicated that the differences between the means for thickness of heat-affected zone over all three power levels were too great to attribute these differences to random sampling fluctuations if the null hypothesis was true. For this reason the null hypothesis has been rejected at the 0.1 level of significance, and the alternative hypothesis accepted as true.

**Research hypothesis II** A hypothesis test was not performed due to the unavailability of data at medium and high moisture content.

**Research hypothesis III** There will be no significant difference among the mean thickness of heat-affected zone of the samples cut at high feed rate, medium feed rate, and low feed rate.

For the main effect feed rate, the significant F-ratio indicated that the differences between the means for thickness of heat-affected zone over all three feed rate levels were too great to attribute these differences to random sampling fluctuations if the null hypothesis was true. For this reason the null hypothesis has been rejected at the 0.1 level of significance and the alternative hypothesis accepted as true.

<table>
<thead>
<tr>
<th>Power Level</th>
<th>Mean Thickness</th>
<th>F-ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7: ANOVA Results
Table 6. Cell means for heat-affected zone in .001 inch.

<table>
<thead>
<tr>
<th>Main Effects</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed rate</td>
<td>8.44</td>
<td>7.37</td>
<td>6.93</td>
</tr>
<tr>
<td></td>
<td>(12)</td>
<td>(12)</td>
<td>(12)</td>
</tr>
<tr>
<td>Power</td>
<td>5.50</td>
<td>6.69</td>
<td>10.55</td>
</tr>
<tr>
<td></td>
<td>(12)</td>
<td>(12)</td>
<td>(12)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Two-way Interaction</th>
<th>Feed Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Feed Rate</td>
<td>5.85 (4)</td>
</tr>
<tr>
<td>Power</td>
<td>5.57 (4)</td>
</tr>
<tr>
<td></td>
<td>5.07 (4)</td>
</tr>
</tbody>
</table>

Research hypothesis IV A hypothesis test was not performed due to the unavailability of data at medium and high moisture content.

Research hypothesis V There will be no significant difference among the interaction effects of power and feed rate on the population means of heat-affected zone, where population is defined by combinations of power and feed rate.

For the two-way interaction effect power by feed rate, the nonsignificant F-ratio indicated that the relationship between heat-affected zone and power does not change at the different levels of feed rate. For this reason the null hypothesis has been accepted at the 0.1 level of significance.

Research hypothesis VI A hypothesis test was not performed due to the unavailability of data at medium and high moisture content.
Table 7. Analysis of variance for heat-affected zone: power by feed rate

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>Sum of Squares</th>
<th>DF</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig of F</th>
<th>F Critical</th>
<th>Decision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main effects</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed rate</td>
<td>14.474</td>
<td>2</td>
<td>7.237</td>
<td>8.088</td>
<td>.002</td>
<td>2.51</td>
<td>S</td>
</tr>
<tr>
<td>Power</td>
<td>167.237</td>
<td>2</td>
<td>83.619</td>
<td>93.458</td>
<td>.000</td>
<td>2.51</td>
<td>S</td>
</tr>
<tr>
<td>Two-way interactions</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed rate by power</td>
<td>3.788</td>
<td>4</td>
<td>.947</td>
<td>1.058</td>
<td>.396</td>
<td>2.17</td>
<td>NS</td>
</tr>
<tr>
<td>Expained</td>
<td>185.499</td>
<td>8</td>
<td>23.187</td>
<td>25.916</td>
<td>.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residual</td>
<td>24.157</td>
<td>27</td>
<td>.895</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>209.656</td>
<td>35</td>
<td>5.990</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

S = Significant,  NS = Nonsignificant
Research hypothesis VII  A hypothesis test was not performed due to the unavailability of data at medium and high moisture content.

Post hoc test  The two-way interaction of feed rate by power is not significant. It is reasonable to use main effect test since both main effect feed rate and main effect power are significant. Statistical conclusions will be made from the significant main effects.

