# 3-D Computer-aided Design (CAD) and Computer Numerical Control (CNC) milling: An alternative to traditional ceramics master moulding technology

Elsje du Plooy

# 3-D Computer-aided Design (CAD) and Computer Numerical Control (CNC) milling: An alternative to traditional ceramics master moulding technology

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By

Elsje du Plooy

Student number: 9734503

Supervisor: Ms C Kühn

Co-supervisor: Mr G Booysen


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## Declaration

I, the undersigned, hereby declare that this dissertation is my own independent work and that this dissertation, or parts thereof, has not previously been submitted by me or anyone else to any other institution in order to obtain a qualification.

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Signature Date

# Summary

This quantitative research project investigates the utilization of emerging technologies within the arts with a view on establishing an interdisciplinary approach between ceramics and engineering. The traditional manufacturing method of producing master moulds is a time-consuming process for the studio ceramicist. This study explores whether computer-aided design (CAD) and computer numerical control (CNC) milling can accelerate the design and manufacturing process when developing master moulds as an alternative to using traditional methods. It investigates whether SolidWorks® can be applied as a suitable CAD design tool for the creation of ceramic vessel forms in order to reduce the design development time frame. It furthermore investigates whether CNC milling can be used as a viable manufacturing technology for the making of vessel prototypes and master moulds from CAD data, the overall objective being to improve and accelerate the plaster of Paris master mould manufacturing process for the batch production of studio-based ceramic artefacts. Findings from this study indicate that emerging technologies have a lot to offer the artist when it comes to providing new possibilities for the creation of artefacts and that SolidWorks® and CNC milling can be utilized as a viable interdisciplinary manufacturing approach between ceramics and digital manufacturing technologies.

## Acknowledgements

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## Definition of terms

| | |
|---|---|
| Additive Manufacturing | Additive Manufacturing is the process of joining or adding materials in layers to form a 3-D model (Black & Kohser, 2013:508). |
| Digital Manufacturing | Digital Manufacturing is the use of a digital or computer-based system for integrated design and manufacturing that works with the product definition to support simulation, visualization, collaboration tools and analytics necessary to optimize the product and manufacturing design process (Zhou, Xie & Chen, 2012:6). |
| Interdisciplinary approach | An interdisciplinary approach refers to the utilization of two or more knowledge areas that are usually considered distinct (such as engineering and the arts) to create new paradigms or ways of knowing and doing within these established disciplines or even to establish a new field or discipline (or new subfield or sub-discipline) (Repko, 2012:21). |
| Parameters | A parameter is a mathematical value or other measurable factor that determines a range of variations forming one of a series that defines a system or the operation of a system (Lombard, 2013:16). |
| Rapid prototyping | Rapid prototyping is a computer generated 3-D scale model of a physical part or assembly that is quickly manufactured from a computer-aided design (CAD) drawing (Black & Kohser, 2013:19). |
| Prototype | A prototype is the first model of an artefact from which other forms are developed or copied (Gibson, Rosen & Stucker, 2010:1). |
| Slipcasting | Slipcasting refers to a method used by ceramicists that involves using watered-down clay, called slip, which is poured into a plaster of Paris mould to create a thin layer of dry clay that is the same shape as the mould (Wardell, 1997:7). |

| | |
|---|---|
| Subtractive manufacturing | Subtractive manufacturing is a technique used to manufacture parts or artefacts by removing material by methods such as cutting/milling or drilling (Afsharizand, Nassehi, Dhokia & Newman, 2013:171). |

## Abbreviations and Acronyms

| | |
|---|---|
| AM | Additive Manufacturing |
| API | Application Program Interface |
| APT | Automatically Programmed Tools |
| CAD | Computer-aided Design |
| CAM | Computer-aided Manufacturing |
| CNC | Computer Numerical Control |
| DDM | Direct-digital Manufacturing |
| IGES | Initial Graphics Exchange Specification |
| MCU | Machine Control Unit |
| STEP | Standard of the Exchange of Product Data |
| STL | Standard Triangulation Language |
| X_T | Parasolid CAD file |

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## Structure of dissertation

Chapter 1 provides a brief background to the study. It states the research problem, aim, research question, individual objectives and research methodology for the study. Chapter 2 provides an empirical and theoretical framework for the study through the review of related literature. Furthermore, it outlines historical and current developments as well as various industry-related approaches to manufacturing. The chapter concludes with select examples from the literature that support the application of an interdisciplinary approach concerning the use of emerging technologies within the arts.

The methodology for this research project follows an action research approach forming a cycle of four steps: plan, act, observe and reflect. The three main research objectives of this study will be addressed by applying the four action research steps to the individual aspects dealt with in Chapters 3, 4 and 5 respectively. Chapter 3 explores the operational features and design parameters of SolidWorks® as a 3-D CAD design technology. Chapter 4 explores the possibility of utilizing CNC milling as a manufacturing technology for the development of vessel prototypes and master moulds. Chapter 5 presents the research findings as gathered from Chapters 3 and 4. Knowledge gained is applied to the design of a range of vessel forms from which CNC milled prototypes and plaster of Paris master moulds are manufactured. In order to test the research concept, a batch production of the artefacts is manufactured. Chapter 6 provides a summary of the overall study and draws conclusions from the results obtained and presents recommendations for further research and development in this area of study. An addendum of additional design geometries and supportive data are included at the end of the dissertation.

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# Chapter 1

# Research proposal

## a) Background to the study

The manufacturing of ceramic master moulds is a core production-orientated activity. The pioneering British ceramicist Bernard Leach (1887 – 1979) (1975:46) criticized the Industrial Revolution (1760 – 1840) for the decelerated impact it had on mass-produced ceramic ware through which artistic standards were compromised. From an industrial design perspective artistic standards refer to the technical quality of work combined with the aesthetic value of the artefact (Industrial Designers Society of America [IDSA], 2010). Aesthetic value refers to the creative or conceptual expression within a work of art (Raizman, 2003:11,12). Artistic standards can also be defined as the degree or level of excellence regarding the technical quality, aesthetic value as well as the visual, conceptual and emotional content which evokes an experience of the object manufactured (Levinson, 2005:6). Leach was trained within the Pre-modernist Japanese tradition and largely focused on the production of utilitarian ceramic ware (Barnard, 2007:19). Because of Leach's pioneering influence on ceramics, his personal philosophy of embracing handmade utilitarian ware and the rejection of machine manufactured ceramics had a significant impact on the progress of ceramics as an art form (Pennings, 2006:124). Leach promoted his philosophy to explore hand skills as the way forward after the disorder and uncertainty that emerged after the Second World War (Herring, 2013:18). Artists influenced by Leach felt that the Modernist industrialized approach was a threat to the artist's individuality rather than a challenge and as such were hesitant to experiment with emerging technologies (Pennings, 2006:127). This mind-set hindered the development of industrial ceramics practice within the Post-modern era (Barnard, 2007:21).

Many contemporary artists apply an interdisciplinary approach to design and manufacture which over time has assisted in bridging the historical gap between art and technology (Thurston, 2009:5). An interdisciplinary approach is defined as a process of addressing an issue, solving a problem or answering a question that may be too wide-ranging to be dealt with by a single discipline and therefore requires interrelated actions from dissimilar disciplines to ultimately provide problem-solving strategies (Repko, 2012:21; Klein & Newell, 1997:393-415; Frodeman, Klein & Mitcham, 2010). The possibility of the artist integrating new technologies for manufacturing purposes requires that the artist incorporates research and development as a key activity within his or her studio practice environment (Thurston, 2009:1). Advances in technology have accelerated manufacturing processes within the engineering industry and allowed for more accurate production methods to evolve. However, the potential that these advances present for and within the field of ceramics has not yet been explored to its full extent, particularly the manufacturing of master moulds for production purposes. Applying an interdisciplinary approach to the integration of emerging technologies in the contemporary ceramicist's studio practice has the potential to fulfil a need that stimulates a decrease in production lead-time. The application of emerging digital technologies furthermore has the ability to strengthen the manufacturing process chain for the development of artefacts across a range of creative disciplines.

In the context of quantitative research the fundamental purpose of action research is to produce practical knowledge that describes a phenomenon numerically rather than using descriptive textual data (McNiff & Whitehead, 2011:14; Wisker, 2009:144). The researcher's epistemological position towards the interdisciplinary nature of this study is to conduct a range of empirical tests that show the viability for the studio ceramicist to successfully engage with emerging technologies. Ontologically the researcher as practising ceramicist is engaged with interdisciplinary practice within the practical research environment, whereby prior technical ceramics knowledge enhances the integration of select emerging technologies. Therefore the subject (namely the researcher as participant observer) and object (that which is being researched, namely CAD and CNC milling as design and manufacturing technologies) are interdependent which gives rise to the reality we experience and therefore this action research approach draws on an extended epistemology (Reason & Bradbury, 2006:9).

**b) Problem statement**

Industry-related needs are driven by globalization which indicates a need for accelerated and improved product design and development strategies. The use of appropriate digital manufacturing technologies can assist the studio-based ceramicist to competitively engage with global markets by improving on design quality through technology-driven product development strategies. The traditional ceramics process of making vessel prototypes and plaster of Paris master moulds is a labour-intensive and time-consuming process for the studio-based ceramicist. At present the initial clay modelled vessel prototype, as well as the so-called plaster of Paris “master mould” cast from the prototype, are done manually. Due to this time-consuming process it is often found that subsequent changes to a design are kept to a minimum. The utilization of 3-D computer-aided design (CAD) as a design input technology and computer numerical control (CNC) milling as an output manufacturing technology can assist the studio-based ceramicist in improving the design quality and accelerate the overall vessel prototype and master mould manufacturing process. This study tests and evaluates the complexity, flexibility, accuracy, speed and cost implications when integrating 3-D CAD and CNC milling as design and vessel prototype development tools. The integration of emerging technologies allows the studio ceramicist to effortlessly alter designs and accelerate the manufacture of master moulds for the batch production of studio ceramic artefacts. This study proposes that by implementing technology-driven design and manufacture solutions, it will contribute to and improve on existing ceramics studio practice.

### c) Research aim

The aim of this study is to establish an interdisciplinary approach between traditional ceramics practice and digital technologies as an alternative manufacturing approach in order to develop vessel prototypes and plaster of Paris master moulds for the batch production of studio-based ceramic artefacts.

### d) Research question

Can the interdisciplinary use of 3-D computer-aided design (CAD) and computer numerical controlled (CNC) milling be applied as alternative design and manufacturing technologies for the development of vessel prototypes and master moulds for a batch production range of vessel forms.

## e) Objectives

### Objective 1: 3-D computer-aided design (CAD): Vessel prototype and master mould design

To apply 3-D CAD technology as a flexible and accurate design intervention tool that reduces the design development time frame for the batch production of studio-based ceramic vessel forms. The suitability of SolidWorks® as a 3-D CAD software program will be examined throughout the design process. Aspects that will be reflected on are the flexibility regarding frequent changes within a design, the complexity of form, the degree of accuracy within geometries and the variable size adjustment of an artefact.

### Objective 2: Computer numerical controlled (CNC) milling: Vessel prototype and master mould manufacture

To apply CNC milling technology as an alternative to manually producing vessel prototypes and plaster of Paris master moulds for the batch production of studio-based ceramic artefacts. Various material types suitable for the CNC manufacture of a range of vessel prototypes will be investigated. Aspects regarding the milling pathway programming, machining time, accuracy of the milling process and levels of complexity will be investigated using a 3-axis CNC milling machine.

### Objective 3: Vessel prototype and master mould testing and analysis

To batch test and analyse the results from the various approaches taken to prototyping and master moulding of the vessel forms in order to determine cost-effectiveness, technical aspects and the overall product-to-market lead time cycle.

## f) Research methodology

This study follows a quantitative positivist paradigm. Quantitative research is an objective systematic approach to problem-solving based on scientific proof. Measurements and observations are done through the use of instruments of the events or objects with an emphasis on numerical data that can be analysed to obtain conclusions (Bloomberg & Volpe, 2012:28; Muijs, 2011:2). The researcher has chosen to apply a quantitative research approach because it places emphasis on measuring written up data as numerical data whereas qualitative research, contrastingly, explores behaviours, perspectives, feelings and experiences of people in order to obtain information about the world. This study applies an Action Research Design as it is suited to the participatory testing and analysis of the individual test geometries as well as the final application thereof (Creswell, 2013:45,46).

Action research refers to a cycle of actions designed to address the objectives of the proposed research project. The procedural representation of a typical action research process follows a cycle of four steps: plan, act, observe and reflect (see Figure 1) (Dawson, 2009:17). The applicability of this methodology to the study is that it allows for a structured cyclic process of investigation and implementation of the findings (Moule & Hek, 2011:69). To execute the individual objectives of the study, research is done by sampling which includes testing and measuring by comparative analysis using the action research steps for data collection and analysis. The results and findings from integrating 3-D CAD and CNC milling will be applied to the manufacture of vessel prototypes and master moulds in order to demonstrate an alternative to traditional manufacturing methods.

**Method objective 1**

To apply 3-D CAD technology as flexible and accurate design intervention tool that reduces the design development time frame for the batch production of studio-based ceramic vessel forms.

**Plan:** To *apply* the design tools in conjunction with the design parameters of SolidWorks® as a 3-D CAD software program for the design of vessel prototypes.

**Act:** To use SolidWorks® to *design* various vessel prototypes. SolidWorks® should allow for easy and flexible changes within the design process irrespective of the complexity and/or stage of the design development process.

**Observe:** To *record* the time required for the overall design process as well as observe the tool feature capabilities and limitations of SolidWorks® as a 3-D CAD design intervention tool.

**Reflect:** To *reflect* on whether SolidWorks® adequately supports the design process by way of determining the allowance for flexible changes and degree of complexity achieved within the design process itself.

**Method objective 2**

To apply CNC milling technology as an alternative to manually producing vessel prototypes and plaster of Paris master moulds for the batch production of studio-based ceramic artefacts.

**Plan:** To *research* the technical specifications of a 3-axis CNC milling machine to ascertain whether its capabilities support the desired complexity of the intended vessel prototypes and master moulds.

**Act:** To *manufacture* the vessel prototypes and master moulds by way of the direct CNC milling process.

**Observe:** To *review* and *collate* all data surrounding technical aspects such as speed, accuracy, complexity and milling time.

**Reflect:** To *reflect* on the overall procedural aspects relating to the CNC milling process in order to ascertain whether it supports the accelerated development of vessel prototypes and master moulds.

**Method objective 3**

To batch test and analyse the results from the various approaches taken to prototyping and master moulding of vessel forms in order to determine cost-effectiveness, technical aspects and the overall product-to-market lead time cycle.

**Plan:** To *test* and *analyse* the manufactured CNC milled vessel prototypes and master moulds.

**Act:** To *test* and *analyse* each plaster of Paris master mould by slipcasting vessel forms, using the established ceramic clay slipcasting technique.

**Observe:** To *determine* the overall cost-effectiveness and measure the production lead-time gained by using CNC milling as a manufacturing technology when compared to traditional ceramic mould manufacturing methods.

**Reflect:** To *reflect* on the overall complexity, structural success and workability of the vessel prototypes and master moulds.

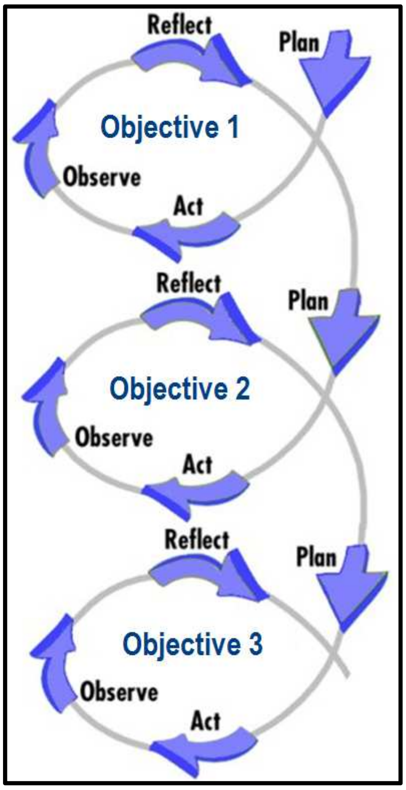


Figure 1: Procedural representation of the action research process for this study. (Kurt Lewin's Spiral Model, Action Research Cycle - mid-1940s.)

Figure 1 provides an outline of the procedural representation of the action research process for this study. The first step of Objective 1 (plan) will be addressed in Chapter 3 and the remaining steps (act, observe, reflect) will be discussed in Chapter 5. Chapter 3 focuses on CAD by providing a brief background on the development and advantages of CAD and the operational features and parameters of SolidWorks® as a design tool. The act of observing during the design process for the development of the vessel prototypes is discussed in Chapter 5. Objective 2, discussed in Chapter 4, follows the same cyclic process where the "plan" step reflects on the technical aspects regarding milling machines, actual milling processes and a suitable milling material. The remaining steps of Objective 2 regarding the milling of the vessel prototypes are addressed in Chapter 5 as part of the overall findings. Also discussed in Chapter 5 are the findings from Objective 3 which deal with the testing and analysis of the manufactured CNC milled vessel prototypes and the plaster of Paris master moulds.

### g) Research population and sample group

In a research design the population group refers to the elements that are being studied and which can be individuals, groups, objects or events from which the researcher obtains results. The population group for this study consists of a range of vessel prototypes. The sample group refers to the number of participants or objects which are used within the research project (Moule & Hek, 2011:85,86). A purposive sample of four vessel forms was selected. A purposive sample refers to a non-random selection of objects or participants that fit the aim of the study (Edmonds & Kennedy, 2013:17). From the range of designed vessel prototypes, four were selected for the purpose of testing complexity, accuracy, design changes and alteration in size in order to accelerate the manufacturing process of master moulds. A set of design criteria was established by means of conducting a pilot study on a range of six test geometries. A pilot study is a small-scale preliminary study conducted in order to evaluate its feasibility regarding aspects related to the overall study in an attempt to strengthen the reliability of the study (Dawson, 2009:98). The six test geometries tested the feasibility of using a CNC machine as well as suitable milling material.

### h) Data collection

Initial primary data was collected by means of performing geometry parameter tests. Through careful measuring and observation the findings were recorded and transcribed using data sheets. A range of six test geometries were developed in order to investigate a suitable milling material to determine the height-width release ratio for moulding purposes.

The flexibility, complexity, accuracy and changes regarding scale of the vessel prototypes were performed on the four final vessel forms designed using 3-D CAD and manufactured using CNC milling. In addition, a time and cost comparison against traditional master mould manufacturing methods was drawn. Time- and cost-related information regarding traditional manufacturing methods was obtained from an experienced practising studio ceramicist.

**i) Data analysis**

The outcomes and results of the test geometries, final vessel prototypes and final master moulds were manually analysed from the recorded data sheets. The analysed data includes the overall time- and cost-related aspects for the design and manufacture of the above-mentioned geometries, forms and moulds. Numerical results are collated in the form of either tables or graphs in order to present condensed summaries. Conclusions and findings of the study are summarized using descriptive textual data.

**j) Reliability and validity**

Reliability refers to the accuracy of the research tool or procedure in order to yield consistent measurements and results and the extent to which a procedure produces constant results (Muijs, 2011:62,63). In the present study the researcher ensures reliability by testing six varying geometries using the SolidWorks® Education Edition 2012-2013 software package and the same 3-axis DAHLI 720 CNC milling machine in order to ensure consistency when manipulating and collecting data. The test geometries were tested and retested twice by making a standardized plaster of Paris mould from each geometry. Reliability within the study was achieved through the multiple slipcasting of vessel forms (15 batch units per vessel form) from the master moulds using a standard slipcasting procedure.

Validity indicates whether the research instruments that are used are accurate and measure what was intended to be measured (Muijs, 2011:56). In general research is considered valid if the measurements used are relevant and accurate and answers the research questions (Edmonds & Kennedy, 2013:3). Validity in the study relies on the repeated testing conducted on the test geometries and the final batch slipcasting of vessel forms. Results verify that the proposed use of technologies and methods improve on accuracy and complexity and facilitate swift design and size changes to artefacts as compared to traditional manufacturing methods.

**k) Delimitations**

- CNC milling technologies have been selected according to the technical specifications of the various machines available for the milling of master moulds as well as their ability to mill the required complexity of form and scale.
- The mechanical engineering aspects and programming of the CNC machine will not form part of this research.
- The design of the vessel prototypes largely focuses on sequentially testing complexity of form.
- A suitable milling material for prototype development will be selected by way of a decision matrix table and will not include an extensive testing of these materials.
- Existing premixed clay slip bodies will be used for the slipcasting of the various vessel forms in order to standardize the testing.
- The traditional manufacturing process of master moulds will be limited to a brief discussion.
- The testing of vessel prototypes and master moulds will be limited to the batch production needs of the studio ceramicist (approximately 15 units) and therefore the results do not reflect mass production industry requirements.

# Chapter 2

# Theoretical framework and literature review

## 2.1 Overview

This chapter provides a chronological overview of the shift towards the increased use of emerging technologies as a design and manufacturing intervention within various creative industries. The overview specifically refers to a number of eras, movements, philosophies and theories that have had an impact on the development of industrialization and more specifically the development of ceramics as discipline. The Industrial Revolution and the Arts and Crafts Movement are discussed to provide background literature highlighting the utilization of technology within the arts. The significance of applying an interdisciplinary approach to manufacturing is discussed in relation to the advantages and benefits that the implementation of emerging technologies holds for creative industries. The chapter concludes by reflecting on the current use of emerging technologies within the field of ceramics.

## 2.2 Introduction

Countless theories proposed on a range of subjects over many centuries have influenced every aspect of society and brought about changes within various social and economic aspects concerning daily life. This directly impacts on the way in which people engage with their environment, in particular also modes of visual communication. Current literature reveals that users from a variety of fields take varying perspectives and approaches when integrating emerging technologies (Séquin, 2005:737). In *Art and Science Now* (2010), Stephen Wilson reflects on the contemporary artist working towards a closer integration between art, technology and science. Over time the artist's attitude to integrating emerging technologies within creative practice has largely been focused on aspects of the digital realm versus analogue processes (Wilson, 2010:200). This focused perspective therefore endeavours to address a significant gap in the literature, particularly concerning the integration of technology in traditional ceramics practice.

## 2.3 Theoretical context and historical background

A paradigm refers to a worldview underlying the theories and methodology of a particular scientific subject (*Oxford Dictionary*, 2013). Concerning epistemology, historian Thomas Kuhn (1922 – 1996) states that new approaches to knowledge generation and understanding within a ruling philosophy that stimulate a change towards another way of thinking bring about a paradigm shift (Kuhn, 1996:6,10). Below reflects select historical developments that outline reasons for the paradigm shift regarding the utilization of emerging technologies within the arts during the Age of Enlightenment as well as the Modernist and Post-modernist periods.