Least significant difference, or LSD, given by:

\[
LSD_{\alpha} = t_{\alpha/2} \cdot \text{Error d.f.} \cdot \frac{S_E}{\sqrt{2/n}}
\]

where \( \alpha = .1 \)

Error d.f. = 27

\[
S_E = \sqrt{S_E^2} = \sqrt{0.895} = 0.946
\]

\( n \) = number of observations in each treatment (cell sample size from main effect) = 12

\[
LSD_{.1} = t_{.05,27} \cdot 0.946 \sqrt{2/12}
\]

\[
= (1.703) (0.946) (.408) = 0.658
\]

<table>
<thead>
<tr>
<th>Feed Rate</th>
<th>3</th>
<th>2</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6.93</td>
<td>7.37</td>
<td>8.44</td>
</tr>
</tbody>
</table>

(1) - (2) = 1.070 > 0.658; significant
(1) - (3) = 1.510 > 0.658; significant
(2) - (3) = 0.440 < 0.658; not significant

<table>
<thead>
<tr>
<th>Feed rate (heat-affected zone)</th>
<th>GROUP</th>
<th>GRP 1</th>
<th>GRP 2</th>
<th>GRP 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>8.44</td>
<td>GRP 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>7.37</td>
<td>GRP 2</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6.93</td>
<td>GRP 3</td>
<td>*</td>
<td></td>
</tr>
</tbody>
</table>
Data description From this analysis, the grand mean of all nine cells and 36 cases was found to be 48.41 (± 0.001) inch with a standard deviation of 6.47. Table 8 shows graphically the cell means of each main effect and the two-way interaction, along with the number of observations in parentheses. The table also shows the manner in which the feed rate and power were labeled from low to high (1-Low, 2-Medium, 3-High). The data were divided into a three row by three column matrix with each cell containing four samples. Table 9 shows the ANOVA results.

Research hypothesis I There will be no significant difference among the mean weight of dross of the samples cut at high power, medium power, and low power.

For the main effect power, the significant F-ratio indicated that the differences between the means for weight of dross over all three power levels were too great to attribute these differences to random sampling fluctuations if the null hypothesis was true. For this reason the null hypothesis has been rejected at the 0.1 level of significance and the alternative hypothesis
Table 8. Cell means for weight of dross in .001 gram

<table>
<thead>
<tr>
<th>Main Effects</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed rate</td>
<td>41.94</td>
<td>49.95</td>
<td>53.35</td>
</tr>
<tr>
<td></td>
<td>(12)</td>
<td>(12)</td>
<td>(12)</td>
</tr>
<tr>
<td>Power</td>
<td>44.17</td>
<td>49.22</td>
<td>51.85</td>
</tr>
<tr>
<td></td>
<td>(12)</td>
<td>(12)</td>
<td>(12)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Two-way Interaction</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed Rate</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>34.88</td>
</tr>
<tr>
<td></td>
<td>(4)</td>
</tr>
<tr>
<td></td>
<td>47.62</td>
</tr>
<tr>
<td></td>
<td>(4)</td>
</tr>
<tr>
<td></td>
<td>50.02</td>
</tr>
<tr>
<td></td>
<td>(4)</td>
</tr>
</tbody>
</table>

accepted as true.

Research hypothesis II  A hypothesis test was not performed due to the unavailability of data at medium and high moisture content.

Research Hypothesis III  There will be no significant difference among the mean weight of dross of the samples cut at high feed rate, medium feed rate, and low feed rate.

For the main effect feed rate, the significant F-ratio indicated that the differences between the means for weight of dross over all three feed rate levels were too great to attribute these differences to random sampling fluctuations if the null hypothesis was true. For this reason the null hypothesis has been rejected at the 0.1 level of significance and the alternative hypothesis accepted as true.

Research hypothesis IV  A hypothesis test was not performed due to the unavailability of data at medium and high moisture content.
Table 9. Analysis of variance for weight of dross: power by feed rate

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>Sum of Squares</th>
<th>DF</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig of F</th>
<th>F Critical</th>
<th>Decision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main effects</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed rate</td>
<td>1188.408</td>
<td>4</td>
<td>297.102</td>
<td>50.693</td>
<td>.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power</td>
<td>823.374</td>
<td>2</td>
<td>411.687</td>
<td>70.244</td>
<td>.000</td>
<td>2.51</td>
<td>S</td>
</tr>
<tr>
<td>Two-way interactions</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed rate by power</td>
<td>365.034</td>
<td>2</td>
<td>182.517</td>
<td>31.142</td>
<td>.000</td>
<td>2.51</td>
<td>S</td>
</tr>
<tr>
<td>Explained</td>
<td>119.353</td>
<td>4</td>
<td>29.838</td>
<td>5.091</td>
<td>.003</td>
<td>2.17</td>
<td>S</td>
</tr>
<tr>
<td>Residual</td>
<td>158.242</td>
<td>27</td>
<td>5.861</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>1466.003</td>
<td>35</td>
<td>41.886</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

S = Significant, NS = Nonsignificant
**Research hypothesis V** There will be no significant difference among the interaction effects of power and feed rate on the population means of weight of dross, where population is defined by combinations of power and feed rate.

For the two-way interaction effect power by feed rate, the significant F-ratio indicated that the relationship between weight of dross and power changes at the different levels of feed rate. For this reason the null hypothesis has been rejected at the 0.1 level of significance and the alternative hypothesis accepted as true.

**Research hypothesis VI** A hypothesis test was not performed due to the unavailability of data at medium and high moisture content.

**Research hypothesis VII** A hypothesis test was not performed due to the unavailability of data at medium and high moisture content.

**Post hoc test** The two-way interaction of feed rate by power is significant. It is not reasonable to use main effects when interaction is present because they compare average effects of feed rate on power. Nonstatistical conclusions for weight of dross will be made from the significant interaction plot of power versus feed rate, see Figure 25.

Least significant difference, or LSD, given by:

\[
\text{LSD}_\alpha = t_{\alpha/2, \text{Error d.f.}} \cdot S_E \sqrt{2/n}
\]

where \( \alpha = .1 \)

\[
\text{Error d.f.} = 27
\]

\[
S_E = \sqrt{\frac{S_E^2}{n}} = \sqrt{5.861} = 2.421
\]

\( n = \text{number of observations in each treatment (cell sample size from two-way interaction)} = 4 \)
\[ \text{LSD}_{.1} = t_{.05,27} \times 2.421 \sqrt{2/4} = (1.703)(2.421)(.707) = 2.915 \]

### Feed Rate 1

<table>
<thead>
<tr>
<th>Power</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed Rate</td>
<td>34.88</td>
<td>42.27</td>
<td>48.67</td>
</tr>
</tbody>
</table>

\( (3) - (2) = 6.40 > 2.915; \text{significant} \)
\( (3) - (1) = 13.79 > 2.915; \text{significant} \)
\( (2) - (1) = 7.39 > 2.915; \text{significant} \)

### Feed Rate 2

<table>
<thead>
<tr>
<th>Power</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed Rate</td>
<td>47.62</td>
<td>50.40</td>
<td>51.82</td>
</tr>
</tbody>
</table>

\( (3) - (2) = 1.42 < 2.915; \text{not significant} \)
\( (3) - (1) = 4.20 > 2.915; \text{significant} \)
\( (2) - (1) = 2.78 < 2.915; \text{not significant} \)

### Feed Rate 3

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\( (3) - (2) = 0.08 < 2.915; \text{not significant} \)
\( (3) - (1) = 5.03 > 2.915; \text{significant} \)
\( (2) - (1) = 4.95 > 2.915; \text{significant} \)
Figure 25. Interaction plot of feed rate versus power for weight of dross
CHAPTER 5. SUMMARY, CONCLUSIONS, DISCUSSIONS, AND RECOMMENDATIONS

The purpose of this study was to investigate the effects of laser power, moisture content of the greenware, and the feed rate on the quality of cut, the thickness of the heat-affected zone, and the amount of dross produced by laser cutting green china ceramics. To determine these possible effects, three separate ANOVAs along with post hoc testing were used to determine significance and their differences. The information gathered will be important if the laser cutting of green china ceramics becomes an alternative for the conventional punching and trimming of greenware.

Research Summary and Conclusions

This section summarizes and concludes the study based on the statistical analysis reported in the previous chapter. A discussion of observations, findings, and conclusions is provided along with recommendations for further research.