In his essay titled "An Answer to the Question: What is Enlightenment?" (1784), epistemological German philosopher Immanuel Kant (1724 – 1804) claims that the Age of Enlightenment (mid-17th and 18th centuries) or, as it is sometimes called, the Age of Reason, is a way of engaging in critical thought about humankind. This mode of thinking refers to using one's own understanding to collectively think about humankind in relation to the world and not to be influenced by tradition, religion or myth. Kleiner (2013:727) suggests that this approach to knowledge generation is rooted in the 17th century alongside achievements by mathematicians, physicists and scientists such as René Descartes (1596 – 1650) and Isaac Newton (1642 – 1727). The emphasis on information and physical experience regarding the world and the rejection of unfounded beliefs form the foundation of the Enlightenment (Meecham & Sheldon, 2005:24). This concept or way of thinking was transferred to the sociopolitical world by philosophers such as John Locke (1632 – 1704), Benjamin Franklin (1706 – 1790), Voltaire (François-Marie Arouet) (1694 – 1778) and Immanuel Kant to support the establishment of a rationally ordered society with a view on creating a better world (Kleiner, 2013:736). The impact on art and technology today is that virtually all of what society value or desire can ultimately be directly or indirectly derived from Enlightenment (Zafirovski, 2010:24). Kant's (2003:31) earlier work titled *The Critique of Pure Reason* (1781) proposed that reason and experience must be united. The Age of Enlightenment gave rise to the artistic movements Neoclassicism and Realism. Neoclassicism focused on the geometric harmony that was used in the civilized societies of Greece and Rome and which embodied the ethics of Enlightenment principals (Harris, 2006:213). Realism, on the other hand, embraces technology and progress, focusing on experience of everyday life (Hodge, 2011:72). Traditional forms of social, political and economic power were questioned and opposed as a result of the enlightenment of man, which introduced critical ways of thinking. This uprising during the Age of the Enlightenment brought about the American

Revolution (1775 – 1783) as well as the French Revolution (1789 – 1799) (Meecham & Sheldon, 2005:24). Disruptions during the Age of Enlightenment shifted the focus of art away from technology to humanity which had a profound impact on the immediate integration of technology within the arts.

Philosophers Theodor Adorno (1903 – 1969) and Max Horkheimer's (1895 – 1973) (2002:4) work *Dialectic of Enlightenment* (1944), refers to the disruption that the Age of Enlightenment brought about within societies. Political, social and economic changes during the Age of Enlightenment fostered a new way of thinking about humanity and the world. This new way of thinking surfaced during the late 19$^{th}$ and first half of the 20$^{th}$ century and which was referred to as Modernism (Meecham & Sheldon, 2005:15). Art movements like Romanticism and Impressionism emerged as a rejection and reaction against Enlightenment (Meecham & Sheldon, 2005:25) with critics like Clement Greenberg and Rosalind Krauss focusing on the arts and supporting the Modernist view on the arts (Harris, 2005:204). Ultimately it is within Modernism that the separation between art and technology originated which further hindered the integration of emerging technologies in the making of art.

The progressive industrial cultures and modern setting of European and American nations during the 1900s led to a worldwide imperialist expansion of colonialism. Through colonialism European and American nations sought to expand their industrial and capital power. Competition and conflict eventually gave rise to World War I (1914 – 1918) and World War II (1939 – 1945) (Gillen & Ghosh, 2007:68). The devastating effects and mass destruction of the two world wars left the world in chaos and a shattered faith in a peaceful future (Gablik, 2004:125). A spirit of rebellion reflected the feelings of the post-war society. This rebellion in turn gave rise to art movements like Dada and Abstract Expressionism. The Dadaists strongly believed that technology controlled by the political aristocracy was to blame for wars and social conflict while the horror and disgust of war was reflected in their work (Kleiner, 2013:835). American art critic and theorist Rosalind Krauss (1996:2) highlights the fact that artists rejected the historical model outlining the way the work of art generates meaning. Modern artists reject traditional art values and standards by removing the framework that separates art from daily life. Their model for creating meaning was to expose and show reality. Their aim, then again, was for the audience to question the standards of art and other social values (Govan, Nicholson & Normington, 2007:18). These actions hindered the utilization and development of emerging technologies within the creation of art. Modernism gave rise to an unstructured approach to meaning-making encouraging artists to abandon all artistic rules (Gablik, 2004:23). Modernism saw the survival of art through a protest against the social order and cut itself loose from social society to seek its own freedom (Gablik, 2004:31). In a society driven by technological developments this approach reduced the relationship of developing an interdisciplinary approach between art and technology.

Politics and economics were the driving force behind the expansion of industrialization and the capital power of European nations. The 18th century development of science and art in European countries like Britain and France was carried forward to their colonies such as Kenya, Uganda and Morocco in Africa. The implication was a removal of cultural identity regarding these colonies' beliefs, values, habits and traditions towards Eurocentrism (Mosquera, 1992:268). Post- colonialism arose as a reaction to colonialism which refers to the dismantling of colonial powers (officially starting during the 1950s) with the subsequent independence of colonies formerly occupied by European nations. Post-colonialism lead to a freedom from Eurocentrism and also lead to a freedom from its mode of production. Technological innovations in post-colonial regimes enabled the improvement of agricultural production and a move beyond subsistence levels of production (Josephson, 2005:150). Post-colonialism also lead to a freedom from political and social interference within societies. Within the arts, this lead to the freedom to express one's own thoughts and feelings through designs and artefacts (Childs & Williams, 1997:8,1). Technological innovations in post-colonial regimes have benefits for example agricultural technologies enabling peasants to improve production in order to move beyond subsistence levels of manufacture (Josephson, 2005:150).

From the mid-20th century, prominent philosophers Martin Heidegger (1889 – 1976), Jacques Derrida (1930 – 2004), Jean Baudrillard (1929 – 2007) and Jean-Francois Lyotard (1924 – 1998) reacted against the Modernist way of creating art and started to raise questions regarding the social changes and the rebellious reactions within art movements brought about by Modernism (Harris, 2006:247). As mentioned, the questioning of the Modernist approach towards life gave rise to a Post-modern new way of thinking. In his work *The Postmodern Condition* (1979), Lyotard (1984:4) proposed that developments in technology would lead to new knowledge. Therefore, from a Post-modern point of view, artists utilizing new technologies are likely to explore innovative opportunities and possibilities for artistic expression (Harris, 2006:247). Although Modernism failed, its strength lies in questioning the way in which technology was implemented. Post-modernism recognizes the potential of technology and incorporates it with the past in order to improve and expand upon ways in which artists communicate (Barrett, 1997:38). This implies that within Post-modernism a paradigm shift occurred, bringing about the integration of technology in art and thereby stimulating interdisciplinary practice.

New developments in any field of human endeavour are not necessarily always universally accepted nor immediately applied without resistance. This holds true for the discipline of product design and manufacturing, whether in the domain of creative practice or industry (Séquin, 2005:747). Even in the face of possible non-acceptance and resistance, practising studio artists across various disciplines should nevertheless exploit advances in technology from all areas of knowledge and avoid isolation since the effective utilization of technology has the facility to stimulate individual development and growth (Zoran & Buechley, 2012:8). In a techno-cultural society with rapid developments in technology, it is neglectful for practising artists to ignore emerging technologies and continue to pursue traditional modes of practice (Wilson, 2010:200). Artists simply have to find new ways in which to engage with technological developments. Art practitioners must be prepared to free themselves from traditional modes and contexts of creating art and continually update their knowledge and skill sets. They should familiarize themselves with cutting edge developments in science and technology and maintain an awareness of the relationship they have with globalization (Wilson, 2010:201).

Tertiary institutions like the Rhode Island School of Design in the United States have recognized the value and potential of an interdisciplinary approach between art and technology. This institution has fused dissimilar fields where new and innovative teaching approaches and strategies for creative problem-solving have been implemented. An interdisciplinary approach leads to trans-disciplinary teaching and learning activities generating new insights and innovative creative outputs (Rose, 2011:3). Applying a symbiotic approach to interdisciplinary practice between dissimilar fields has impacted on the artist's "user" approach to technologies (Wilson, 2002:3). Introducing CAD and CNC milling technologies for improved production in the ceramics studio could nonetheless require that the ceramicist needs to undergo a transformation in his or her basic practice, specifically with regard to being open-minded to the retraining and expansion of existing skill sets.

In the *Manifesto of the Communist Party* (1848), Karl Marx and Friedrich Engels (1848:2) claimed that the Industrial Revolution brought about a capitalist environment. In this capitalist environment technological developments led to the invention of machinery which in its turn gave rise to the Industrial Revolution (1760 – 1840) in England (Schafer, 2008:24). Alongside the momentous impact on social life, the effect that the Industrial Revolution had on art is quite significant. Adorno and Horkheimer (2002:98) argued that art produced by the capitalist society during the Industrial Revolution using technology was of a low standard. This claim by Adorno and Horkheimer supports the belief that the Industrial Revolution was an example of the weakness of Enlightenment where the utilization of technology failed to improve and develop art. Art critic Clement Greenberg (1980:5), in his essay titled "Modern and Postmodern," agrees that industrialization threatened aesthetic standards and led to its decline within the arts. Walter Benjamin's (1969:8) essay titled "The Work of Art in the Age of Mechanical Reproduction" (1936), criticizes the mechanical age for the separation of art from its fundamental roots within its culture. The uniqueness, or, as Benjamin refers to, the "aura" of an artwork, is destroyed with mechanical reproduction. Although Benjamin's essay focuses more specifically on photography, it brought forward different questions at the dawn of the 21$^{st}$ century, amongst others technological reproducibility as a characteristic of mass production and how it challenges the concept of artistic praxis as predominant measure for authenticity in the digital age (Emerling, 2005:101).

The impact that the Industrial Revolution had was that individuals representing the arts reacted strongly against the intrusion of machines into their domain. The Arts and Crafts Movement (1850 – 1900) developed as a reaction against the Industrial Revolution (1760 – 1840). Members of the Arts and Crafts Movement such as John Ruskin (1819 – 1900) and William Morris (1834 – 1896) feared that industrialization could destroy the environment of traditional skills and methods for the creation of art. There was furthermore the very real concern that the quality and the design of goods being manufactured by machines may not be of a high standard as opposed to manually designed and manufactured goods. Thus an increase in the exploration of aesthetic design and decoration was emphasized with a view on maintaining high artistic standards and workmanship of functional objects intended for the broader public (Kleiner, 2013:826). Morris also linked art and industry by applying the aesthetic values and principles of fine art to the production process affiliated with industrial design (Stankiewicz, 1992:860). Regrettably, the impact that the Arts and Crafts Movement had on sound industrial design practice and mass-produced objects started to diminish during the later 1900s (Stankiewicz, 1992:865). This occurred since the Arts and Crafts Movement failed to live up to changing times and neglected to recognize that Western

Europe was adopting new production methods that led to commercial and technological advancement (Cluckie, 2008:144).

Walter Gropius (1883 – 1969) was the founder of the Bauhaus School in 1919. An important aim of the Bauhaus School was to apply design principles for the manufacturing of artefacts through the implementation of technology for mechanized mass production. Unfortunately Adolf Hitler closed down the Bauhaus School in 1933 thus terminating this approach (Harris, 2006:39). As in the case of the Bauhaus School, this research study aims to integrate emerging technologies within the design and manufacture process of ceramic artefacts. The strength of both the Arts and Crafts Movement and the Bauhaus School was the attempt to incorporate design principles that would increase the artistic value of mass-produced artefacts. However, unlike the Bauhaus school, the weakness of the Arts and Crafts Movement was that it did not strive to utilize technology within the final production process.

Ceramics, like all other art forms, was greatly influenced and transformed by the Industrial Revolution as well as the First and the Second World Wars; regrettably it also struggled to find its place in a modern society after these two wars. The development of ceramics during the Post-modern age failed to keep abreast with other artistic developments. Rob Barnard (2007:18) elaborates on this issue in his essay "The Idea of the New". Barnard states that ceramicist Bernard Leach, who spent most of his time in Japan, returned to England in 1920 and found a disordered ceramic environment, crumpled by the Industrial Revolution and confused by the Modernist perspective of the future trends in arts by other art fields. Leach, a follower of the *Mingei* (folk arts) movement in Japan, found that the principals of the former Arts and Crafts Movement supported his philosophy of handmade functional ceramic ware for everyday use. Leach's ideas and approach towards ceramics were widely accepted and adopted by ceramicists in England (Barnard, 2007:20). This approach and focus limited ceramicists from making intellectual explorations regarding ceramics and the principals of design and kept them from questioning the direction that ceramics as discipline was taking within the broader context of Modern and Post-modern artistic developments. Studio ceramicists tend to overlook the potential of emerging technologies and in this regard further perpetuate the gap between ceramics and technology (Barnard, 2007:21). To date limited manufacturing developments have been made that strengthen the relationship between the production of ceramics and the use of emerging technologies. The current competitive globalized context within which we find ourselves, however, indicates that there is a need for all artists to engage in technology-driven interdisciplinary practices.

Ceramic master moulding technology is essentially an ancient technique used for the production of ceramic artefacts. As early as 500 BC, the Greeks developed the ceramics reproduction press moulding technique. Early press moulds were made from clay and which were fired until hard enough to be used for the reproduction of several copies. This technique involved pressing slabs of clay on the inside of the mould cavity to enable the imprint of motifs on the outer surface of artefacts as well as pressing clay over a mould form to imprint motifs on the inside surface of the artefact (Frith, 1985:6). These first moulds were very delicate and complex in design in contrast to moulds produced during the Modernist period (late 19th and first half of the 20th century) in which complexity of design was most often compromised (Charleston, 1968:32). These complex early designs displayed high artistic standards through the depiction of characteristic narrative motifs of mythological Greek gods, animals and war scenes (see Figure 2). Regrettably this attention to detail was lost with the onset of industrialization where the focus was on basic forms suited to mass production.

Figure 2: A Greek moulded amphora (storage jar), two dolphins among waving sea tendrils, both sides (3rd – 2nd century BC). Ceramics, 8.26 cm

The Chinese were the first to develop round plate-shaped moulds made of fired clay. The plate-shaped moulds were used in conjunction with a rotating wheel which can be regarded as a low technology invention. Usually one person would rotate the wheel by hand or with a stick and another would lay a slab of unfired clay on the mould, thereby shaping the press moulded form over the fired clay master mould. This method of formation was a lot quicker than the original press mould method used by the Greeks. Thereafter the Romans refined the Chinese plate moulds by designing deeper bowl-shaped fired clay moulds (Frith, 1985:8). It was not until the 16th century that plaster of Paris was used by the Italians as a moulding material to reproduce ceramic artefacts (Frith, 1985:5). Presently plaster of Paris is still used within the ceramics industry for the production of ceramic ware. Most of the technological developments regarding moulding have been conducted on the chemical composition of plaster of Paris in order to improve material properties such as strength, durability and permeability for the slip-casting of hollow forms or the carving of solids for further product development. The mineral gypsum is used for the manufacturing of a range of plasters. A calcination (heating) process is used to remove the chemically-bound water from finely ground gypsum. In controlling the calcination process different size and shapes of crystals are formed which result in different types of plasters. Depending on the crystalline structure (size and shape) these plasters have different characteristics regarding water absorption, density and durability. Some plasters will have a high density with low water absorption and others types will have high water absorption but are not very durable. For example Puritan Pottery Plaster has a very hard surface and does not ware out as quickly as the more absorbent USG No. 1 Pottery plaster which is less durable (Sharma, 1997:379).

Although industry has seen limited developments in master moulding skills and plaster of Paris technology, at present the traditional manufacturing and construction of plaster of Paris master moulds still remain time-consuming and highly skilled processes. A further drawback associated with this method is that in order to change a prototype design or to alter the size of the artefact, the entire mould manufacturing process from the prototype to the master mould needs to be redone.

This brief outline on the historical development of the master mould process illustrates the limited developments within the ceramics industry from ancient times to recent years as far as the studio ceramicist is concerned. Emerging technologies therefore have the potential to enhance methods for the manufacturing of prototypes and master moulds intended for production. The application of applicable emerging technologies within the ceramicist's daily studio practice furthermore has the potential to enhance innovation when developing distinctive ceramic artefacts.

## 2.4 Emerging technologies in art

An interdisciplinary approach is defined as a process of addressing an issue, solving a problem or answering a question that is too wide-ranging to be dealt with by a single discipline and therefore requires interrelated actions from dissimilar disciplines to provide problem-solving strategies (cf. Chapter 1.a). Repko (2012:27) further defines the term interdisciplinary as the crossing of boundaries in order to resolve problems that would not be possible from the perspective of a single discipline. In the context of this study an interdisciplinary approach between traditional ceramics practice and the utilization of digital technologies as an alternative manufacturing approach are investigated by crossing the boundaries between art and engineering-based technologies.

According to Zoran and Buechley (2013:9), the use of computers should not merely be seen as simply another aid in the process of design or production, but that technology should be applied with a view on the extension of the possibilities available to artists when creating new creative objects. The intent is not to discard or replace traditional methods, but to discover and add new methods and techniques to existing methods and techniques for creating distinctive objects. Although the industrial use of CAD and CAM developed within the engineering discipline, other fields of manufacturing recognized its potential as a tool for the creation of products. With the development of CAD and CAM, the line between fields of specialization, for example art and design, medicine, architecture, jewellery and the industrial design sectors, has been blurred. Companies introducing technologies like CAD and manufacturing techniques such as CNC milling already utilize the principle of customization. For example, within architecture CNC milling allows for several customized, individual components to be produced in the same amount of time it would take to make a single component (Feng, 2012:118). Within ceramics production there is a need to explore customization in order to enhance the aesthetic value of artefacts, specifically for batch production purposes. With CAD's facility to enhance the design process and the capability of CNC milling to carve a variety of materials such as plaster of Paris, polyurethane as well as wood and stone, renewed possibilities are presented to the artist. Incorporating emerging technologies within artistic practice facilitates a unique interdisciplinary crossover between 3-D creative practice and engineering-based manufacturing technologies (Albert, 2011:95).

On-going developments in materials and manufacturing technologies have allowed artists to be exposed to new modes of creation that benefit artists with the production of complex ideas (Thurston, 2009:1). Examples below demonstrate that emerging technologies are being used more frequently within the arts and therefore reinforces the idea that interdisciplinary research remains an area of study that continues to evolve. GarE (pronounced “Gary”) Maxton (2009:2) is a typical example of an engineer who bridged the gap between emerging technologies and art. Maxton utilizes CAD and CNC milling for the creation of complex puzzle-like sculptures. The puzzles consist of interlocking metal puzzle-like pieces which are cut using a CNC milling machine (Figure 3). The technology utilized in this example has assisted the artist with the production of a very complex sculpture that would be very difficult and time-consuming to produce manually.

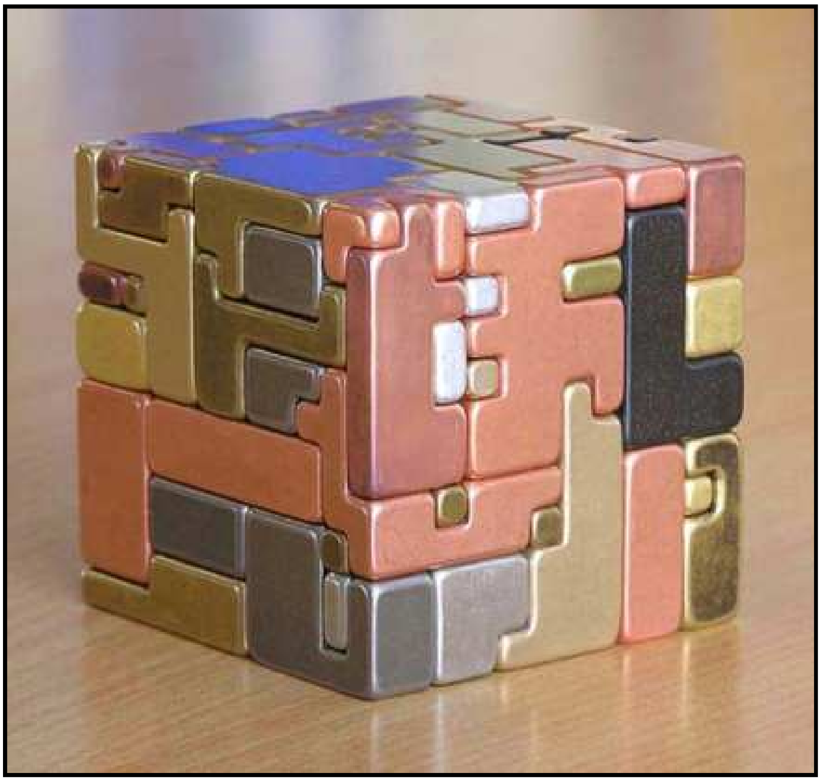

Figure 3: GarE Maxton, *Conundrum III* (2009). Sculpture, 75 mm x 75 mm x 75 mm

Sculptor Michael Rees (Hisle, 2010:1) contributes significantly to the world of digital art. Early on in his career Rees noticed the potential of an interdisciplinary approach between art and technology. From the early 1990s Rees incorporated digital technology within his creative process. Rees uses various digital manufacturing techniques to create monumental sculptures, e.g. *Putto 4 over 4* (Figure 4), which was created using CNC milling technology as part of the manufacturing process. What makes Rees’s use of technology unique is that he takes his art beyond the virtual realm by employing cutting-edge digital technology to create monumental real-life objects often too complex to be manufactured by traditional processes (Bard, 2003: 5).

Figure 4: Michael Rees, *Putto 4 over 4* (2010). Sculpture, 3,66 m x 2.23 m x 3,54 m

3-D CAD as design intervention tool has the advantage of reducing the overall design development time frame. At present some industrial companies like Denby Pottery located in Derbyshire, England, have implemented strategies to improve on the aesthetic value of mass-produced ceramic ware. Denby Pottery states that to be competitive in today's market, quality in product design and manufacture is very important (Hawley, 2012:1). Senior Denby Pottery designer Gary Hawley (2012:1) emphasizes the fact that the ceramic market is extremely competitive and that there is an increased demand for a variety of designs to meet the requirements of industry needs. When applying traditional techniques and approaches to design, the designers at Denby Pottery were limited in the creation of new designs and products. Although the designers and sculptors are highly skilled, to create a prototype could nonetheless still take four to six weeks to complete. For this reason Denby Pottery was hesitant to regularly implement new product ranges. The challenge for Denby Pottery was that they needed to reduce the time frame for developing a new concept and prototype. Consequently, in September 2003, the use of 3-D CAD for the development of designs and 3-D printing technology were implemented for the first time to manufacture concept models (in December 2006 the company purchased a second 3-D printer). These concept models were first printed using synthetic composite materials, but recently Denby

Pottery has printed concept models using a ceramic clay body (Hawley, 2012:2). The printing of a ceramic object using ceramic materials gives a more realistic representation of what the final product will look like. This furthermore enables better communication with clients resulting in profitable design decisions that reflect customer demands (Hawley, 2012:2). As additive manufacturing processes develop, a long-term possibility is that direct-digital manufacturing (DDM), the manufacture of finished products, will eliminate the prototype development process and be used directly for mass production purposes. Large scale direct manufacturing in time brings with it the unique advantage of mass individualization, also termed mass customization (Black & Kohser, 2013:508).