Restatement of the problem

The problem of this study was threefold:

1. To investigate the quality of cut as affected by the power, moisture content, and feed rate.
2. To investigate the thickness of the heat-affected zone as affected by the power, moisture content, and feed rate.
3. To investigate the weight of dross as affected by the power, moisture content, and feed rate.

Conclusions

Quality of cut

1. High feed rate by low moisture content produces the worst quality of cut (841.67 winch).

2. High feed rate by high moisture content produces the best quality of cut (289.58 winch).

3. The higher the moisture content the better the quality of cut. In spite of interaction, there is a trend between feed rate and moisture content with quality of cut increasing linearly.

4. For paired comparison between the mean quality of cut at low moisture content, low feed rate was significantly better than high feed rate.

5. For paired comparisons between the mean quality of cut and medium moisture content, medium feed rate was significantly better than low feed rate, and high feed rate was significantly better than low feed rate.

6. At high moisture content, there was a significant difference between the mean quality of cut for all paired comparisons of low, medium, or high feed rate. The high feed rate gave the best quality of cut, and the low feed rate gave the worst quality of cut.

7. High power by low feed rate produces the worst quality of cut (645.83 winch).
8. High power by high feed rate produces the best quality of cut (527.08 µinch).

9. For paired comparisons between the mean quality of cut at low feed rate, medium power was significantly better than low power, and medium power was significantly better than high power.

10. At medium feed rate, there was no significant difference between the mean quality of cut for all paired comparisons of low, medium, or high power.

11. For paired comparisons between the mean quality of cut at high feed rate, high power was significantly better than low power, and high power was significantly better than medium power.

**Thickness of the heat-affected zone**

1. The widest heat-affected zone occurred at low feed (8.44 x 10^{-3} inch).

2. The narrowest heat-affected zone occurred at high feed (6.93 x 10^{-3} inch).

3. For paired comparisons between the mean heat-affected zone, medium feed rate produced a significantly narrower heat-affected zone than low feed rate, and high feed rate produced a significantly narrower heat-affected zone than low feed rate.

4. The widest heat-affected zone occurred at high power (10.55 x 10^{-3} inch).

5. The narrowest heat-affected zone occurred at low power (5.50 x 10^{-3} inch).
6. There was significant difference between the mean heat-affected zone for all paired comparisons of low, medium, or high power.

7. There was no heat-affected zone at either medium or high moisture content.

**Weight of dross**

1. High power by high feed rate produces the greatest weight of dross (55.05 x 10^{-3} gram).

2. Low power by low feed rate produces the least weight of dross (34.88 x 10^{-3} gram).

3. The higher the feed rate the greater the weight of dross. In spite of interaction, there is a trend between power and feed rate with weight of dross increasing curvilinearly.

4. The higher the power the greater the weight of dross. In spite of interaction, there is a trend between power and feed rate with weight of dross increasing curvilinearly.

5. At low feed rate, there was a significant difference between the mean weight of dross for all paired comparisons of low, medium, or high power. The high power gives the greatest weight of dross, and the low power gives the least weight of dross.

6. For paired comparisons between the mean weight of dross at medium feed rate, high power was significantly greater in weight of dross than low power.

7. For paired comparisons between the mean weight of dross at high feed rate, medium power was significantly greater in weight of dross
than low power, and high power was significantly greater in weight of dross than low power.

8. There was not weight of dross at either medium or high moisture content.

Discussion

After any machining process the surface properties of the product must be considered. This study provides the processing parameters relating to the laser cutting of one type of china greenware. The study was interested with power of the laser beam, moisture content of the greenware, the feed rate at which it is cut, and any relationship between them. It attempted to qualify and quantify the effects and any relationship with respect to the quality of cut, thickness of the heat-affected zone, and the weight of dross. This discussion gives an insight of observations, findings, and conclusions.

Quality of cut

The higher the moisture content the better the quality of cut in spite of an interaction. This trend may be due to laser fusion cutting. When a laser beam and an assist gas interacts with a specimen, moisture is vaporized and molten clay is blown clear of the kerf.