The utilization of CNC milling as a manufacturing technology – as an alternative to the manual manufacturing process – has the advantage of accelerating the overall production process. Over the past few years some South African artists have used CNC milling technology for the manufacturing of commissioned public artworks. The well-known South African sculptor Arend Eloff collaborated with the renowned Loop Art Foundry in White River, Mpumalanga, on a bronze casting project. Eloff was commissioned by Golden Horse Casino in Pietermaritzburg to sculpt, bronze cast and install three life-size horses for their reopening. According to Leoni Canada (2007:1), co-owner of the Loop Art Foundry, such a project, on average, would require four to six months to complete. With the use of CAD and CNC milling, this project was completed in a mere five weeks. Eloff first created a marquette of the horse. The marquette was then sent to the Technology Transfer and Innovation Unit at the Vaal University of Technology (VUT), Vanderbijlpark, South Africa. A CAD designer scanned the marquette and then sectioned the 3-D file of the horse into separate parts that would fit the milling machine's bed size. Master moulds were made from the CNC milled iso-resin polyurethane parts from which wax patterns were produced for further investment casting of the edition (see Figure 5).

Figure 5: Arend Eloff, *Golden Trinity* (2007). Cast Bronze, 4.5 m high

The exploration of an interdisciplinary manufacturing approach combining traditional processes and emerging technologies has been recognized by several ceramic artists who have integrated CAD/CAM technologies in their studio practice. Such an artist is Jonathan Keep. Keep (2013:1) has used CAD computer software to develop his ceramic ideas; however, at first the facility to print in ceramic materials was unavailable. With *Spherical Harmonics: Experiments in 3-D Printed Ceramic Form* Keep (2013:1) explored various mathematical CAD computations of the work *Spherical Harmonics* in order to extend the vocabulary of the CAD form. Keep then experimented with printing the computer generated forms in ceramic material using the commercially available RepRap 3-D printer. Keep converted the RepRap printer's mechanism to print using a clay body and distilled water as binder (see examples presented in Figure 6 below). The layer-by-layer printing technology is similar to the traditional hand-building ceramic technique whereby an object is formed by joining clay coils in order to build the desired object (Keep, 2013:2).

Figure 6: Jonathan Keep, *Seeds* (2013). Three-D printed, 70 mmm x 80 mm x 80 mm

Although there are differences between the design intentions, production volume and the target market, both the industry and the studio ceramicist have realized the benefits that 3-D CAD (as a design tool) and CAM technologies (for production) have to offer in order to improve ceramic products. CAD speeds up procedural changes within the design process. CAD and CAM as design intervention tools facilitate the overall manufacturing process as they stimulate effective communication between designer and manufacturer throughout the product development cycle. The integration of emerging technologies have the potential to develop into a product development support tool that will enable designers, manufactures and engineers to apply them concurrently in design, development and product evaluation phases in order to achieve maximum benefits (Liu, Campbell & Pei, 2013:22-28).

## 2.5 Conclusion

Technology as the catalyst for political, social, artistic and economic changes at times goes unnoticed. Technology’s predominant impact is evident in political events like the First and the Second World Wars and the rebellious reactions against technology in art movements like Dadaism during the era of Modernism. Outlining shifts within Post-modernism reveals that the attitude towards technology has changed, especially within the arts. Artists have recognized the potential and possibilities of an interdisciplinary approach between technology and art. This is evident in the examples by artists Michael Rees, GarE Maxton and Arend Eloff as these examples demonstrate the limitless possibilities that the implementation of technology present as a new tool for conceptualization and manufacturing.

The approach to the design and production of ceramic ware within industry compared to that of the studio ceramicist is somewhat different. The industry approach is to identify needs within the global market and mass produce products to fulfil those needs. Mass production does not specifically focus on aesthetics and is therefore not predominantly driven from an aesthetic perspective, but focuses on a design solution suited to the product development process (Shin, 2009:2). For the batch production studio ceramicist it is essential to create artefacts with the emphasis on aesthetics and uniqueness tailored to a niche market. The implementation of emerging technology as outlined in examples by Denby Pottery and studio ceramicist Jonathan Keep shows that the potential exists for technology to contribute towards the establishment of an enhanced product design and development approach that adds value to the broader sector of ceramic producers.

# Chapter 3

# 3-D Computer-aided Design (CAD): Vessel prototype and master mould design

## 3.1 Overview

This chapter focuses on 3-D computer-aided design (CAD) and aims to determine its feasibility when introduced into the product design and development process for the manufacturing of ceramic vessels. Firstly, the early developments and advantages of using CAD as a design intervention tool are outlined. The chapter furthermore provides an overview on the application of design for digital manufacturing to provide a context for the application of SolidWorks® as interoperable 3-D software design program. The main operational features and design parameters of SolidWorks® are highlighted in order to demonstrate its suitability to the study. The chapter concludes presenting the results from a range of test geometries designed using SolidWorks®. These geometries were used to predetermine the suitability of a milling material and the height-width release ratio when milling the vessel prototypes for further master mould development.

## 3.2 Introduction

Since the late 1970s the boundaries outlining approaches to design within creative, architectural and engineering industries have become progressively blurred (Lovejoy, Paul & Vesna, 2011:14). This is largely due to the increased use of CAD as design tool. The interoperable functionality built into most CAD software programs facilitates the boundary crossover within the design realm. For the purpose of this study, software interoperability is defined as an information management process that enhances the ability for different compliant applications to exchange and translate digital data between the designer, manufacturer and relevant technologies (Chungoora & Young, 2011:435). CAD allows for the pre-visualization and analysis of an object which enhances the interaction between designer and manufacturer refining the evaluation of products prior to further new product development (Liu et al., 2013:26). Its ability to allow for alterations and adjustments prior to manufacturing accelerates the design process which in its turn improves the lead time on productivity. If integrated, these standard industry-driven advantages of using CAD as design tool can also benefit the studio artist (Aouad, Wu, Lee & Onyenobi 2012:53).

## 3.3 CAD

The development of CAD can be traced back to the introduction of Automatically Programmed Tools (APT) during the 1950s. The 1960s saw the most important research phase for interactive computer graphics. CAD is defined as the technology that includes the use of computer systems that provide support in the creation, analysis, modification, and optimization of the design process (Leu & Joshi, 2011:9). The word 'design' started to appear along with the acronym CAD, extending beyond the elementary concept of drafting. The first CAD programs, however, could only create two-dimensional (2-D) drawings. Although simple and limited in capabilities, these first CAD programs set the stage to revolutionize approaches to design and manufacturing (Leu & Joshi, 2011:8). During the 1970s the research efforts of the previous decade resulted in the application of instrumental design. The 1980s is remembered as an era of rapid technological advances. During this era various aspects of design and manufacturing developed and new theories and algorithms were introduced to accelerate the design and manufacturing processes within the engineering discipline. The main industry focus of research and development fell on CAD and computer-aided manufacturing (CAM) systems and specifically on the integration of these two processes. CAM can be defined as a computer system that plans, manages and controls the manufacturing process through a computer interface (Leu & Joshi, 2011:10). This resulted in the development of CAD software that could produce 3-D geometric designs and the development of integrated CAM systems to provide improved engineering and manufacturing applications (Leu & Joshi, 2011:9).

CAD ultimately owes its development to three different sources. The first resulted from a challenge to automate the drafting process which was subsequently pioneered by General Motors Research Laboratories, mainly for its time-saving advantages. The second source evolved from prototype testing through CAD software simulation, pioneered by high-tech industries such as aerospace. The third catalyst for CAD's development resulted from attempts to facilitate the flow from the design process to the manufacturing process. Due to this product development strategy, a link between the CAD design and CAM manufacturing stages of the production process was formed (Nafziger, 2012:2).

From an industry design perspective Black and Kohser (2013:15) elaborate on the impact of the development of CAD on the industry. With the advancement of programming languages into an object-orientated approach, the original purpose of CAD as merely a drawing system has drastically changed. Modules with their own API's (application program interface) are used to build modern parametric feature-based modeller and freeform surface programs that can employ various engines for simulation functions. These capabilities have led to a new form of prototyping called digital prototyping. Design verification and testing of digital prototypes can be simulated on screen in contrast to physical prototypes. CAD is not only a design tool, but has become part of and significantly supports the product development process.

The advantages that modelling with CAD systems offer over traditional methods are significant for the designer. The utilization of CAD automates the design process and assists in precision drawing and design activities (Best & De Valence, 2012:296). CAD furthermore reduces design time significantly because the accuracy of drawings is increased with the utilization of CAD. Manually creating a model with complex geometry involves a great deal of measuring on paper, but in CAD these measurements are done automatically and effortlessly. In addition, due to a parametric design method, time is saved when carrying out repetitive designing work (Chougule, 2010:1). Designs can speedily be altered, edited and changed without erasing and redrawing; this is not the case when drawing by hand. Data can be stored in digital format allowing CAD systems to store entities that are frequently used in digital libraries (Chougule, 2010:9). CAD also improves the overall visualization of the concept of a model. The computer model can be rotated on any axis, allowing the designer to view the model from different perspectives in order to obtain an overall sense of the final prototype and to approve designs by simulating real-world conditions using rendering applications. Rendering effects enhance communication between designers, customers and manufacturing engineers. Effects such as shading, colouring and material choice offer a realistic appearance of the model allowing the final user an opportunity to evaluate and reflect. Furthermore, the internal shape of a part can be revealed through the modelling of sectional drawings to illustrate the technical interaction among an internal system or multiple parts. This allows extended visualization for more complex forms (Peddie, 2013:80). Ultimately, CAD supports CAM systems and the resulting integration of design and manufacturing allows for prototyping concept/demonstration models prior to manufacture (Valamanesh & Shin, 2012:4).

The term Digital Manufacturing (DM) refers to solutions that support collaborative manufacturing process planning and application of integrated tool suites between engineering disciplines from the design stage to the final manufacturing of the product (Peddie, 2013:37). Designers try to define their design ideas but it is not that simple to clarify a 2-D drawing. Although designing and manufacturing are conceptually separate processes within the product development system, the nature of the production system, however, must be taken into consideration. It is critical for the designer to know, for example, the manufacturing techniques by which the product might be manufactured, the properties of different materials, and whether the scale of manufacturing is economically viable since all these manufacturing elements will influence the final product. This overlap in approach towards design and manufacturing in the production system is the reason why CAD and CAM are generally considered as a system and not necessarily as separate entities (see Figure 7) (Black & Kohser, 2013:11). Valamanesh and Shin (2012:3) rightly assert that designing with an emphasis on digital manufacturing will stimulate creative thinking which will in turn develop original design concepts into more innovative and complex design ideas. This can assist the studio ceramicist in the production process to create more complex and innovative designs while maintaining a competitive batch production output. Figure 7 is a diagram illustrating a design system revealing the overlap in approach towards design and manufacturing.

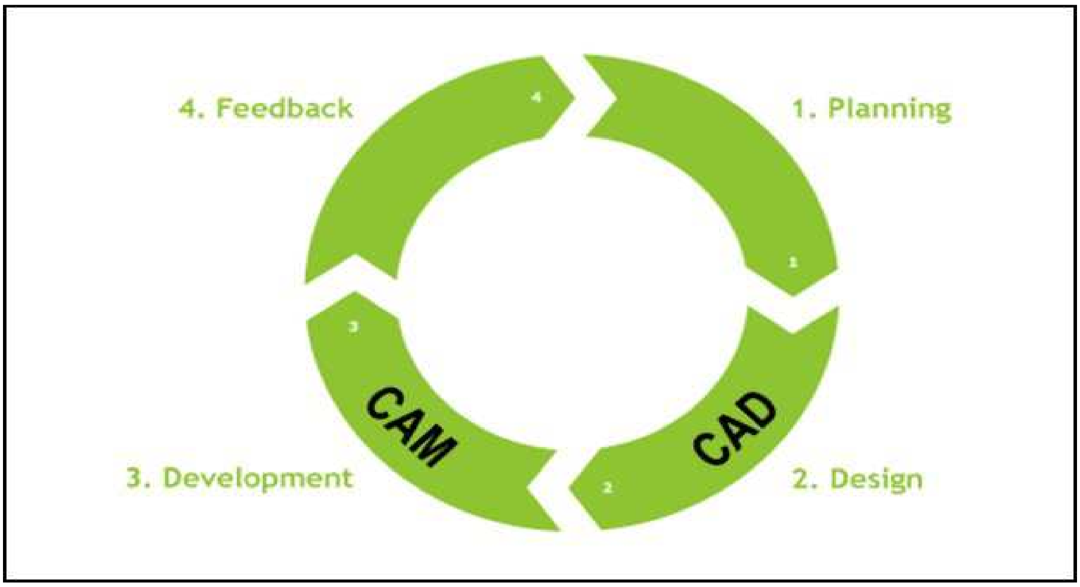


Figure 7: Diagram illustrating a design system

## 3.4 SolidWorks software program

SolidWorks® is a registered trademark of Dassault Systèmes SolidWorks Corporation. It is a design software application that utilizes a parametric feature-based approach to create 2-D and 3-D drawings, 3-D parts, and assemblies of models (Lombard, 2013:3). In a parametric model, each predefined feature, such as fillets, bosses and cuts, has parameters associated with it. These parameters control the model or feature geometry through design variables such as length, width and height that can be varied at any time during the design (Lombard, 2013:16).

### 3.4.1 Operational features and design parameters

Parameters refer to the values which determine the size, shape, behaviour, and characteristics of the model or assembly. Parameters within SolidWorks® can be either numeric or geometric. Numeric parameters refer to dimensional values such as the diameter of a circle or other shapes or the length and degrees of a line. Geometric parameters include conditions like *tangent*, *horizontal*, *vertical*, *co-linear*, *co-radial*, *concentric*, *perpendicular*, *parallel*, *equal* and *fixed*. Through equations, numeric parameters such as dimensions can easily be altered to capture the most complicated design intent. The dimensions and relations drive the geometry due to the parametric nature of SolidWorks®. Dimensions within a sketch can be altered and controlled independently, or even outside the sketch by relationships to other parameters (Shih & Schilling 2013:6).

The building blocks of a model or part in SolidWorks® are known as features. Features are furthermore divided into two groups. Shaped-based features may include features such as holes, bosses and slots (see Figure 8) and operation-based features refer to operations like filleting, drafting and shelling (see Figure 9). The feature-manager in SolidWorks® allows the designer to revisit the history of a design or part as a result of the feature-based nature of the software program. This permits the designer to make changes to the design, add additional features or to alter the order of operations to be performed (Lombard, 2013:20). Figures 8 and 9 illustrate the shaped-based and operation-based features of SolidWorks®.


Figure 8: Diagram of shaped-based features


Figure 9: Diagram of operation-based features

### 3.4.2 Design considerations

The component database that consists out of entities such as lines, points and arcs forms an essential part of any CAD model (Chougule, 2010:10.2). The accuracy of geometry drawings is very important. Elements like lines and intersections must be exact as it is impossible to change the design to a readable file for the manufacturing of a model if the measurements of the drawing are not absolutely accurate. If these design rules are not strictly adhered to, it may lead to a CAD drawing that appears accurate to the eye, but the Computer Numeric Control (CNC) part that is eventually generated will not correspond to what was actually intended, resulting in an inaccurate model (Fitzpatrick, 2011:736). Through material processing these graphic entities are used to transform the model or object into existence. The term material processing refers to the conversion of a material into a useful object with a desired shape and form for a proposed service environment. The material processing procedures can be divided into casting, material removal (subtractive manufacturing), deformation, consolidation and the latest addition, additive manufacturing (AM) (Black & Kohser, 2013:266). For the purpose of this study subtractive manufacturing will be used through CNC milling to machine the vessel prototypes. The casting process will be used to create the plaster of Paris master moulds from the vessel prototypes and to create the final clay slipcast vessel form from the plaster of Paris master moulds.

During the design phase various aspects of the processing procedures need to be taken into consideration. The first design aspect to consider is that the plaster of Paris mould must be able to easily release from the slipcast ceramic object. To facilitate this, the mould must be divided into two or more sections through parting lines positioned at the highest sections of the object. The position of the parting line needs to be placed in a way that no undercuts are formed. Secondly the draft of the object needs to be considered which will ensure easier release of the object during the demoulding stage (see Figure 10). Draft is the term used to describe the angle or taper that an object is smaller on its end in comparison to its base (Black & Kohser, 2013:271). A third consideration is solidification shrinkage, which refers to the volumetric difference between the liquid form and the solid form of a material. To mitigate the effect of solidification shrinkage a riser, or 'spare' as it is called in ceramics, must be incorporated in the design. A riser refers to an additional section incorporated into the mould that is also filled with casting material to compensate for shrinkage occurring during solidification (see Figure 10) (Wardell, 1997:46). The shrinkage factor is normally an accepted ceramics characteristic, unlike engineering where exact measurements are critical. The artefact will shrink with a certain percentage, but the shrinkage is constant for the entire artefact, ensuring correct proportions. The fourth consideration to be taken into account entails the solidification time and which refers to the time that elapses from the pouring to the complete solidification stage of a material (Black & Kohser, 2013:278). From a ceramics perspective the solidification time is governed by factors such as the type of clay slip body, the size of the mould and the consistency of the clay slip body itself (Wardell, 1997:75). Figure 10 demonstrates the draft angle to ensure easier release and an added riser to mitigate solidification shrinkage.

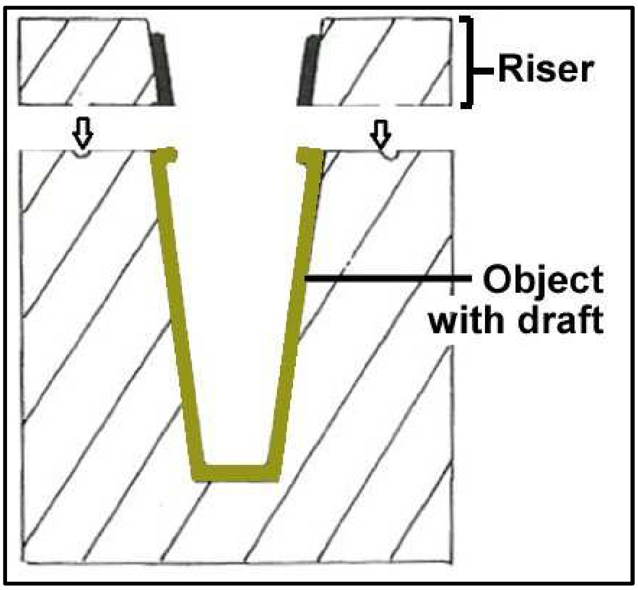


Figure 10: Example of riser and draft for a mould

### 3.5 Test geometry design specifications

Initial research was done whereby a simple CAD designed vessel form mould cavity was CNC milled. Figure 11 shows the first directly milled plaster of Paris test geometries.

Figure 11: Direct CNC milled plaster of Paris test geometries, 168 mm x 120 mm x 55 mm

Although Figure 11 reflects positive results, some technical complications were encountered and identified. During the milling high dust formation occurred which presented problems for the DAHLI 720 3-axis milling machine that was available to the researcher and owned by the engineering department at the Central University of Technology at the time of the practical testing. The DAHLI 720 is largely suited to metal engineering-related manufacturing purposes and is not equipped with a router able to mill materials with a very high dust formation. Due to the aforementioned dust formation, the bed slides and milling head of the milling machine was susceptible to costly damage. Secondly, when attempting to mill a large form or solid block (compare the example shown in Figure 11 – a negative), the milling depth is limited due to the length of the milling cutters. Cutter lengths are limited to ensure restricted movement of the cutter due to vibration and therefore no extensions are used on milling cutters. Compensation on complexity of the surface form or pattern may also occur because of the vertical cutting angle of the router tool. These limitations are reduced when a positive – as opposed to a negative – pattern are milled. When directly milling, the plaster of

Paris individual mould parts need to be milled even if the pattern or design is a mirror image. Two identical aligning parts are needed in order to form an enclosed shape for slipcasting purposes, therefore increasing milling time and cost. At the time of writing the cost to design an artefact produced at the Product Development Technology Station at the Central University of Technology, Free State, amounted to ZAR175 per hour (student tariff). The programming time for the cutter path amounted to ZAR175/h. The set-up time to prepare the machine for milling and to fasten the milling material on the milling bed was charged at ZAR100/h. The time that the machine uses to mill the part, i.e. the machine time, amounted to ZAR300/h (commercial tariff). If the part or object to be milled required some finishing, the rate was ZAR75/h. To determine cost-effectiveness the researcher was invoiced in relation to the time required for each step and not per hour. Figure 12 displays a data sheet evaluating the time and cost implications for creating two negative plaster of Paris mould pieces.

| **Initial test geometry: Design time and cost layout** | | |
|---|---|---|
| | **Time** | **Cost (ZAR)** |
| Design time | 15 min | R 43.74 |
| Mould design time | 30 min | R 87.48 |
| **Total** | **45 min** | **R 131.22** |

Figure 12: Initial test geometry: Design time and cost layout

| **Initial test geometry: Milling time and cost layout** | | | | |
|---|---|---|---|---|
| | **Mould A** | **Mould B** | **Mould A** | **Mould B** |
| | **Time** | **Time** | **Cost (ZAR)** | **Cost (ZAR)** |
| Programming time | 25 min | 25 min | R 72.90 | R 72.90 |
| Set-up time | 30 min | 30 min | R 49.98 | R 49.98 |
| Machine time | 1h50 | 1h50 | R 550.00 | R 550.00 |
| Finishing time | 0 min | 0 min | R 0.00 | R 0.00 |
| Total | 2h45 | 2h45 | R 672.88 | R 672.90 |
| **Grand Total** | **5h30** | | **R 1 345.76** | |

Figure 13: Initial test geometry: Milling time and cost layout

Slipcasting is the process of pouring a clay and water mixture, to which a deflocculant is added, into a plaster mould. Water is removed from the slip through a capillary action of the plaster resulting that on the inner surface of the mould a layer of clay is built up (Wardell, 1997:7). A deflocculant is a soluble alkali. It exchanges its ions (charged atoms) with those of the clay particles so that the clay particles are all of a similar powerful electrostatic charge. The deflocculant prevents the clay particles from combining with each other. It causes the particles to slide past one another and therefore acts as a lubricant and the slip mixture needs less water but still remains fluid enough to be poured (Frith, 1985:149). The surface of the plaster of Paris mould is attacked by the deflocculant in the clay's slip body and becomes pitted and deteriorates after several castings. The soluble salts slowly causes holes to form on the inside surface of the plaster of Paris mould. Depending on the complexity of the design, the type of plaster and the hardness of the plaster mould, between 30 to 40 casts can be made from a single plaster of Paris mould before the surface starts to wear down (Wardell, 1997:79). If the design contains fine detail, the tendency is to erode quicker and fewer casts can be made; a new plaster of Paris mould then needs to be manufactured.