On specimens of low moisture content, molten and heat-affected clay is present on the kerf and some molten clay solidifies at the bottom of the kerf. However, specimens that were cut at either medium or high moisture content had neither a heat-affected zone nor dross. In addition, the samples cut at medium and high moisture content were observed
to have a wider kerf than those cut at low moisture content.

A profilometer was used to measure surface roughness (average roughness from a reference line), and the recording instrument compensates for any surface waviness and indicates only roughness. This suggests that surfaces with the same average roughness may be very different. Specimens of high moisture content had finishes comparable to a rough machined metal surface. Specimens of medium moisture content were much rougher, containing flaws and waviness. Specimens of low moisture content were measured as the roughest surface even though no flaws or waviness was apparent.

It is interesting to note that in evaluating the samples macroscopically, the high moisture content samples still appeared to have the best quality of cut, but medium moisture content samples appeared to have the worst quality of cut (see Figure 20). Low moisture content samples had an inherent shine on the heat-affected zone which may disguise the actual roughness.

**Heat-affected zone**

The findings with respect to the heat-affected zone are consistent with laser processing logic. Low feed rate causes a wide heat-affected zone, and high feed rate causes a narrow heat-affected zone. High power causes a wide heat-affected zone, and low power causes a narrow heat-affected zone. It is important to note the heat-affected zone occurs only for specimens with a low moisture content.
**Weight of dross**

In spite of an interaction between feed rate and power, there are trends with the amount of dross produced. The higher the power the greater the weight of dross is a reasonable trend. However, the trend of higher feed rates resulting in greater weight of dross is not consistent with reason. This uncanny trend may be explained through laser fusion cutting. At low feed rates most of the laser beam will pass straight through the kerf, and with an assist gas dross is blown clear of the kerf. At higher feed rates the melt depth decreases since the interaction time of the beam, assist gas, and the specimen decreases and the result is greater amounts of dross at the bottom of the kerf. It is important to note that dross occurs only for specimens with a low moisture content.

**Related remarks**

Processes, their development and their uses, are not the only ones possible and should not be slavishly and blindly followed. Obviously, there are basic principles that are crucial, but all processes need to be modified and automated. Automation does not mean that works will eventually be replaced by machines, but that they either feed machinery, maintain complicated equipment or make the changeover.

The experimentation in laser processing that is encouraged is not a senseless use of new techniques with old materials to find a better processing solution. Lasers are tools which do not come in contact with the work piece, this provides a means of material processing without
any mechanical stresses. It is this fact which allows laser cutting of the greenware across the range of moisture content.

Being able to laser cut the greenware at higher moisture content does not mean a shorter process cycle time. At any rate, greenware must be thoroughly dry prior to firing. The advantages of laser cutting the greenware over conventional punching and trimming are reliability, repeatability, flexibility, efficiency, and effectiveness.

The study of "The Effects of the Processing Parameters on the Laser Machining of a Green China Ceramic" is an attempt to provide an alternative to the conventional punching and trimming of the greenware. This study does not attempt to generalize the findings to other green ceramics. The ideas, their development, and results are only to be taken as guidelines and not as rules for laser processing green china. There are no shortcuts or agreed on procedures, but there is encouragement for investigation and study.

Recommendations for Further Research

This research generated many interesting questions which could be answered by future researchers. To facilitate this, the following recommendations have been made.

1. It is recommended that a materials science research be carried out to determine the composition of dross and to determine if alterations of the slip recipe may reduce or eliminate dross.

2. It is recommended that the shapes and the heat-affected zones of laser cut greenware be studied for dimensional changes after
both drying and firing.

3. It is recommended that other processing parameters such as depth of cut and kerf width be studied.

4. It is recommended that comparative research be carried out for various other green ceramics.

5. It is recommended that the ceramic industry make a comprehensive economic appraisal concerning the feasibility of laser cutting green ceramics.
BIBLIOGRAPHY


ACKNOWLEDGEMENT

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Dr. Mary Huba
Dr. Victor Tamashunas

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Thanks to my many friends at Iowa State University who helped along the way.