After completing a cycle of planning, acting, observing and reflecting and considering all the disadvantages of milling the plaster of Paris directly, it was decided to research an alternative material suited to the durability and the technical aspects suited to the select milling machine. As an alternative the vessel prototype was milled from Necurite 630 (recycled polyurethane) from which a plaster of Paris master mould was cast. See Figure 14 for the transformation of a designed shape to a master mould. Using the operational features and design parameters of SolidWorks®, a range of six test geometries were designed. The first set of test geometries were specifically designed to determine the suitability and durability of Necurite 630 (to be discussed in Chapter 4) as an alternative material for milling the vessel prototype or pattern as often referred to by engineers. The first set of geometries determined whether the material could provide an adequate surface finish and facilitate a high degree of complexity. The second set of geometries were designed to determine the height-width release ratio for moulding and casting purposes in order to establish design rules for the design of vessel forms.

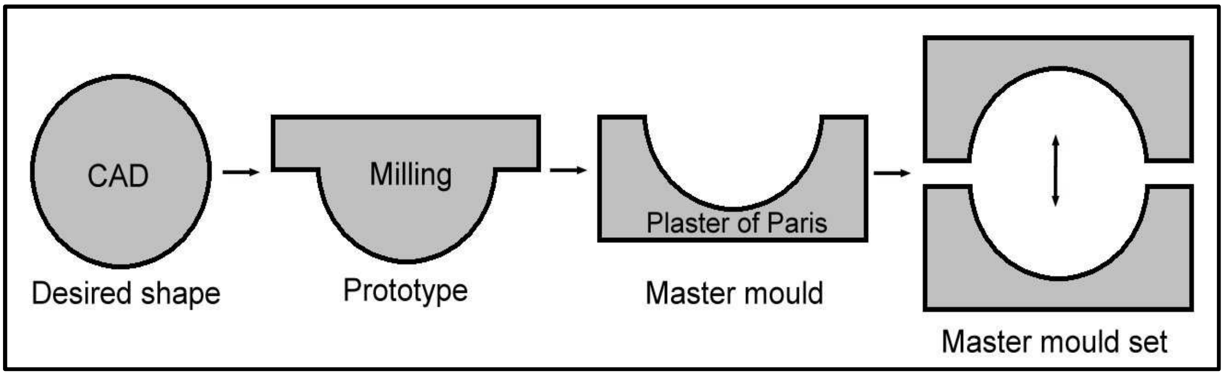


Figure 14: Transformation from designed shape to master mould

The standard base width of 10 mm between the extrusions for all the test geometries was used to save set-up time and machining time; a different width might have required some post-processing, which would increase costs, as discussed in Chapter 4. A larger milling cutter takes less time to remove material and therefore it was decided upon a 10 mm cutter base width for the final cut. The base width of the first extrusion is 3 mm, thereafter the width of each extrusion increases by 1 mm to reach 10 mm for the last extrusion as shown in Figure 16. Due to cost implications, the above-mentioned estimate range of variation within the width of the extrusions was decided upon for use throughout the study since it provided adequate results. These measurements were used to test the limits of the milling process in order to establish design parameters. A sequential draft of 1° was added to geometries 2, 4 and 6. Since the individual tests were designed to release from a single part without undercuts, no parting lines were necessary.

### 3.5.1 Test geometry 1

Figures 15 and 16 show the rendered 3-D design and the 2-D drawing of test geometry 1. The height of each extrusion is 10 mm. The extrusions are perpendicular to the base forming a 90° angle.

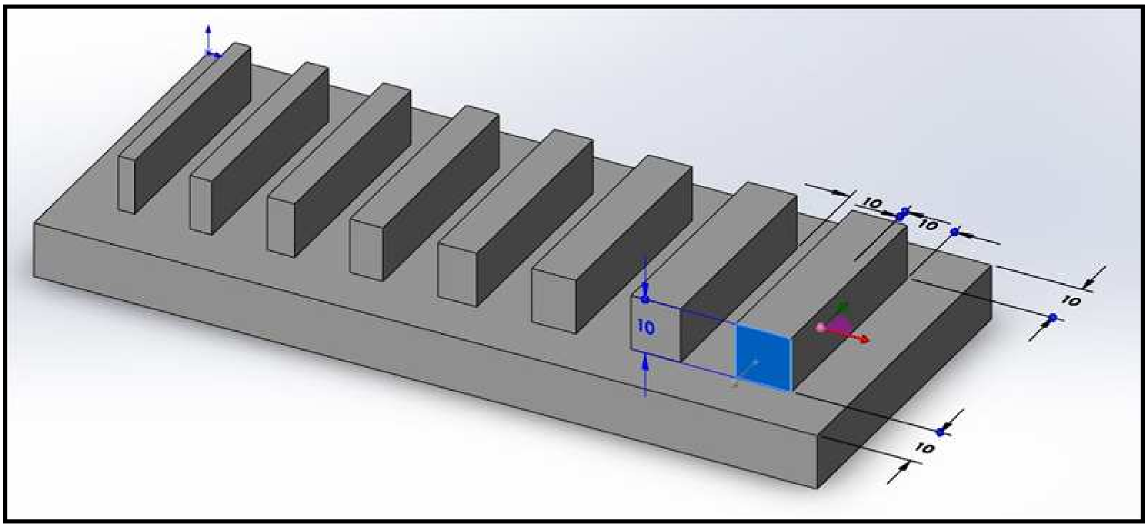


Figure 15: Test geometry 1: 3-D design

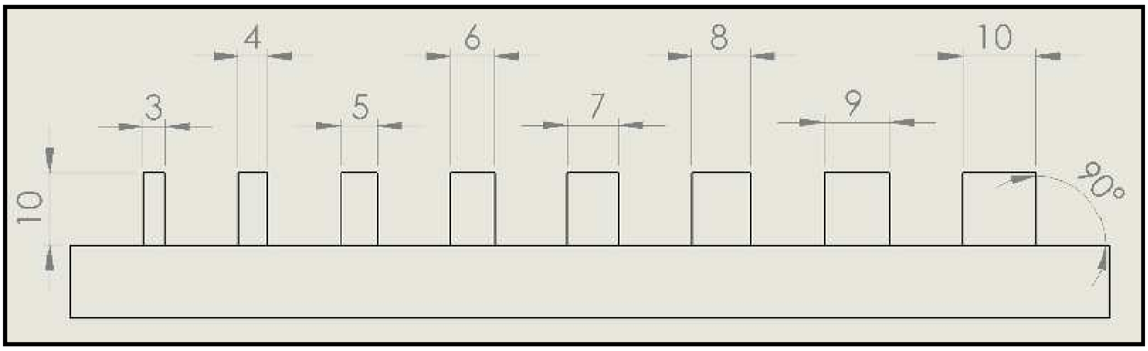


Figure 16: Test geometry 1: 2-D CAD drawing – with dimentions

Figure 17 indicates that the total time required to design test geometry 1 was fifteen minutes.

| Test geometry 1: Data sheet – Design time and cost layout | |
|---|---|
| **Design Time** | 15 min |
| **Design Cost** | R 43.65 (ZAR) |

Figure 17: Test geometry 1: Data sheet – Design time and cost layout

### 3.5.2 Test geometry 2

Figures 18 and 19 show the rendered 3-D design and the 2-D drawing of test geometry 2. The height of each extrusion is 10 mm. Each extrusion has a 1° draft forming a 91° angle with the base.

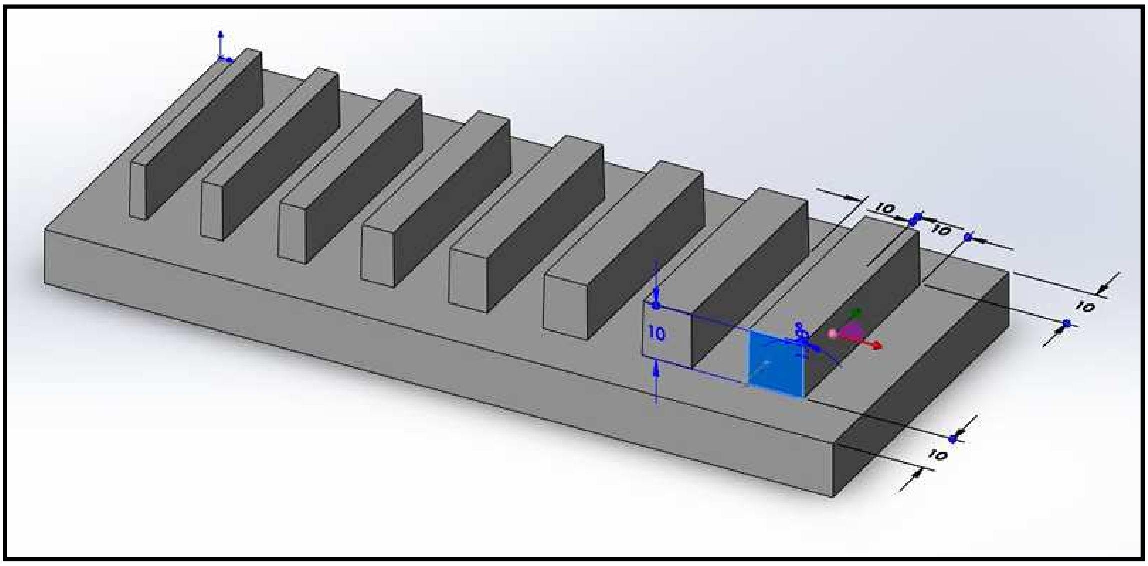


Figure 18: Test geometry 2: 3-D design

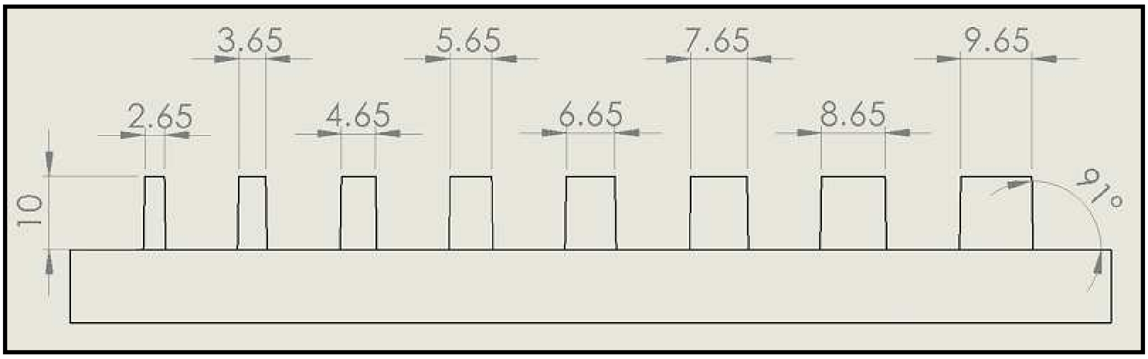


Figure 19: Test geometry 2: 2-D CAD drawing – with dimentions

Figure 20 indicates that the design time of test geometry 2 took five minutes. This was achieved by modifying the existing design of test geometry 1 by adding a draft of 1° to each extrusion.

| Test geometry 2: Data sheet – Design time and cost layout | |
|---|---|
| **Design Time** | 5 min |
| **Design Cost** | R 14.55 (ZAR) |

Figure 20: Test geometry 2: Data sheet – Design time and cost layout

### 3.5.3 Test geometry 3

Figures 21 and 22 show the rendered 3-D design and the 2-D drawing of test geometry 3. The height of each extrusion is 20 mm. The extrusions are perpendicular to the base forming a 90° angle.

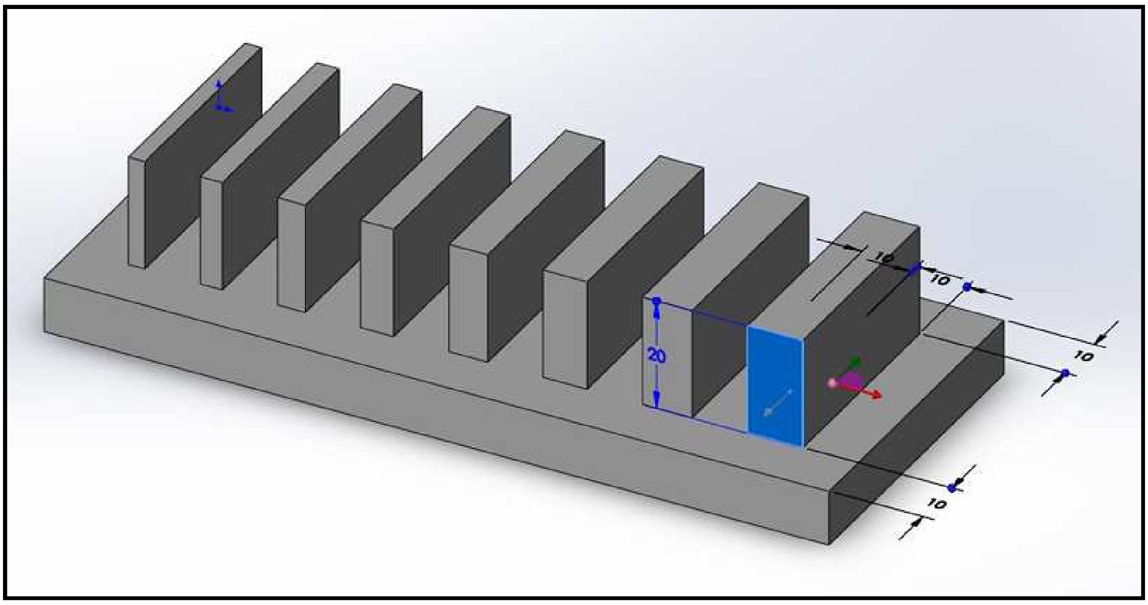


Figure 21: Test geometry 3: 3-D design

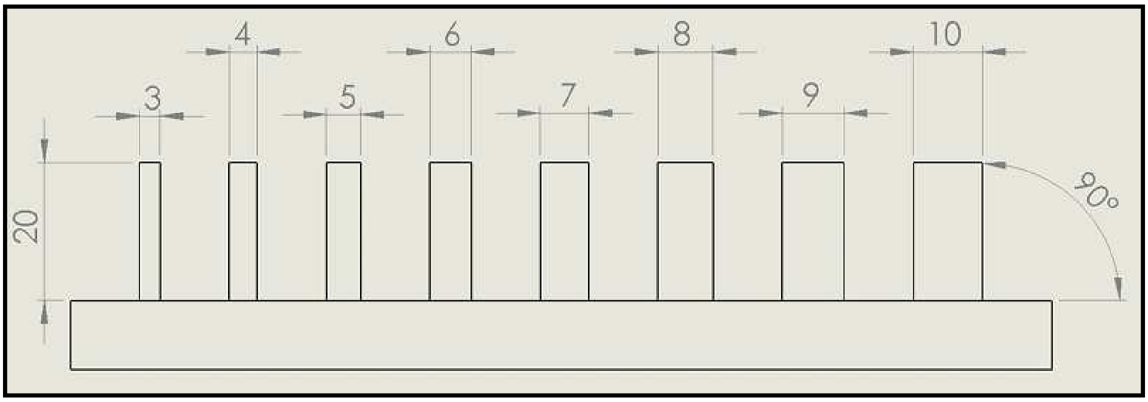


Figure 22: Test geometry 3: 2-D CAD drawing – with dimentions

Figure 23 indicates that the design time of test geometry 3 took five minutes. This was achieved by modifying the height of each extrusion of test geometry 1 from 10 mm to 20 mm.

| Test geometry 3: Data sheet – Design time and cost layout | |
|---|---|
| **Design Time** | 5 min |
| **Design Cost** | R 14.55 (ZAR) |

Figure 23: Test geometry 3: Data sheet – Design time and cost layout

### 3.5.4 Test geometry 4

Figures 24 and 25 show the rendered 3-D design and the 2-D drawing of test geometry 4. The height of each extrusion is 20 mm. Each extrusion has a 1° draft forming a 91° angle with the base.

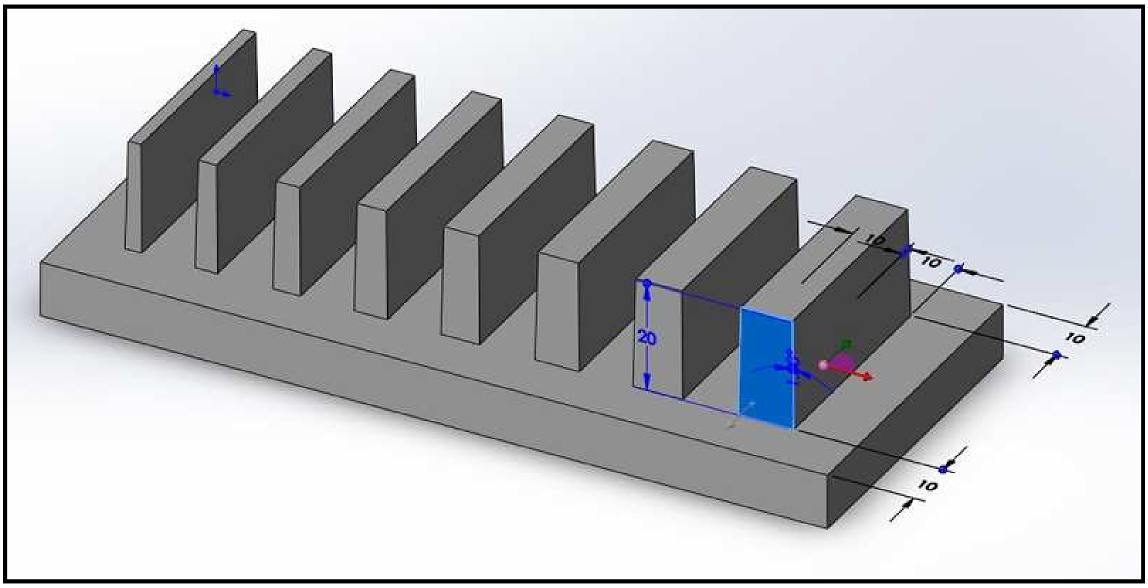


Figure 24: Test geometry 4: 3-D design

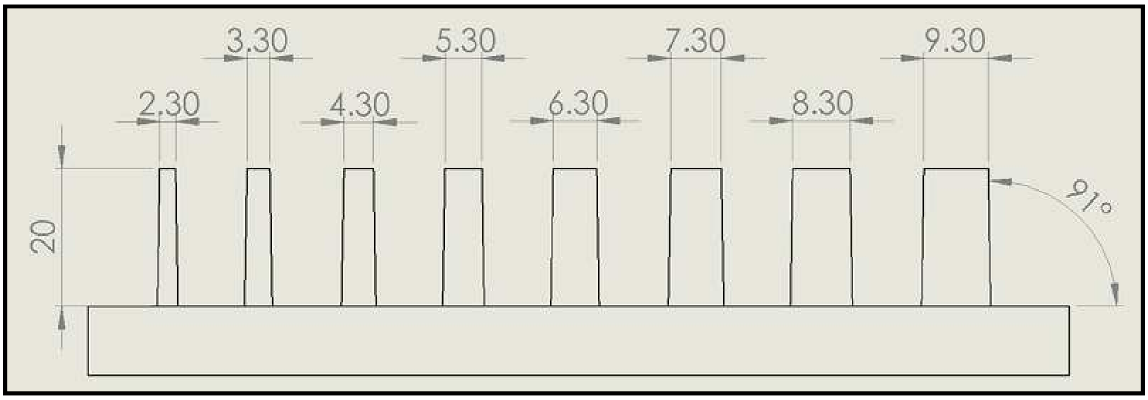


Figure 25: Test geometry 4: 2-D CAD drawing – with dimentions

Figure 26 indicates that the design time of test geometry 4 took five minutes. This was achieved by modifying the height of each extrusion of test geometry 2 from 10 mm to 20 mm.

| Test geometry 4: Data sheet – Design time and cost layout | |
|---|---|
| **Design Time** | 5 min |
| **Design cost** | R 14.55 (ZAR) |

Figure 26: Test geometry 4: Data sheet – Design time and cost layout

### 3.5.5 Test geometry 5

Figures 27 and 28 show the rendered 3-D design and the 2-D drawing of test geometry 5. The height of each extrusion is 30 mm. The extrusions are perpendicular to the base forming a 90° angle.