All praises and thanks to God.
APPENDIX A. DETAIL DRAWINGS OF MOLDS
Figure 26. Details of the case mold showing the overall dimensions as well as a section view.
Figure 27. Details of the plaster mold showing the overall dimensions as well as a section view.
APPENDIX B. JQT POWER TABLE FOR FINDING SAMPLE SIZE
Table 9. JQT power table for finding sample size

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APPENDIX C. CALCULATION OF SAMPLE MOISTURE CONTENT PERCENT OVER TIME, AND A GRAPH OF MOISTURE CONTENT VERSUS TIME

Calculation of Sample Moisture Content Levels

\[
\text{Percent Moisture} = \frac{\text{(Air dry weight)} - \text{(Oven dry weight)}}{\text{Oven dry weight}} \times 100
\]

where

\begin{align*}
\text{Air dry weight} & = \text{weight of the water saturated sample at a particular point in time} \\
\text{Oven dry weight} & = \text{unsaturated dry weight. Mean oven dry (250°F for 30 minutes) weight of samples is 9.82 grams.}
\end{align*}

From the plot of drying time versus moisture content percent:

- High moisture content = 20% (samples dried for 5 hours),
- Medium Moisture content = 13% (samples dried for 8.5 hours), and
- Low moisture content = 6% (samples dried for 49 hours).
Data For Plot of Drying Time Versus Moisture Content Percent

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Mean Moisture Content % (X)  
31.57  29.48  22.89  19.22

Std. Dev. (σ)  
5.09  5.05  5.70  5.85
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Mean Moisture Content (%) = 7.35  
Std. Dev. (σ) = 3.60
Figure 28. Drying time versus moisture content percent
APPENDIX D. SPECIFICATION AND DETAILS OF EQUIPMENT USED FOR MEASURING THE DEPENDENT VARIABLES

Profilometer Used to Measure Surface Roughness

Surface irregularities result during processing and material processors are in search of smooth finishes on parts for aesthetic purposes and as a mark of pride. To measure surface texture (roughness, waviness, lay, and flaws), a standard was developed by the American National Standards Institute. The surface irregularities, as well as the symbols for specifying surface texture, are shown in Figure 28.

In industry, surface texture is usually given as "average surface roughness," in microinches (μinch). Measurement of average roughness using a stylus is the only standardized way of measuring surface roughness. The readings may be either arithmetical or root mean square average deviation height from the reference surface. The internationally recognized designation for average roughness is "Ra."

Profilometer systems are direct reading shop instruments for measuring the surface roughness, and there are standard models that also measure peak count and other parameters. This study is concerned with one measure of surface texture, surface roughness, recorded as the quality of cut data.

Standard profilometer systems meet or exceed the requirements of American National Standard ANSI B46.1-1978 and other international standards which define surface roughness.
Figure 29. Standard terminology and standard lay symbols to describe surface finish. The quantities are given in µinch.
A profilometer system consists of three major components: 1) a tracer, which is moved across the surface being measured and includes the diamond stylus that follows surface irregularities, 2) a pilotor, the motor driven unit that moves the tracer at constant known speed across the surface being measured, and 3) an amplifier, connected to the tracer by a cable. Figure 29 shows a profilometer system.

The instrument measures the number of roughness peaks per inch above a preselected height by passing the tracer point over the surface. The vertical movement of the tracing point is converted into fluctuating voltage that is related to the height of the surface irregularity. The amplifier receives the voltage from the tracer, amplifies it, and integrates it so that it may be read as digital.

Accuracy and repeatability of surface roughness measurement can be obtained by following simple instructions and taking simple precautions. A handout from the Bendix Corporation, Dayton, Ohio by the Automation and Measurement Division, 1980, suggests:

Errors can be attributed to:
1) improper functioning or adjustment of equipment,
2) the data gathering and interpretation process,
3) the part surface itself, and
4) the environment in which the measure is made.

Equipment

1. Nearly all commercially available instruments will meet standard requirements when built.

2. Electronic components and circuits after long use, or a short period of misuse, wear or loosening of components can affect performance.
Figure 30. Sheffield profilometer systems for measuring surface roughness
3. Using calibration checks will indicate this condition. There are two philosophies regarding calibration of surface roughness measuring equipment:

   Calibration of Components. The tracer and amplimeter are each calibrated separately to manufacturer's standards.