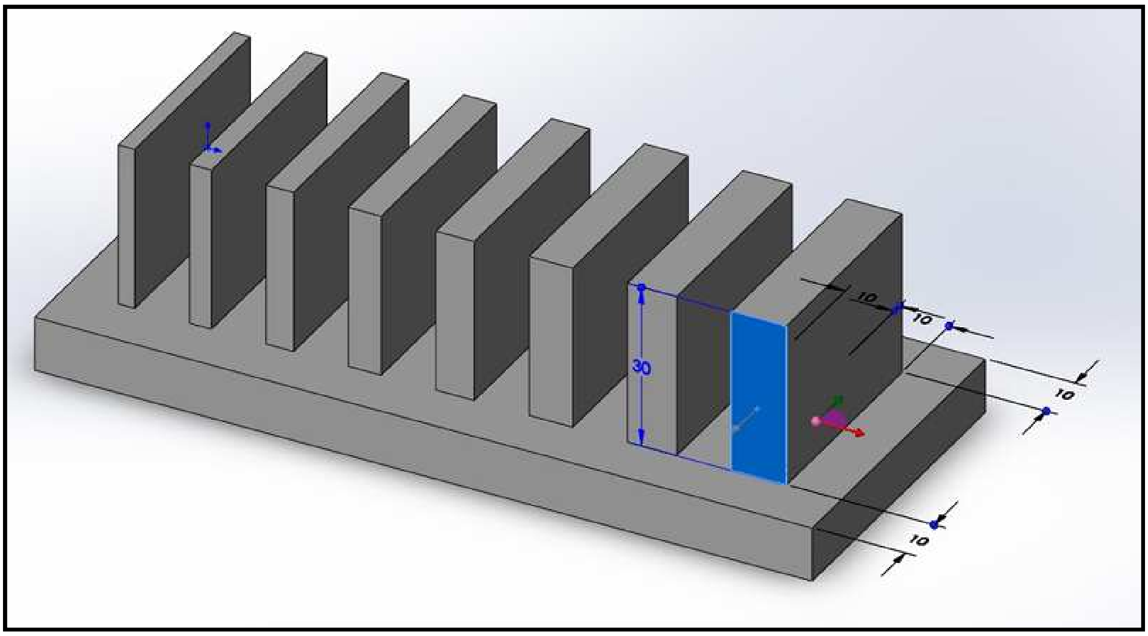


Figure 27: Test geometry 5: 3-D design

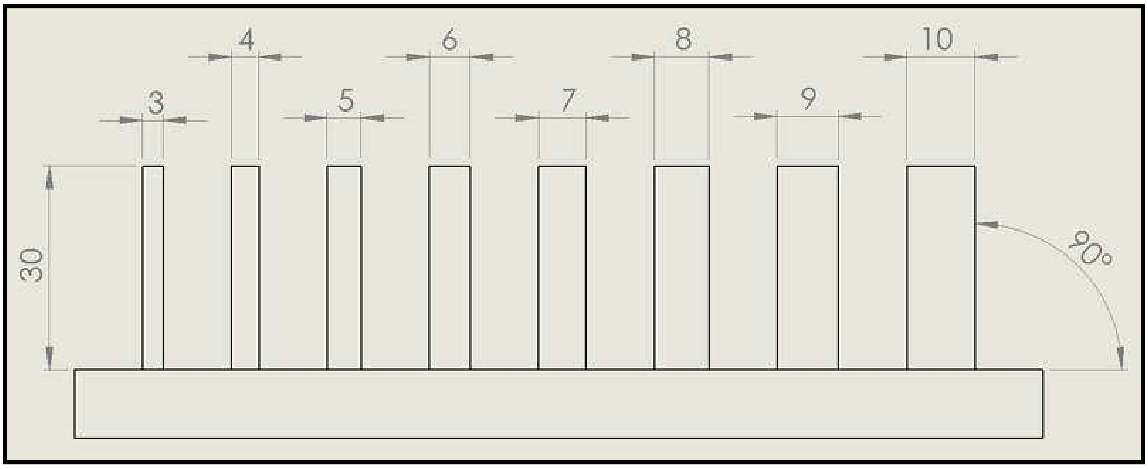


Figure 28: Test geometry 5: 2-D CAD drawing – with dimentions

Figure 29 shows that the design time of test geometry 5 took five minutes. This was achieved by modifying the height of each extrusion of test geometry 1 from 10 mm to 30 mm.

| Test geometry 5: Data sheet – Design time and cost layout | |
|---|---|
| **Design Time** | 5 min |
| **Design Cost** | R 14.55 (ZAR) |

Figure 29: Test geometry 5: Data sheet – Design time and cost layout

### 3.5.6 Test geometry 6

Figures 30 and 31 illustrate the rendered 3-D design and the 2-D drawing of test geometry 6. The height of each extrusion is 30 mm. Each extrusion has a 1° draft forming a 91° angle with the base.

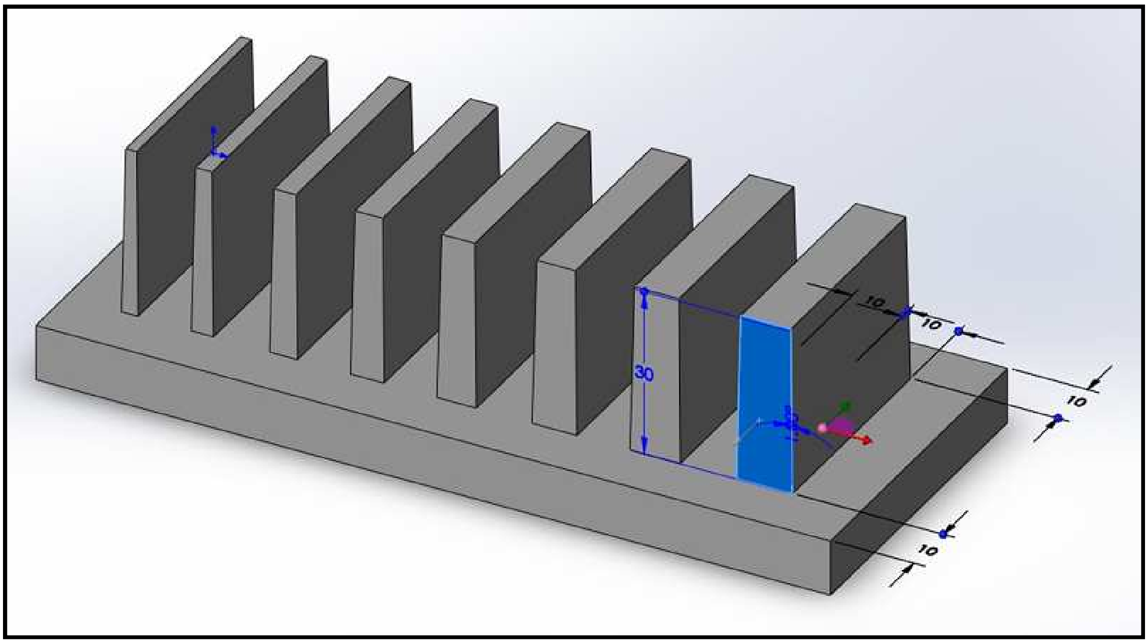


Figure 30: Test geometry 6: 3-D design

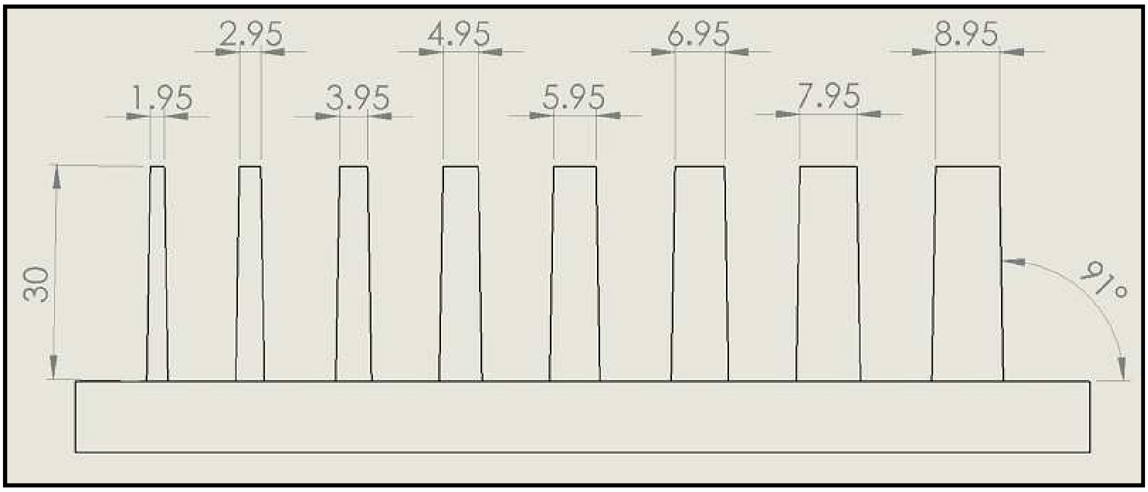


Figure 31: Test geometry 6: 2-D CAD drawing – with dimentions

Figure 32 shows that the design time of test geometry 6 took five minutes. This was achieved by modifying the height of each extrusion of test geometry 2 from 10 mm to 30 mm.

| Test geometry 6: Data sheet – Design time and cost layout | |
|---|---|
| **Design Time** | 5 min |
| **Design Cost** | R 14.55 (ZAR) |

Figure 32: Test geometry 6: Data sheet – Design time and cost layout

## 3.6 Interpreting the results

Figure 33 below clearly indicates a marked acceleration concerning the total design time. The initial geometry, i.e. test geometry 1, took fifteen minutes to design from start to finish. By utilizing CAD software to modify existing designs, the remainder of the test geometries took a minimum of five minutes each to design. SolidWorks® has the ability of design intent, meaning that, without the designer's intervention, SolidWorks® automatically and accurately calculated the sequential measurements of the extrusions. To modify a test geometry design from a previous design was three times faster than developing the initial design. The accuracy and speed obtained when using SolidWorks® as a design tool far exceeds the traditional method of drawing by hand. The traditional method necessitates that test geometries need to be individually drawn by hand and changes cannot easily be made to existing drawings. The various figures presented above also show the ability of CAD, in this case SolidWorks®, to clearly render a visual 3-D representation of the design in 3-D format. While this is possible with most modern design applications, SolidWorks® also indicates whether the design is fully defined, meaning that all geometries are correctly drawn. With many software programs the design might look accurate to the naked eye, but the geometries are often not watertight causing problems during the manufacturing stage. For example, lines that are not intersecting may cause unexpected results such as holes to be manufactured during the CAM process. Figures 33 and 34 below provide graphs indicating a summary of the time and cost results for the six test geometries respectively.

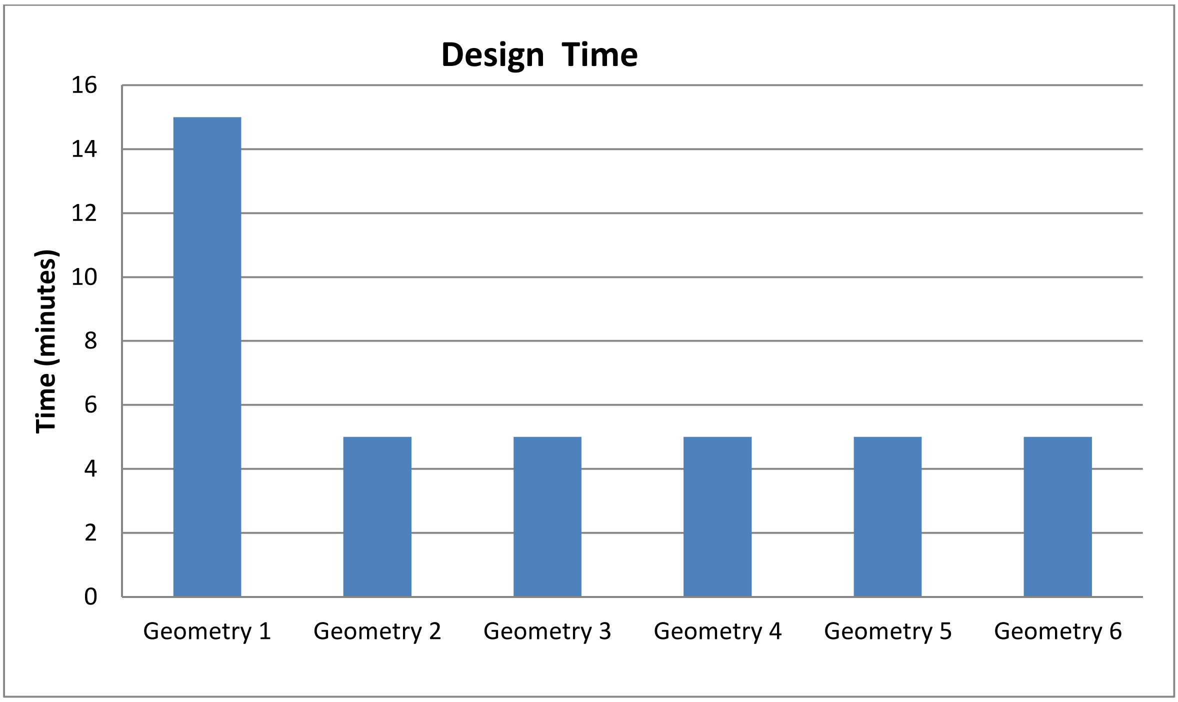


Figure 33: Summary – design time – six test geometries

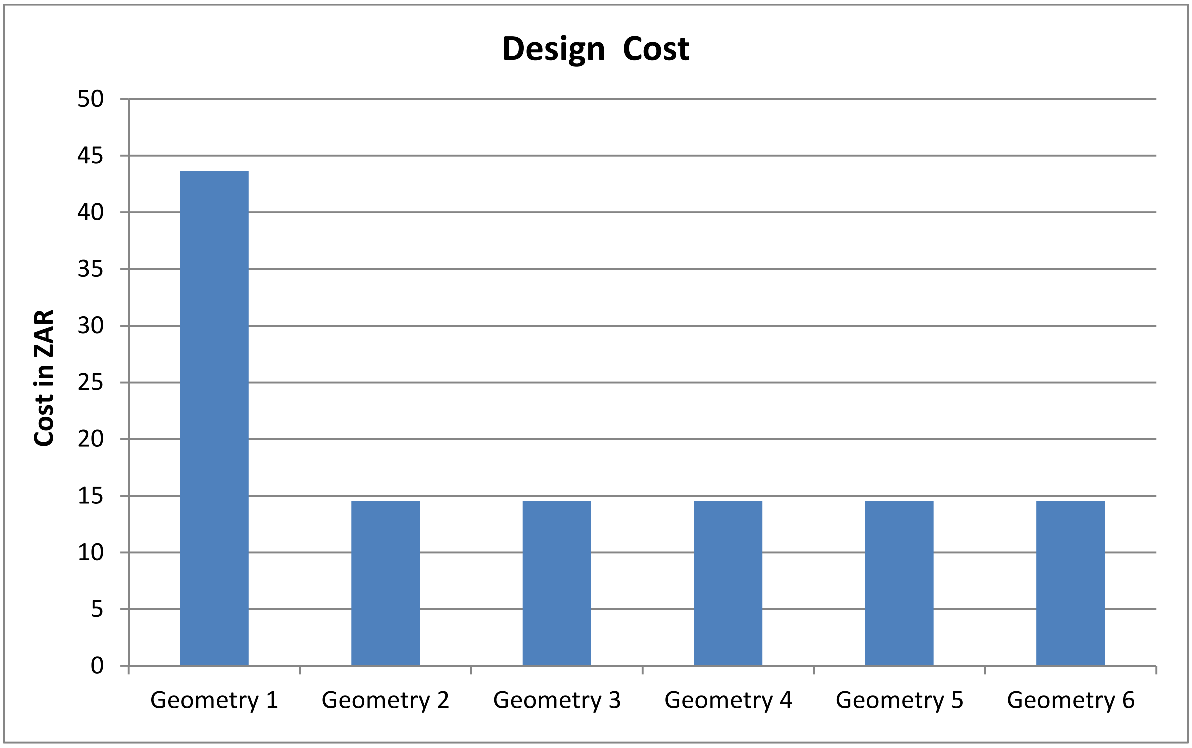


Figure 34: Summary – design cost – six test geometries

### 3.7 Conclusion

This chapter has specifically outlined the significant role that CAD can play in assisting the overall manufacturing process and it is evident that the utilization of CAD within the design process has become essential to any product development initiative. SolidWorks® is a very efficient program that assists the designer to quickly create designs and allows for fast changes. This ensures that design costs are reasonable and affordable. SolidWorks® proves to be a suitable 3-D design software program that can easily assist the studio ceramicist during the initial design stage and with design changes further on during the product development phase. Results obtained from the CNC milled test geometries will be applied as design parameters for the development of vessel prototypes to be subsequently discussed in Chapter 4.

# Chapter 4

# Computer numerical controlled (CNC) milling: Vessel prototype and master mould development

## 4.1 Overview

This chapter explores various technical aspects regarding CNC milling as a manufacturing technology in order to establish design parameters and to determine a suitable milling material for the development of a range of vessel prototypes as outcome of this study. With a view on underlining the possibilities and advantages of CNC milling as a manufacturing technology, the discussion commences with providing background information on CNC milling as technological development. The identification of CNC milling specifications suitable to the research objectives forms an essential prerequisite to the studio-practice application of the study. The central discussion focuses on the analysis of a range of CNC milled test geometries derived from the CAD data presented in Chapter 3. An analysis of the plaster of Paris moulds and slipcasting results of the aforementioned test geometries determines the durability of the prototyping material and workability of established design parameters.

## 4.2 Introduction

Professors Black and Kohser, the former an industrial systems engineer and the latter a manufacturing processes engineer, draw attention to the fact that CNC milling represents an advanced manufacturing technology within the field of engineering that is suited to several industrial enterprises (Black & Kohser 2013:706). The workplace reveals that CNC milling machines are maintained and operated by qualified engineering or machinist staff; it does not, generally speaking, occupy a distinct place within the discipline designated as the arts. Even so, there is no valid and compelling reason why engineering and the arts cannot collaborate in an interdisciplinary endeavour. With specific reference to subtractive fabricating technologies, such as CNC milling, Jeremy Gardiner (2010:148) rightly states that CNC milling has the potential to expand artistic conceptualization and expression and must be exploited by artists in order to determine to what extent this technology facilitates innovative artistic conceptual development. Even though the utilization of CNC milling and the advantages, potential and possibilities which it presents have been explored within the field of ceramics, this has not been done to any large extent or degree. As such a need exists to establish its potential and possibilities for the batch production of ceramic artefacts, specifically concerning the processes that accelerate the product-to-market lead time (Hoskins, 2012:19).

### 4.3 CNC Milling

Computer numerical controlled (CNC) milling is defined as a manufacturing process for fabricating components or parts in a production environment. It is controlled and distributed by a computerized controller that uses motors to drive linear and rotary axes (Black & Kohser, 2013:689). Following World War II (1939 – 1945), and due to constant modifications and developments within the discipline of design, the United States Air Force realized the need for faster and improved manufacturing strategies for aircraft parts (Fitzpatrick, 2011:718). As a result the first numerically controlled (NC) machine was built at the Massachusetts Institute of Technology (MIT) in 1952. Technological developments during the 1970s made it possible to incorporate a dedicated computer into the NC controller, a technique aptly termed computer numerical control or CNC (Black & Kohser, 2013:686).

There is practically no limit to the range of materials that CNC milling as a manufacturing process can accommodate. Metallic materials include iron, copper, aluminium, lead titanium, steel and bronze. Non-metallic materials include wood, glass and plastics as well as various polymers and foams (Black & Kohser, 2013:60). CNC milling machines are very accurate and depending on the type and category of machine, various degrees of accuracy can be obtained within a range of 0.00304 mm for superior accuracy and 0.0254 mm for more average standards (Black & Kohser, 2013:702). A CNC machine can automatically change tools and speeds and feeds as needed for different operations, minimizing operator involvement and resulting in reduced human error (Black & Kohser, 2013:693). CNC milling machines can furthermore produce very smooth surfaces between 0.8 and 6.3 microns for average applications. Under special conditions lower values between 0.20 to 0.80 microns and higher values between 6.3 and 25 microns can be obtained (Black & Kohser, 2013:919).

Owing to automation and the subsequent reduction in human error, parts are accurately manufactured resulting in a lower waste percentage of material, thus saving on time and money. CNC milling is furthermore a replicable and consistent manufacturing method. Once a tool path and machine set-up is done, a potentially unlimited number of identical work pieces can be produced (Chougule, 2010:11.4). In addition, parts and moulds of nearly any size can be manufactured with CNC machining. A model can be scaled up and then divided into smaller sections fitting the bed size of the milling machine. Most types of CNC machine tools offer the advantage of high flexibility. Since computers control these machines, running a different work piece is very simple. As such it enhances and improves customization. The benefit of flexibility leads to fast part changeovers. CAM programs (the tool paths) can be easily loaded and allows for shorter set-up times and therefore changeovers are much faster, consequently reducing manufacturing time, resulting in an accelerated product-to-market lead time (Chougule, 2010:11.12).

Notwithstanding the obvious advantages that the utilization of CNC milling has to offer, a CNC milling machine has a high initial investment cost due to not only expensive hardware, but expensive software as well (Chougule, 2010:11.3). As the complexity of the object increases, the number of set-ups and tool changes for the milling process likewise increases, making the manufacturing process more time-consuming and less cost-effective. The more material that needs to be removed the longer the machine time, which adds to the cost. A qualified machinist or milling operator is moreover required for programming tool paths and for machine set-up and operations to be carried out (Chougule, 2010:11.13). The cost and skill requirements of using CNC milling as a manufacturing system can be a disadvantage to the studio ceramicist, but skilled services are readily available.

Society now operates in a digital world where information technology and computers develop constantly, influencing nearly every aspect of daily life. To be competitive in a global marketplace, there is a constant need for rapid manufacturing process development (Black & Kohser, 2013:12). Through digital manufacturing, a wide diversity of pre-production simulation is applied which forms the link between the virtual world and the physical world. Industry manufactures objects using an array of technologies. These include subtractive machining processes like milling and turning, additive processes and techniques such as composite layups, moulding processes via compression, transfers or the injection of materials (Zhou, Xie & Chen, 2012:6). Digital manufacturing solutions assist in identifying the manufacturing procedures and steps necessary for the fabrication of a product. It supports the testing of the various procedures and steps required to achieve precision and accuracy. It also assists in generating work and machine instructions for the manufacturing of a product. The result, consequently, is a completely automated or digital manufacturing system. In this way the quality of products can constantly be improved upon and manufacturing costs are reduced. The outcome is an accelerated product development and subsequently a shorter product-to-market lead time (Black & Kohser, 2013:527). Subtractive manufacturing like CNC milling as a digital fabrication technology in this regard is a developing field supporting aesthetic possibilities within art and design fields (Zoran & Buechley, 2013:5).

## 4.4 CNC milling: Technical aspects

### 4.4.1 CNC milling machine

The machine tool refers to the physical milling machine which produces the model by removing excess material (Figure 35). Control of the relative motion between a cutting tool and the work piece creates the desired geometry. Depending on the relative motion between the tool and work piece, milling machines can be divided into rotating spindle machines called horizontal and vertical mills or machines with a rotating work piece referred to as a lathe. Electronically controlled milling machines can be broadly classified as manual data input milling machines, programmable milling machines, machining centres and flexible cell manufacturing systems (Black & Kohser, 2013:678). Figure 35 is an example of a CNC milling machine.