   Calibration of System. By the use of a precision roughness specimen.

Data Gathering

Existing standards detail the setup, operating, and interpretation requirements to obtain consistent results.

Part Surface

A common explanation of nonrepeatability of Ra readings on a part surface is the fact that all surfaces vary to some degree. Surfaces produced by some normal manufacturing processes may vary by as much as 30% from one area of the surface to another. Even in these cases, measurement accuracy can be improved by adhering to standard measurement principles and techniques.

Environment

A clean environment is necessary.

Points to remember when measuring surface roughness:

If no surface roughness (Ra) is specified, the surface produced is assumed to be satisfactory.

If no cutoff is specified, the .030" instrument setting is assumed.

The cutoff specified should include all surface irregularities and roughness spacings that are of interest.

To obtain meaningful measurements, the stroke length in one direction on the part surface must be at least five times the cutoff.
On meter display instruments, the average roughness (Ra) value is the mean reading about which the needle tends to dwell.

Arithmetic average roughness (Ra) should not be used in an attempt to control flaws, scratches, or other irregularities. Use a peak count measurement as a supplementary measurement.

A Sheffield profilometer system (Group GL for general purpose use) was used in measuring surface roughness. The following are specifications for the system:

Amplifiers = QE
Measures = Average Roughness (Ra)
Display = Meter. Continuous reading, meter damping per B46 standard or Hi-damp.
Ra ranges = 0-3 "
   = 0-10 "
   = 0-30 "
   = 0-100 "
   = 0-300 "
   = 0-1000 "

Peak count range = QE does not have peak count feature

Cutoffs:
   With V-series pilotors = 0.010", 0.030", 0.100"
   With A, R-series Pilotors = 0.003", 0.010", 0.030"
Dimensions = 5.2" x 11.6" x 9.4"
Weight = 10 lbs.
Power Input = 115 V or 230 V A.C., 50/60 Hz
Power Consumption = 3 watts
Linean Pilotors = VE
Tracer Used = Type LK tracer with type FT skidmount
Stroke Lengths = .050" - 2.5"
Tracing Speed = 0.3"/sec.
Dimensions = 6.5" height, 4.25" width, 10.25" depth
Weight = 7 lb.
Power Input = 115 V A.C., 60 Hz (230 V and/or 50 Hz optionally available)
Power Consumption = 1 watt

Filocular microscope used to measure thickness of heat-affected zone

The Gaertner Microscope has been a standard piece of equipment in inspection and quality control departments, tool and die shops, and industrial and research laboratories for many years. The microscope seen in Figure 30 was used for making precision measurement of the heat-affected zone on laser cut specimens.

Specifications:
Filocular direct reading to 0.001 inch
Protractor ocular direct reading to one minute
Measures linear dimensions up to four inches
Measures angular dimensions through a full 360°
Magnification = 30X
Field, diameter on object = 0.255 inch
Working Distance (objective to work) = 2.4 inches
Thickness of work accommodated, maximum 5.4 inches
Figure 31. Filocular microscope
Depth of Throat = 5.25 inches
Stage Dimensions = 7.625 inches diameter
Height = 19.3 inches
Dimensions of Base = 18.5 inches x 22 inches
Weight = 84 pounds

Sensitive scale used to weigh dross

A Mettler AE240 electronic analytical balance was used for laboratory weighing of dross. The AE240, shown in Figure 31, is a dual range balance. It offers a 41 g range with 0.01 mg readability and a 205 g range with 0.1 mg readability. Some other specifications are:

- Power supply = adjustable voltage 115 or 230
- Permitted ambient conditions = temperature, 50-104°F; relative humidity 25-85% (noncondensing)
- Weigh pan = 3.125 inches
- Headroom above weighing pan = 8.5 inches
- Balance Housing (WxDxH) = 8.125" x 16.125" x 11.5"
- Net weight = 22.75 pounds
Figure 32. Mettler AE240 electronic analytical balance