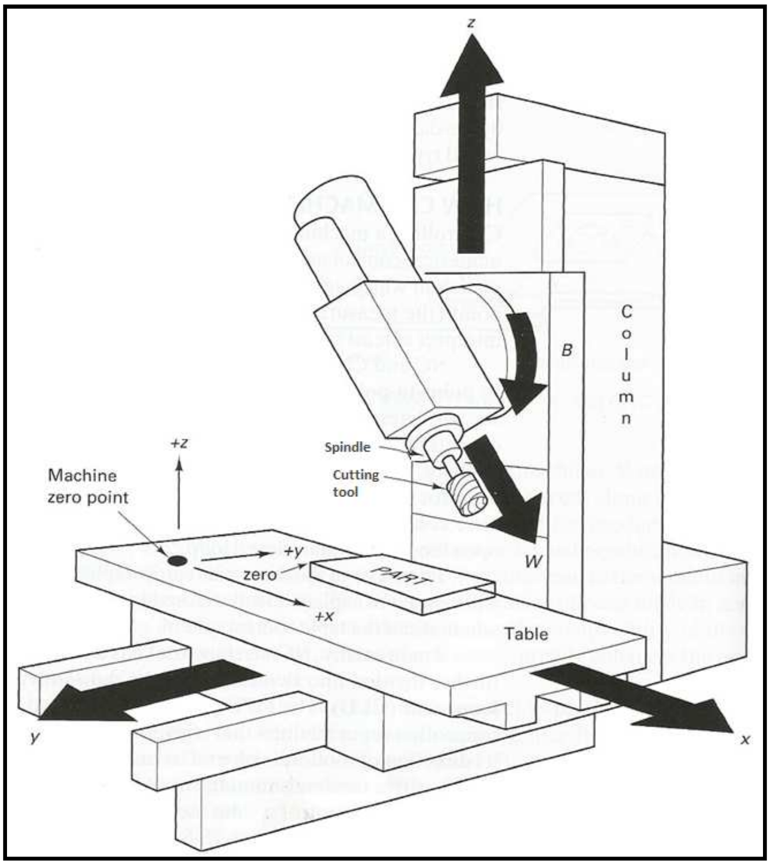


Figure 35: Example of a CNC milling machine

Variable movement is achieved using a combination of the different axes movements. Figure 36 illustrates that universally a total of nine standard axes can be used by milling machines:

- Straight movements X, Y and Z are the primary linear axes.
- A, B and C are the primary rotary axes that rotate around X, Y and Z respectively.
- The auxiliary or secondary axes U, V and W perform straight-line movements parallel to X, Y and Z respectively.

Figure 37 illustrates that the head is controlled by the Z-axis and the W-axis controls the spindle or quill with separate commands (Fitzpatrick, 2011:672).

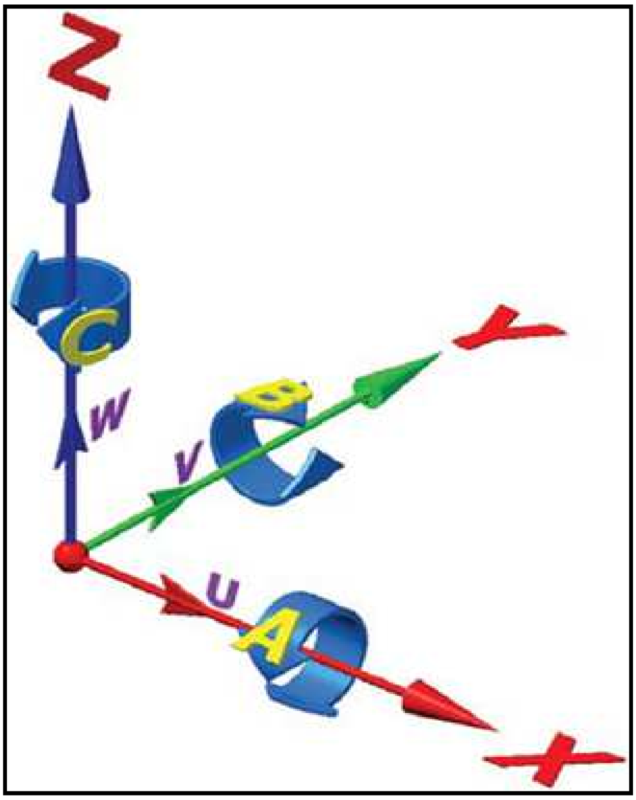


Figure 36: Nine universal axes movements for milling machines

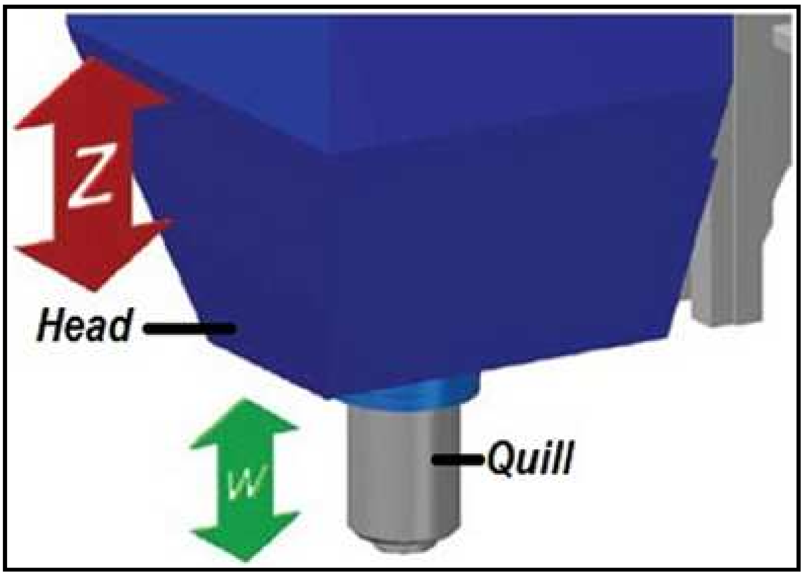


Figure 37: Movement of parallel Z- and W-axes controlled by separate commands

According to Fitzpatrick (2011:675), CNC milling machines can also be classified based on the number of axes they control:

- Two-axis motion machine – axes move in two orthogonal directions.
- Three-axis motion machine – axes move in three directions, generally along the three primary linear axes (i.e. X, Y and Z).
- Four-axis motion machine – axes move in four directions and involve three linear and one rotary axis motion.
- Five-axis motion machines – axes move in five directions, normally the three linear motions with two rotary motions.

These machine applications clearly illustrate the versatility and multifaceted capabilities of CNC milling technology. As mentioned, due to machine availability and complexity of design, a 3-axis CNC milling machine was used for the purpose of this study.

#### 4.4.2 Part programming

As previously defined, CAM is a computer system that plans, manages and controls the manufacturing process through a computer interface (cf. Chapter 3.3) (Leu & Joshi, 2011:10). CAM systems read the lines or surfaces of the CAD drawing from the design file to create a code (language) referred to as the part geometry. The part geometry is translated by the software controlling the milling machine to create the designed object (Fitzpatrick, 2011:734).

Each system stores data in a unique format and therefore presents limited interoperability and it is not possible to simply send a file from one CNC machine to another. A file or drawing first needs to be converted to a standard format and only then is it possible to exchange files between various CAD and CAM systems. Depending on the CAD system, popular standard formats to be used are IGES, STL, X_T and STEP (Chougule, 2010:10.1). The X_T (Parasolid File) format will be used for the purpose of translating CAD data in this study since it is compatible with all the hardware and software used at the Product Development Technology Station (PDTS – Central University of Technology Free State) facility conducting the milling.

Part programming refers to the programming and planning of the processing steps and actions of the machine tool to be performed during the manufacturing process. The first phase of part programming is to translate a representation of the model into recognizable CNC milling geometry and dimensional specifications (G-codes). Secondly, to program the cutter path, a step-by-step set of instructions needs to be carried out by the machine tool in order to fabricate the designed model (Black & Kohser, 2013:695). The programming of the cutter path to control the speed and motion of the cutting tool is specified through the actual cutting and the cutting tool parameters.

Cutting tool parameters refer to tool angles, the nose radius of the cutting tool, the edge radius of the cutting tool, material, hardness, finish and coating (Black & Kohser, 2013:534). Cutting parameters include the cutting feed, cutting speed, spindle speed (*Ns*), feed rate (*fm*), axial depth of cut (*d*) and radial depth of cut (see Figure 38). Cutting feed is the distance which the work piece or cutting tool moves during one revolution of the spindle and tool. Cutting speed refers to the speed on the surface of a work piece in relation to the edge of the cutting tool during a cut. The spindle speed denotes the speed at which the spindle and tool rotate in revolutions per minute. The feed rate refers to the speed of the cutting tool as it makes a cut in relation to the work piece. Axial depth of cut is the depth of the tool along its axis in the work piece while radial depth of cut refers to the depth of the tool during a cut along its radius in the work piece (Black & Kohser, 2013:665). All these settings are important to increase production and are interdependent. Figure 38 is an illustration of the cutting parameters.

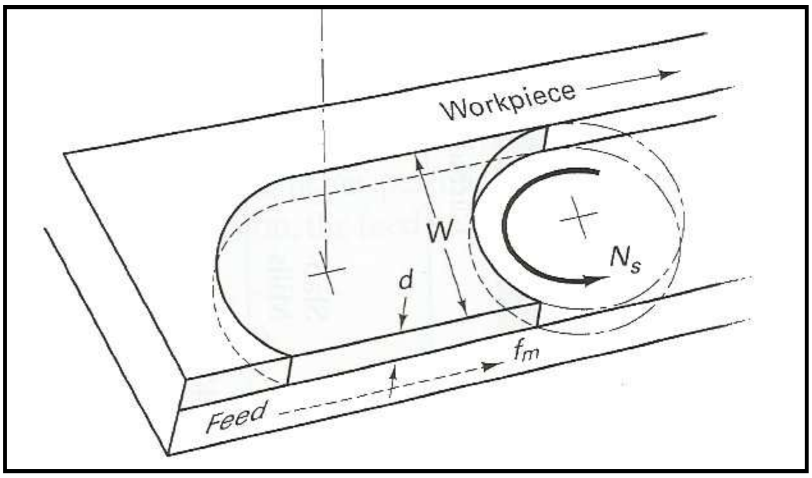


Figure 38: Cutting parameters

### 4.4.3 Machine Control Unit

An essential feature of a CNC milling machine is the controller known as the machine control unit (MCU). The function of the MCU is to read and interpret the instructions from the part program to control the milling machine. The MCU gives commands in a sequential order to each motor of the machine tool and controls the direction, speed and the length of movement (Fitzpatrick, 2011:714).

### 4.4.4 Milling material

Different materials, with reference to their milling and moulding capabilities, were considered to find an alternative to plaster of Paris as a milling material. Information and specifications were provided by the company Advanced Materials Technology (AMT) Composites who are leading suppliers of milling materials. A delimitation of this research study states that an expansive number of potential materials will not be tested, but only suitable materials will be selected for testing that support the concept of integrating emerging technology as an alternative to traditional methods for the manufacturing of master moulds. Supawood, Resin (Fastcast Polyurethane F19) and Tooling boards (Necurite 630) were considered as suitable milling materials. Supawood is an inexpensive milling material, but has a high dust formation with medium dimensional stability. Furthermore, since the machined prototype is to be used for the manufacturing of plaster of Paris master moulds, the possibility exists that moisture from the plaster of Paris may be absorbed by the wood which will cause expansion. This characteristic can influence accuracy and create difficulty for the mould to release from the master mould. Resin (Fastcast Polyurethane F19) is a machineable material; combined with filler, however, it is very expensive, especially when used in large quantities and therefore not a viable milling material choice for this study.

Tooling boards, also known as machine slabs or modelling boards, are typically used for the milling of master and working moulds, prototype tooling, patterns and jigs instead of hard wood and metal. Tooling boards are easily bonded together to form larger surfaces using polyurethane resins such as Axson Fastcast F16 or epoxy adhesive (AMT Composites, 2010:1). These boards are normally manufactured from filled polyurethane which has a low density, but the surface is dense and easy to seal, if needed. Tooling boards are also a very consistent material that has very high dimensional stability characteristics and has low dust formation. Tooling boards are also lighter, more economical and easily machined compared to steel and aluminium. Many grades of tooling boards are available ranging in machining speed, strength, cost and density suited to various applications (AMT Composites, 2010:1). Figure 39 below outlines a cost comparison between the three different materials, i.e. tooling boards (Necurite 630), Supawood and Resin. Costs involved were provided by the material supplier (AMT Composites, November 2012, quoted in ZAR).

| **Material cost comparison** | |
|---|---|
| | **Cost/m$^3$** |
| **Tooling board** | R 30 400/m$^3$ |
| **Supawood** | R 7 522/m$^3$ |
| **Resin** | R 75 000/m$^3$ |

Figure 39: Material cost comparision (cost/m$^3$) (AMT Composites, Sep 2012.)

Figure 40 presents a decision matrix table of the essential elements that were taken into consideration for the assessment of the material to be ultimately selected for machining vessel prototypes. For the purpose of this study it was important to select a material that is cost-effective, be able to manufacture complex prototypes (geometries), has a good dimensional stability and requires a low dust formation. With the assistance of an experienced milling engineer, a value of 1 to 5 was assigned to these specifications that were obtained from a universal technical information data sheet regarding the set standards for each material. As indicated a value of 1 to 5 is employed where 1 denotes “very poor” while 5 denotes “very good”.

| Material decision matrix table | | | |
|---|---|---|---|
| | **Tooling board: Necurite 630** | **Supawood** | **Resin: F19 Fast cast polyurethane** |
| **Cost** | 3 | 5 | 1 |
| **Dimension stability** | 5 | 3 | 5 |
| **Density** | 5 | 3 | 5 |
| **Dust formation** | 4 | 1 | 5 |
| **Total** | 17 | 12 | 16 |

Figure 40: Material decision matrix table

From the matrix table presented in Figure 40 above, it is evident that Necurite 630 achieved the highest value, therefore indicating good material workability. Necurite 630 has the following appealing characteristics making it most suitable for the milling of the intended vessel prototypes:

- It is made of recycled polyurethane that is cheaper than most other materials.
- It has good edge stability that ensures that edges will not easily chip or crack.
- Its high dimensional stability limits the impact of environmental changes such as moisture or temperature.
- Its high density (high mass per unit volume) ensures a high surface finish.
- It is scratch-resistant to ensure that the surface will not easily scratch when used to cast moulds from.
- Its workable surface is suitable for finishing operations like using sandpaper.
- It is suitable for the manufacturing of complex geometries (AMT Composites, 2010:1).

The milling parameters regarding the cutting speeds and feeds of a milling material is very important. It provides guidelines and assists engineers with the milling process, especially when an engineer is not familiar with a particular material. Figure 41 provides milling parameters regarding Necurite 630 to ensure optimal milling results (AMT Composites, 2010:2).

| Necurite 630 milling parameters (cutting speeds and feeds) | | |
|---|---|---|
| | **Roughing Finishing** | **Finishing** |
| **Type of tool** | Finishing tools d=80mm | Finishing tools d=80mm |
| **Tool diameter [d] (mm)** | 80 | 80 |
| **Cutting speed [Vc] (m/sec.)** | 50 | 50 |
| **Speed [n] (1/min)** | 12000 | 8000 |
| **Feed speed (m/min)** | 10 | 7.5 |
| **Tooth speed [fz] (mm)** | 0.21 | 0.21 |
| **Number of teeth [z]** | 4 | 4 |
| **Cutting depth [ae] (mm)** | 4 | 0.5 |
| **Cutter mark length [fzeff] (mm)** | 38 | 5 |

Figure 41: Milling parameters of Necurite 630. (AMT Composites, 2010.)

### 4.4.5 Machining processes

The subtractive CNC milling machine process of removing material generates a wide variety of surface textures. The cutting processes leave a variety of surface patterns on the designated milled material which is generally referred to as the surface finish, whereas roughness refers to the visible finely spaced surface irregularities. The machining process, therefore, consists of three different operational types, i.e. roughing, semi-finishing and finishing. Depending on the design requirement, the operational types can be run more than once to achieve superior results, but resulting in higher costs. For ceramics a reasonable surface finish is necessary; further finishing can be done by hand, thus keeping milling costs down. Each operation is performed by task-dedicated and optimized cutting tools to ensure a uniformly dispersed working allowance in each operation. The choice of the specific tool type to be used depends on the decision of the engineer machinist according to design specifications and the material to be milled. Various milling cutters are commercially available for the different machining operations and materials (Black & Kohser, 2013:914).

Figure 42 provides an example of the TaeguTec ChaseMill TE90AX cutter that was used for roughing the test geometries. Here "D" (16 mm) refers to the cutting edge diameter, "*l*" (30 mm) refers to the cutting edge length, "L" (90 mm) refers to the overall length of the cutter and "d" (16 mm) refers to the shank diameter.

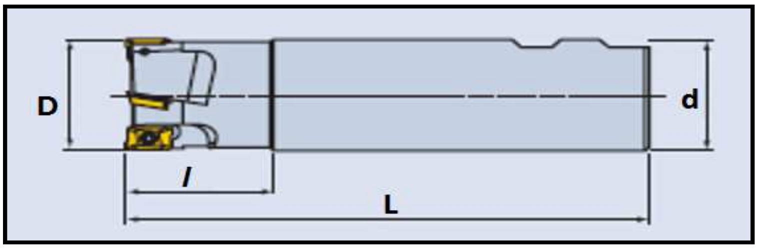


Figure 42: TaeguTec ChaseMill

Figure 43 provides an example of the Somta Carbide End Mill 2 Flute Long Series that was used for finishing the test geometries. For this milling cutter the "d" (10 mm) refers to the cutting edge diameter, "$l_2$" (32 mm) refers to the cutting edge length and "$l_1$" (102 mm) refers to the overall length of the milling cutter.

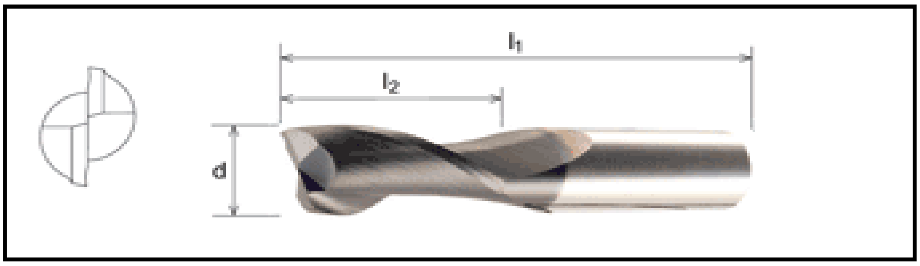


Figure 43: Somta Carbide End Mills – 2 Flute – Long Series

During the initial CAD design stage, the designer should take into consideration the correct specifications and availability of milling cutters as well as when planning the milling pathway since cutters are restricted according to type, width, length and depth of cut (see Addendums 4 and 5).

### 4.5 Data collection: Test and re-test geometries 1- 6

The testing of various geometries in this chapter focuses on the suitability, durability and limitations of Necurite 630 as a milling material in order to determine if it will provide an adequate surface finish and facilitate a high degree of complexity for the manufacturing of the intended vessel prototypes. A range of six test geometries was designed for testing the height-width release ratio for moulding and casting purposes in order to establish design parameters for the vessel forms. Figures 44 to 72 below represent the results of the test geometries in the following order: The CNC milled results, the plaster of Paris moulding test, the plaster of Paris moulding re-test and the slipcasting test. The results will be used to compile data sheets from which interpretations, realizations and insights as well as concluding results will be gathered. The test geometries were designed to examine the overall structural limit of the material in conjunction with the casting processes. The extrusion width of each test geometry increases with 1 mm from 3 mm to 10 mm for all the test geometries. For a structured layout the re-test of the plaster of Paris moulding attempts are discussed under its specific test geometry. In practice different moulding attempts were carried out on the six test geometries for the first test. The best results obtained were applied again as a re-test on all the six test geometries.

### 4.5.1 Test geometry 1

#### 4.5.1.1 CNC milling result – test geometry 1

Test geometry 1 was designed with an extrusion height of 10 mm and no draft. The milling results achieved for test geometry 1 were very good. No extrusions broke off during the milling process and a very smooth surface finish was achieved requiring no additional hand finishing. The edges were very stable and no chips occurred. Figure 44 shows the result for CNC milling test geometry 1.


Figure 44: Test geometry 1 – CNC milling

#### 4.5.1.2 Plaster of Paris mould results – test and re-test geometry 1

<u>Test – test geometry 1</u>

The result proved to be unsuccessful since it was impossible to release the plaster of Paris mould from the CNC milled geometry. Consequently the sides of the mould had to be cut away using a chisel to release the plaster of Paris mould. Figure 45 illustrates the result of the plaster of Paris mould test.

Figure 45: Test geometry 1 – plaster of Paris mould

Re-test – test geometry 1

Results obtained from the first moulding attempts (to be discussed in geometries 3 to 6) reveal that a mould with less surface contact and a harder, denser plaster block provides better results. For the re-test attempt of all the test geometries, a water to plaster ratio was altered from 1:1.5 to a 1:2 mixture. As may be seen in Figure 46, very good results were obtained. The release of the master mould was easily achieved by applying a small amount of pressure while wiggling the plaster of Paris mould from the CNC milled geometry. Figure 46 shows the result of the plaster of Paris mould re-test of geometry 1.

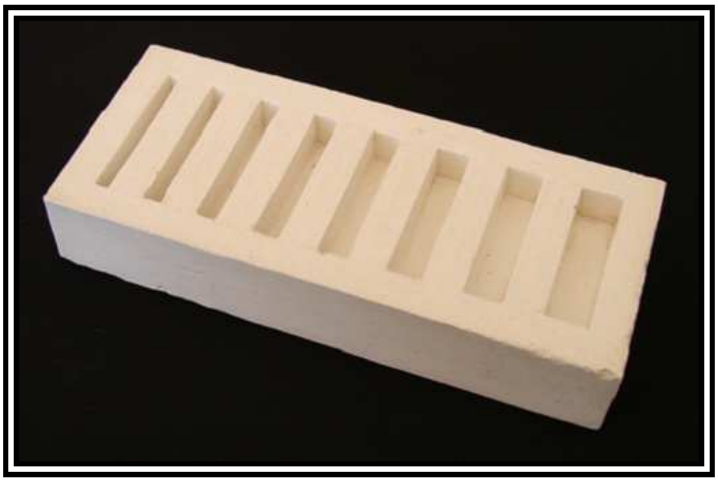

Figure 46: Test geometry 1 – re-test – plaster of Paris mould

#### 4.5.1.3 Slipcasting result – test geometry 1

The 3 mm extrusion broke off during the release of the ceramic body from the plaster of Paris mould. A possible explanation is that a tile or slab-like form tends to curl upwards. The slab-like base of test geometry 1 slightly bent upwards during drying. This might have weaken the area where the 3 mm extrusion is attached to the slab-lake base causing it to break off in an attempt to release the ceramic body from the plaster of Paris mould. The thinner extrusion dries faster than the thicker extrusions because it consists of less clay; therefore the thicker extrusions have time to alter and compensate for the bending of the slab-like base of the test geometry. Figure 47 shows the slipcasting result for test geometry 1.

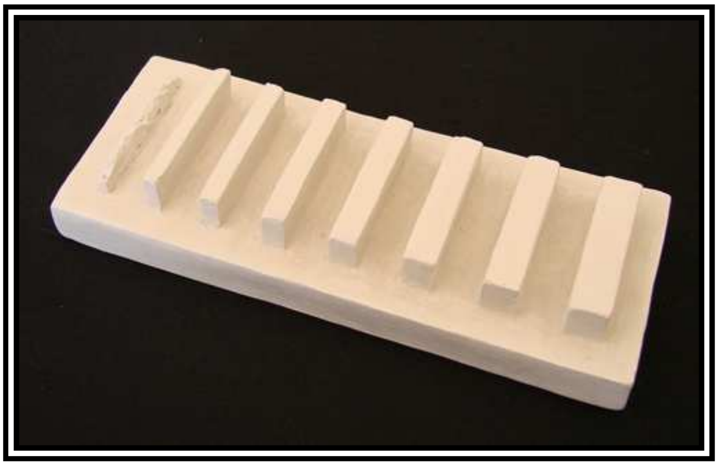

Figure 47: Test geometry 1 – slipcasting

Figure 48 provides a data sheet with information regarding the manufacturing procedures for test geometry 1.

| Test geometry 1: Data sheet – manufacturing procedures | | |
|---|---|---|
| **Milling time and cost results** | | |
| | **Time** | **Cost (ZAR)** |
| Programming time | 40 min | R 116.40 |
| Set-up time | 20 min | R 33.20 |
| Machine time | 17 min | R 85.00 |
| Finishing time | 0 min | R 0.00 |
| **Total** | **1h17** | **R 234.60** |
| | | |
| **Plaster of Paris mould results** | | |
| **Test** | | |
| Water-to-plaster ratio | 1:1.5 | |
| Release agent | Soft soap | |
| Result | Unsatisfactory | |
| | | |
| **Re-test** | | |
| Water-to-plaster ratio | 1:2 | |
| Release agent | Soft soap | |
| Result | Good | |

Figure 48: Test geometry 1: Data sheet – manufacturing procedures

### 4.5.2 Test geometry 2

#### 4.5.2.1 CNC milling result – test geometry 2

Test geometry 2 was designed with an extrusion height of 10 mm and a 1° draft. No extrusions broke off during the milling process and a very smooth surface finish was achieved. Figure 49 shows the result for CNC milling test geometry 2.

Figure 49: Test geometry 2 – CNC milling

#### 4.5.2.2 Plaster of Paris mould results – test and re-test geometry 2

<u>Test – test geometry 2</u>

Since the result of test geometry 1 revealed that a one-piece mould from the milled test geometry was impossible to release, it was decided to partition test geometry 2 into a two part mould. Although the result was successful, it was still difficult to release the plaster of Paris mould parts from the milled test geometry 2. Figure 50 illustrates the result of the plaster of Paris mould test.

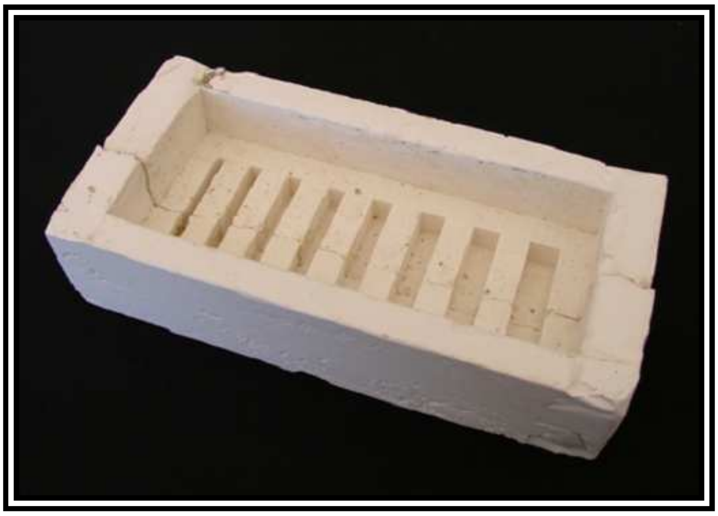

Figure 50: Test geometry 2 – test – plaster of Paris mould

Re-test – test geometry 2

Similar to test geometry 1, the release of the re-test for geometry 2 was easily achieved. Due to the 1° draft, less wiggling was required to release the plaster of Paris mould from the milled geometry. Figure 51 shows the result of the plaster of Paris mould re-test of test geometry 2.

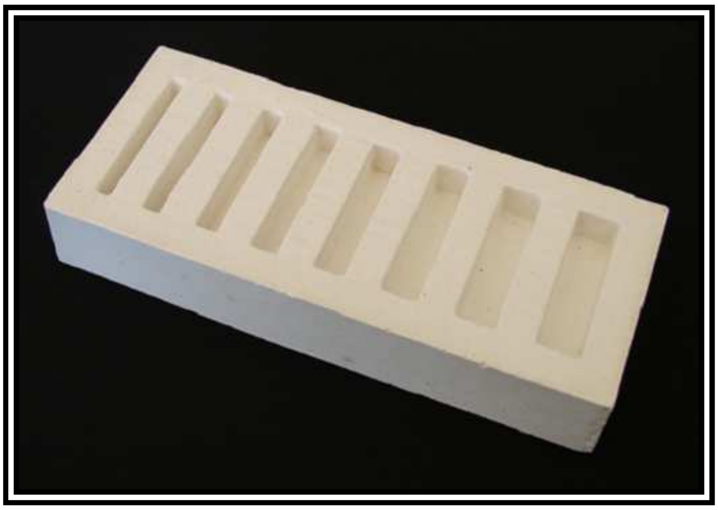

Figure 51: Test geometry 2 – re-test – plaster of Paris mould

#### 4.5.2.3 Slipcasting result – test geometry 2

When releasing the ceramic body from the plaster of Paris mould, the 3 mm extrusion broke off, thus giving the same result as with test geometry 1. At this stage it is conclusive that because of the bending of the slab-like base and the thinner extrusion shrinking faster, causing a weakness, the 3 mm extrusion will subsequently break during the mould release. Figure 52 shows the slipcasting result for test geometry 2.

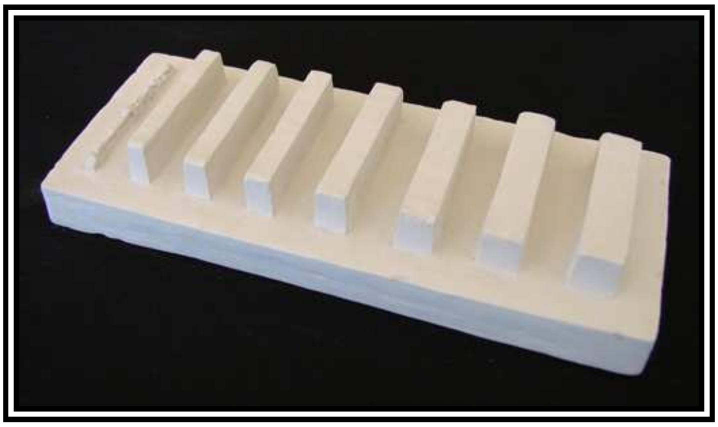

Figure 52: Test geometry 2 – slipcasting

Figure 53 provides a data sheet with information regarding the manufacturing procedures for test geometry 2.

| **Test geometry 2: Data sheet – manufacturing procedures** | | |
|---|---|---|
| **Milling time and cost results** | | |
| | **Time** | **Cost (ZAR)** |
| Programming time | 40 min | R 116.40 |
| Set-up time | 20 min | R 33.20 |
| Machine time | 19 min | R 95.00 |
| Finishing time | 0 min | R 0.00 |
| **Total** | **1h19** | **R 244.60** |
| | | |
| **Plaster of Paris mould results** | | |
| **Test** | | |
| Water-to-plaster ratio | 1:1.5 | |
| Release agent | Soft soap | |
| Result | Reasonable | |
| | | |
| **Re-test** | | |
| Water-to-plaster ratio | 1:2 | |
| Release agent | Soft soap | |
| Result | Good | |

Figure 53: Test geometry 2: Data sheet – manufacturing procedures

### 4.5.3 Test geometry 3

#### 4.5.3.1 CNC milling result – test geometry 3

Test geometry 3 was designed with an extrusion height of 20 mm and no draft. The extrusion with a width of 3 mm broke off during the milling process due to the slight vibration that was caused by the milling machine motor. A very smooth surface finish was achieved. The edges were very stable and no damage occurred resulting in precise 90° edges. Figure 54 shows the result for CNC milling test geometry 3.

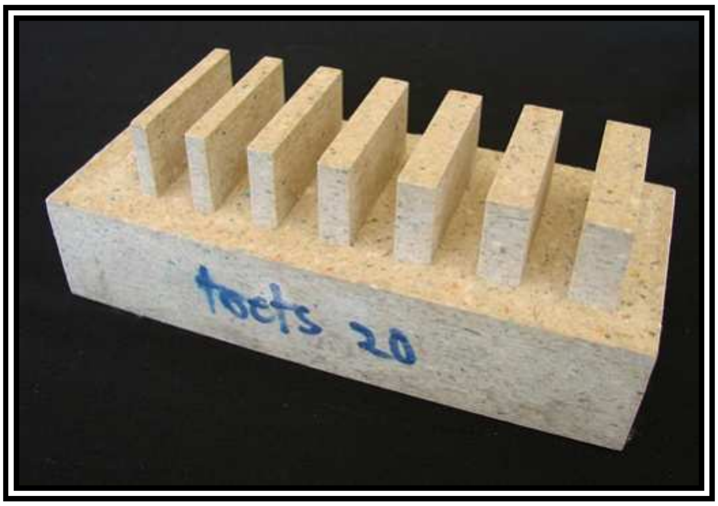


Figure 54: Test geometry 3 – CNC milling

#### 4.5.3.2 Plaster of Paris mould results – test and re-test geometry 3

<u>Test – test geometry 3</u>

With the difficulties of releasing the plaster mould from the milled geometry that occurred with test geometries 1 and 2 it was decided to change the moulding attempt and only mould over the extrusions and the slab surface to which the extrusions are attached in order to reduce the contact surface and aid in releasing. Figure 55 shows a drawing of the changed moulding attempt. As in the case of test geometry 1 and 2, the sides of the plaster mould extend to the sides of the milled Necurite 630 block by approximately 10 mm which made it difficult to release. For test geometries 3 to 6 it was decided to change the moulding attempt and to mould only the vertical extrusions.

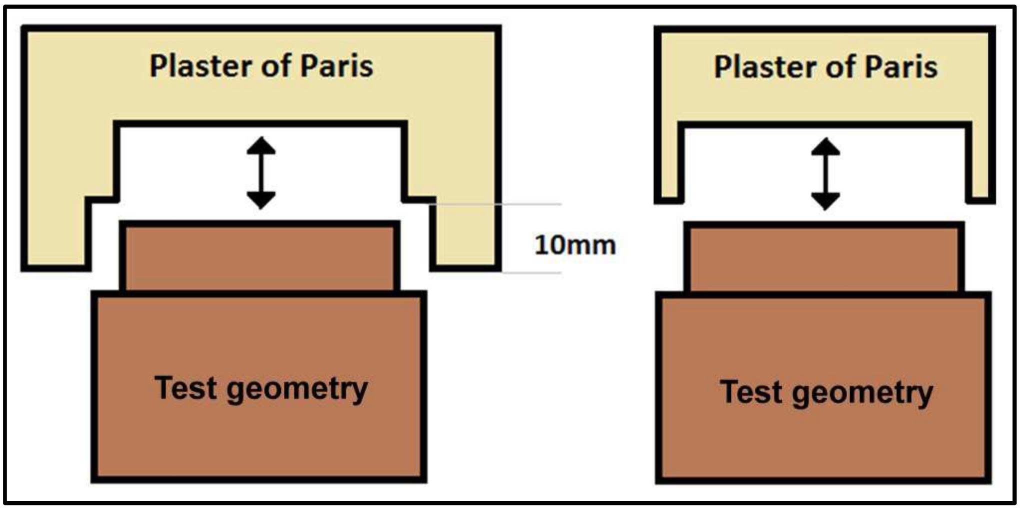


Figure 55: Plaster of Paris moulding attempts

Figure 56 illustrates the result of the plaster of Paris mould test for test geometry 3 with the changed moulding method.

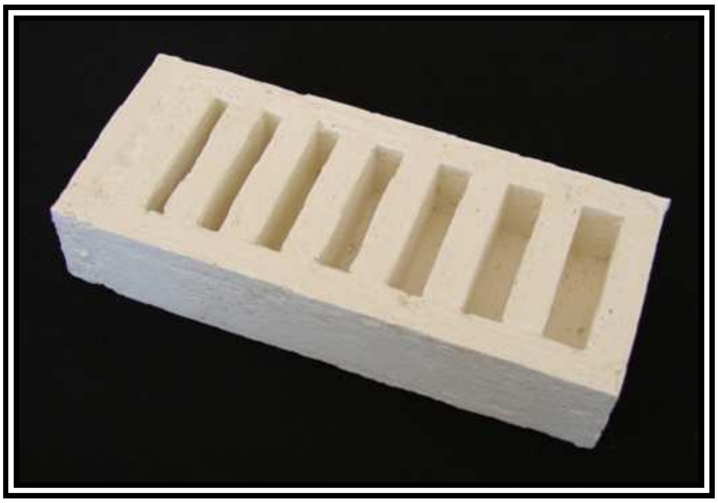

Figure 56: Test geometry 3 – test – plaster of Paris mould

Re-test – test geometry 3

For the re-test of test geometry 3 the result achieved when releasing the plaster mould from the milled geometry was satisfactory. It was nonetheless more difficult to release the mould in comparison to test geometry 1 and 2 because of the deeper extrusions. Figure 57 shows the result of the plaster of Paris mould re-test for test geometry 3.

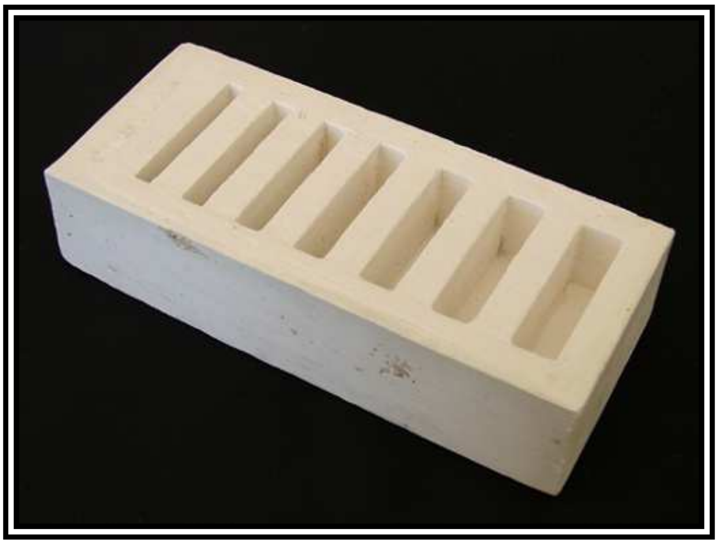

Figure 57: Test geometry 3 – re-test – plaster of Paris mould

#### 4.5.3.3 Slipcasting result – test geometry 3

With test geometry 3 the same result was obtained as with test geometries 1 and 2. The slab-like base bent upwards on drying causing the 4 mm extrusion to break off during the release of the ceramic body from the plaster of Paris mould. Figure 58 shows the slipcasting result for test geometry 3.

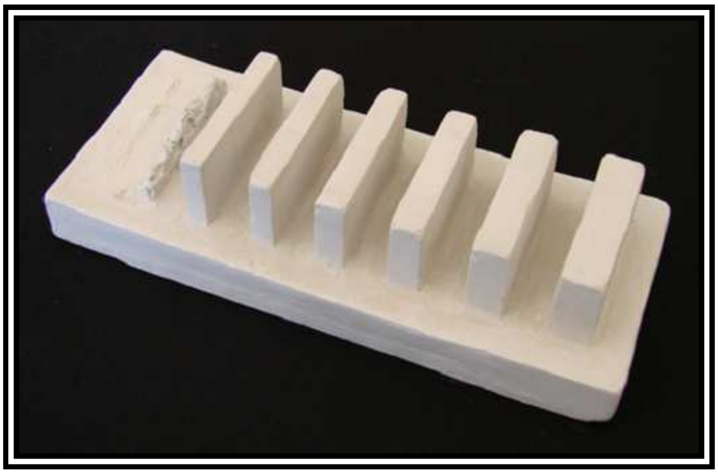

Figure 58: Test geometry 3 – slipcasting

Figure 59 provides a data sheet with information regarding the manufacturing procedures for test geometry 3.

| **Test geometry 3: Data sheet – manufacturing procedures** | | |
|---|---|---|
| **Milling time and cost results** | | |
| | **Time** | **Cost (ZAR)** |
| Programming time | 40 min | R 116.40 |
| Set-up time | 20 min | R 33.20 |
| Machine time | 39 min | R 195.00 |
| Finishing time | 0 min | R 0.00 |
| **Total** | **1h39** | **R 344.60** |
| | | |
| **Plaster of Paris mould results** | | |
| **Test** | | |
| Water-to-plaster ratio | 1:1.5 | |
| Release agent | Soft soap | |
| Result | Satisfactory | |
| | | |
| **Re-test** | | |
| Water-to-plaster ratio | 1:2 | |
| Release agent | Soft soap | |
| Result | Good | |

Figure 59: Test geometry 3: Data sheet – manufacturing procedures

### 4.5.4 Test geometry 4

#### 4.5.4.1 CNC milling result – test geometry 4

Test geometry 4 was designed with an extrusion height of 20 mm and a 1° draft. The milling result shows that the extrusion with a base width of 3 mm broke off during the milling process due to vibration. The surface finish was very smooth with excellent edge stability. Figure 60 shows the result for CNC milling test geometry 4.


Figure 60: Test geometry 4 – CNC milling

#### 4.5.4.2 Plaster of Paris mould results – test and re-test geometry 4

<u>Test – test geometry 4</u>

The same moulding attempt was used for test geometries 3 and geometry 4 and satisfactory results were obtained. It was easier to release the mould cast from the milled geometry 4 compared to test geometry 3 due to the 1° draft. Figure 61 illustrates the result of the plaster of Paris mould test.

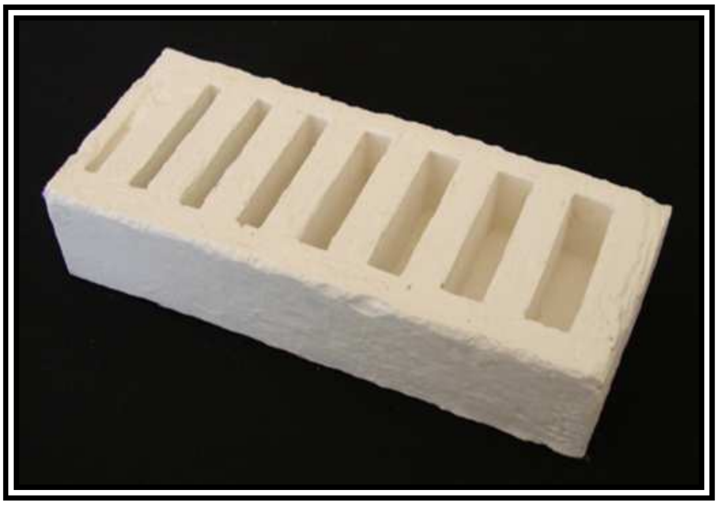

Figure 61:  Test geometry 4 – test – plaster of Paris mould

Re-test – test geometry 4

The re-test of test geometry 4 yielded excellent results with no damage caused to the plaster of Paris mould.  Figure 62 shows the result of the plaster of Paris mould re-test for test geometry 4.

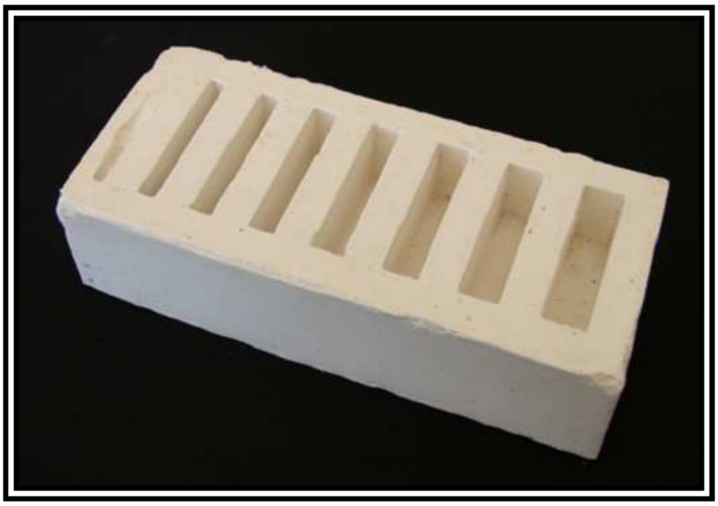

Figure 62: Test geometry 4 – re-test – plaster of Paris mould

#### 4.5.4.3 Slipcasting result – test geometry 4

The 4 mm extrusion broke off during the release of the ceramic body from the plaster of Paris mould. As with test geometry 1, 2 and 3 the slab-like base bent upwards causing the 4 mm extrusion to break off. Figure 63 shows the slipcasting result for test geometry 4.

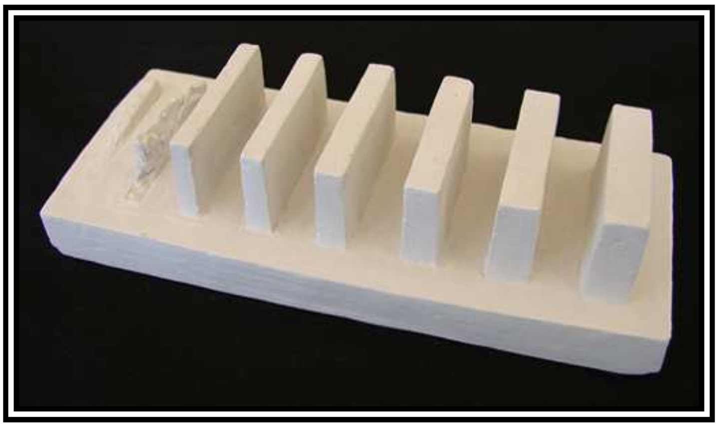

Figure 63: Test geometry 4 – slipcasting

Figure 64 provides a data sheet with information regarding the manufacturing procedures for test geometry 4.

| Test geometry 4: Data sheet – manufacturing procedures | | |
|---|---|---|
| **Milling time and cost results** | | |
| | **Time** | **Cost (ZAR)** |
| Programming time | 40 min | R 116.40 |
| Set-up time | 20 min | R 33.20 |
| Machine time | 44 min | R 220.00 |
| Finishing time | 0 min | R 0.00 |
| **Total** | **1h44** | **R 369.60** |
| | | |
| **Plaster of Paris mould results** | | |
| **Test** | | |
| Water-to-plaster ratio | 1:1.5 | |
| Release agent | Soft soap | |
| Result | Satisfactory | |
| | | |
| **Re-test** | | |
| Water-to-plaster ratio | 1:2 | |
| Release agent | Soft soap | |
| Result | Good | |

Figure 64: Test geometry 4: Data sheet – manufacturing procedures

### 4.5.5 Test geometry 5

#### 4.5.5.1 CNC milling result – test geometry 5

Test geometry 5 was designed with an extrusion height of 30 mm and no draft. The milling result for geometry 5 shows that the extrusions with respectively a width of 3 mm and 4 mm broke off during the finishing operation of the milling process due to vibration. However, the 5 mm extrusion broke off during the release of the plaster of Paris mould from the milling geometry and not during the milling process itself. A very smooth surface finish was achieved on the remaining extrusions. Figure 65 shows the result for CNC milling test geometry 5.

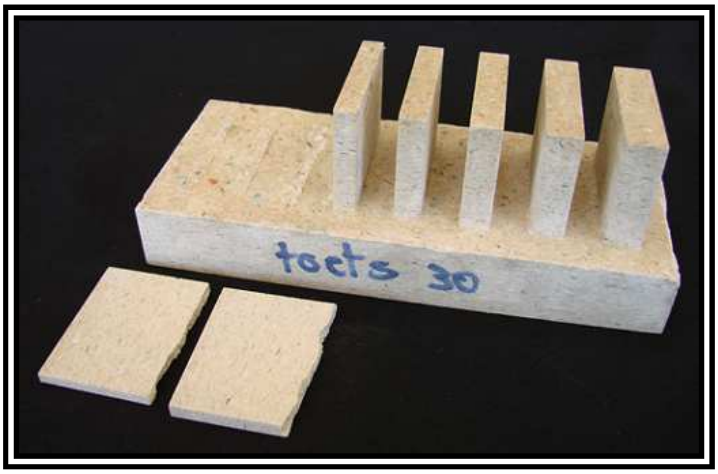


Figure 65: Test geometry 5 – CNC milling

#### 4.5.5.2 Plaster of Paris mould results – test and re-test geometry 5

<u>Test – test geometry 5</u>

It was decided to change the moulding attempt and to mix a softer plaster of Paris block (water to plaster ratio of 1:1) in order to ascertain whether a lower density plaster block might result in easier releasing. The result, however, was that the softer plaster of Paris block crumbled into pieces with the slightest pressure applied. Figure 66 illustrates the result of the plaster of Paris mould test for test geometry 5.

Figure 66: Test geometry 5 – test – plaster of Paris mould

Re-test – test geometry 5

For the re-test of test geometry 5 a water to plaster ratio of 1:2 was used. Although the plaster of Paris mould was released from the milled geometry without any damage, it was extremely difficult to release the mould. It took a number of minutes and a great deal of pressure to release the mould and as a result the 5 mm extrusion broke off. Figure 67 shows the result of the plaster of Paris mould re-test for test geometry 5.

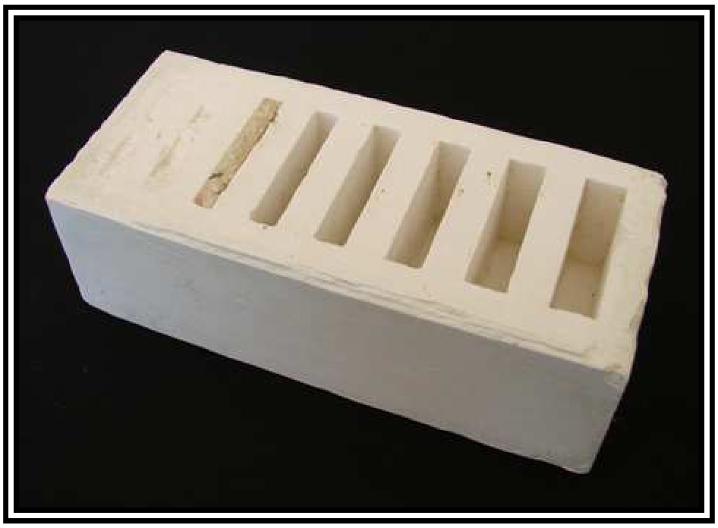

Figure 67: Test geometry 5 – re-test – plaster of Paris mould

#### 4.5.5.3 Slipcasting result – test geometry 5

In an attempt to obtain better results the slipcasting body was removed sooner from the plaster mould. A slipcasting should not be removed from a plaster of Paris mould if the clay body is not sufficiently dry because handling the body may cause damage. Unfortunately, as with the 5 mm extrusion regarding test geometry 4, the 6 mm extrusion also broke off during the release of the ceramic body from the plaster of Paris mould. Although the slip body was left to dry properly and not handled, due to limited surface adherence, the remaining extrusions unfortunately warped slightly while drying. Furthermore, as a result of clay that was stuck in the corners of the plaster mould, the edges of the extrusions of the slipcast body were poorly formed. Recommendations with a view on solving these problems will be discussed in section 4.6.3 below. Figure 68 shows the slipcasting result for test geometry 5.

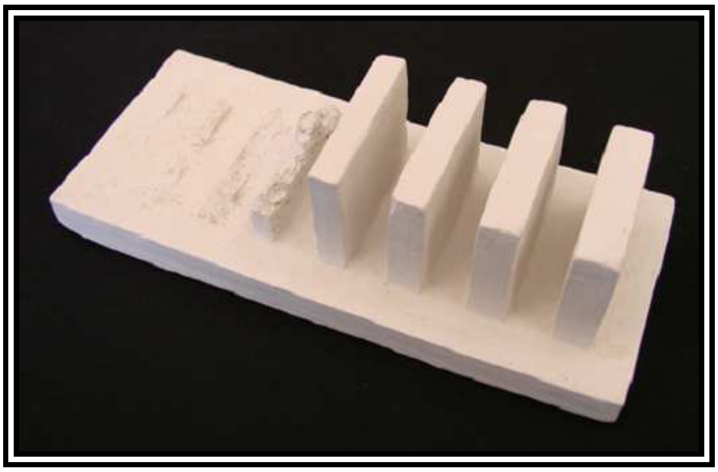

Figure 68: Test geometry 5 – slipcasting

Figure 69 provides a data sheet with information regarding the manufacturing procedures for test geometry 5.

| Test geometry 5: Data sheet – manufacturing procedures | | |
|---|---|---|
| **Milling time and cost results** | | |
| | **Time** | **Cost (ZAR)** |
| Programming time | 40 min | R 116.40 |
| Set-up time | 20 min | R 33.20 |
| Machine time | 63 min | R 315.00 |
| Finishing time | 0 min | R 0.00 |
| **Total** | **2h03** | **R 464.60** |
| | | |
| **Plaster of Paris mould results** | | |
| **Test** | | |
| Water-to-plaster ratio | 1:1 | |
| Release agent | Soft soap | |
| Result | Unsatisfactory | |
| | | |
| **Re-test** | | |
| Water-to-plaster ratio | 1:2 | |
| Release agent | Soft soap | |
| Result | Good | |

Figure 69: Test geometry 5: Data sheet – manufacturing procedures

### 4.5.6 Test geometry 6

#### 4.5.6.1 CNC milling result – test geometry 6

Test geometry 6 was designed with an extrusion height of 30 mm and a 1° draft. The milling result for geometry 6 shows that during the finishing process the extrusions with respectively a 3 mm, 4 mm and 5 mm base width broke off during the milling process. A very smooth surface finish was achieved on the remaining fins. Figure 70 shows the result for CNC milling test geometry 6.


Figure 70: Test geometry 6 – CNC milling

#### 4.5.6.2 Plaster of Paris mould results – test and re-test geometry 6

<u>Test – test geometry 6</u>

The same method (a softer plaster block; water to plaster ratio of 1:1) as used with test geometry 5 was applied for geometry 6 in order to see if a 1° draft would obtain better releasing results; similar results, however, were achieved. With slight pressure the plaster of Paris mould crumbled into pieces. Figure 71 illustrates the result of the plaster of Paris mould test for test geometry 6.

Figure 71: Test geometry 6 – test – plaster of Paris mould

Re-test – test geometry 6

With the re-test the plaster of Paris mould was released from the master mould without any damage. The release difficulty was moderate, but with a 1° draft far easier than releasing test geometry 5. Figure 72 shows the result of the plaster of Paris mould re-test for test geometry 6.

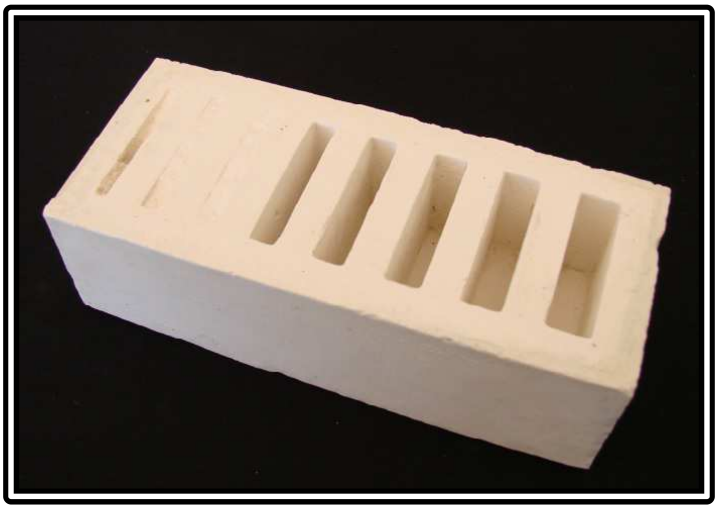

Figure 72: Test geometry 6 – re-test – plaster of Paris mould

#### 4.5.6.3 Slipcasting result – test geometry 6

As with test geometry 5 the release of geometry 6 was done slightly before the slipcast body was dry. Due to a 1° draft and less shrinkage no extrusions broke off during the release of the ceramic body from the plaster of Paris mould. Slip that got stuck in the corners of the mould caused the edges of the extrusions to be damaged. Due to there being no support for the extrusions, they warped slightly during drying. A recommendation to address these problems is put forward in section 4.6.3 below. Figure 73 shows the slipcasting result for test geometry 6.

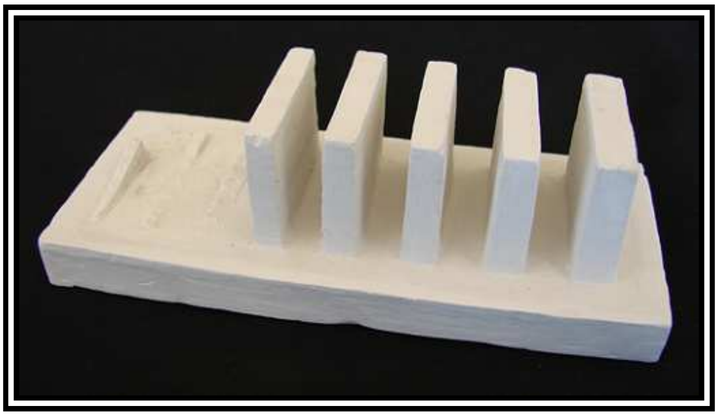

Figure 73: Test geometry 6 – slipcasting

Figure 74 provides a data sheet with information regarding the manufacturing procedures for test geometry 6.

| **Test geometry 6: Data sheet – manufacturing procedures** | | |
|---|---|---|
| **Milling time and cost results** | | |
| | **Time** | **Cost (ZAR)** |
| Programming time | 40 min | R 116.40 |
| Set-up time | 20 min | R 33.20 |
| Machine time | 69 min | R 345.00 |
| Finishing time | 0 min | R 0.00 |
| **Total** | **2h09** | **R 494.60** |
| | | |
| **Plaster of Paris mould results** | | |
| **Test** | | |
| Water-to-plaster ratio | 1:1 | |
| Release agent | Soft soap | |
| Result | Unsatisfactory | |
| | | |
| **Re-test** | | |
| Water-to-plaster ratio | 1:2 | |
| Release agent | Soft soap | |
| Result | Good | |

Figure 74: Test Geometry 6: Data sheet – manufacturing procedures

## 4.6 Data analysis and interpretation

Data was compiled and collated from the individual data sheets to compare the individual test geometries to one another.

### 4.6.1 Milling results of Necurite 630 for the test geometries 1 - 6

Figure 75 below provides a graph indicating the time required for each step in the milling process for each of the six test geometries. The steps in the milling process include the set-up time, program time and the machine time.

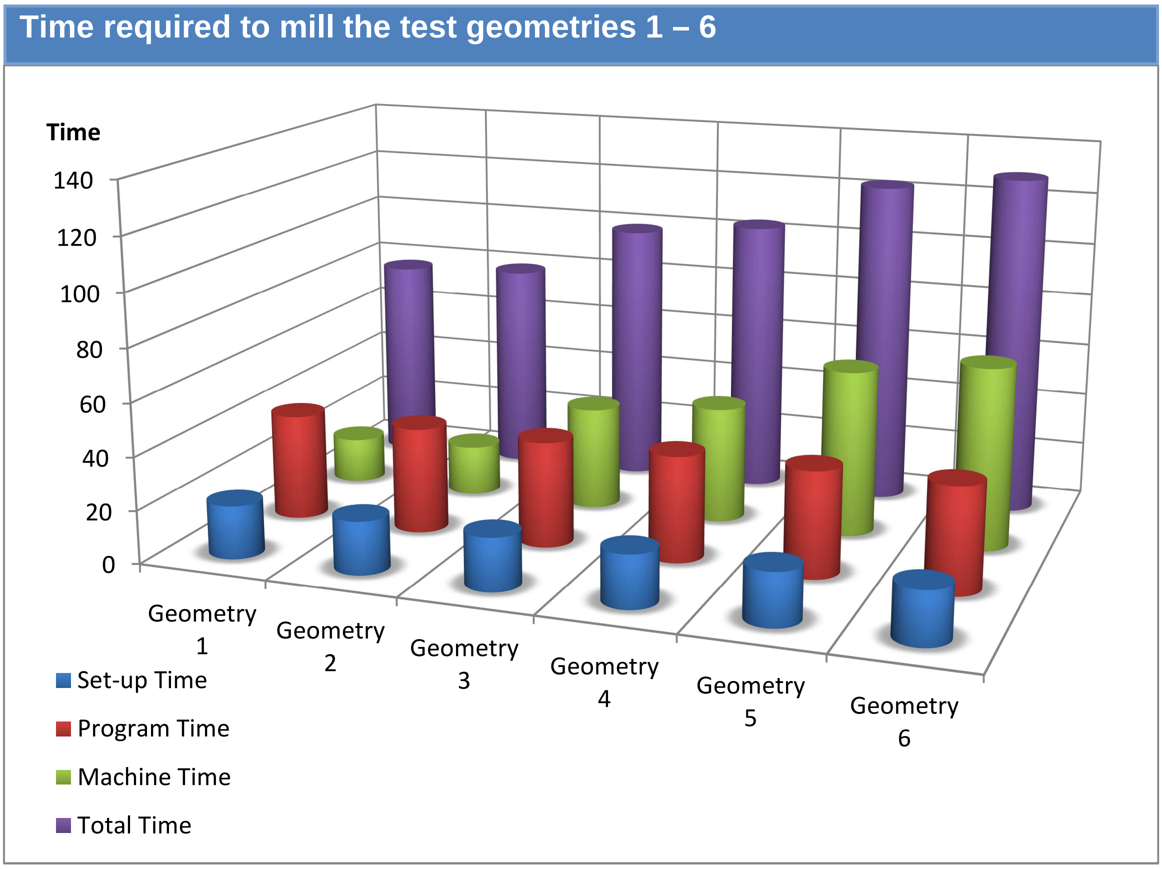


Figure 75: Time required to mill the test geometries 1 – 6

Figure 76 below provides a graph for the respective test geometries indicating the costs related to each step in the milling process with the correlating colours assigned to Figure 75 above.

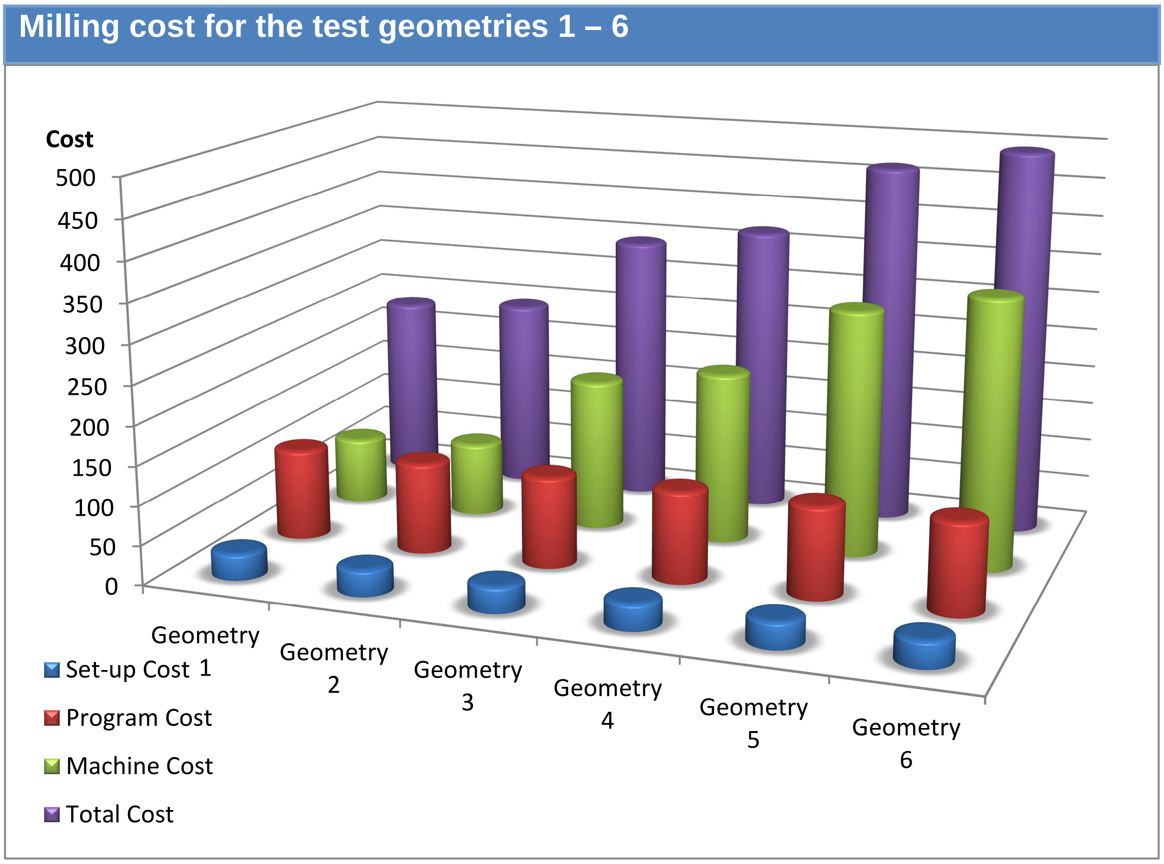


Figure 76: Milling cost for the test geometries 1 – 6

Figure 76 indicates that it takes longer to remove more material as can be seen by the increase in machine time between test geometry 1, 3 and 5. There is a clear correlation between the machine time and the volume of material that needs to be removed. A slight increase in machine time is also evident when a 1° draft is added to the test geometries; this indicates that more complex forms will take longer to mill. Due to the smooth surface finish that was obtained during the machine step, no extra finishing was necessary on the test geometries and therefore resulted in no additional finishing time and costs.

Figure 77 below provides a comprehensive data sheet for the milling results of the six test geometries indicating (by means of a red cross) the extrusions that broke off during the milling process.

| Data sheet: Test geometries – milling results | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Extrusion height (mm) | Draft | Extrusion Width (mm) | | | | | | | |
| | | | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Test geometry 1 | 10 | 0° | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Test geometry 2 | 10 | 1° | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Test geometry 3 | 20 | 0° | ✗ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Test geometry 4 | 20 | 1° | ✗ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Test geometry 5 | 30 | 0° | ✗ | ✗ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Test geometry 6 | 30 | 1° | ✗ | ✗ | ✗ | ✓ | ✓ | ✓ | ✓ | ✓ |

Figure 77: Data sheet: Test geometries – milling results

The project engineer explained that the thin extrusions broke off due to the slight vibration caused by the milling machine. The longer the extrusion the more susceptible it is to breaking. The milling results indicate that with a height of 10 mm and a 1° draft, the width of a part within a design can be as small as 3 mm. With a height of 20 mm and a 1° draft, the width of the smallest part or section within a design should not be smaller than 4 mm. With an extrusion height of 30 mm and no draft, the width of the smallest part or section of the design should be at least 5 mm. With a 1° draft and a height of 30 mm, the smallest part or section should be at least 6 mm. The test geometries reveal that Necurite 630 tooling boards as a milling material worked exceptionally well. Excellent milling results were achieved with the test geometries. With Necurite 630 a very smooth surface finish was achieved within a reasonable milling time. The geometries were designed to test the limits of the milling material and as expected some of the thinner extrusions broke off during the milling process.

### 4.6.2 Summary: Plaster of Paris moulding results for the test geometries 1 – 6

The plaster of Paris moulds of the milled test geometries required a few trial and error runs. Gradual variances in test geometries 1 to 6 were designed to test the overall limits of both the milling and moulding process. Different moulding attempts were applied in order to explore a suitable moulding approach. Figure 78 provides a data sheet of the plaster of Paris moulding results for the six test geometries. A black addition symbol indicates that the extrusion broke off during the milling process and could thus not form part of the testing during the moulding process. A red cross indicates that the **release** attempt of the plaster of Paris mould from the milled geometries were unsuccessful.

| **Data sheet: Test geometries 1 – 6 – moulding results (test)** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Extrusion height (mm) | Draft | Extrusion Width (mm) | | | | | | | |
| | | | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Test geometry 1 | 10 | 0° | ✗ | ✗ | ✗ | ✗ | ✗ | ✗ | ✗ | ✗ |
| Test geometry 2 | 10 | 1° | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Test geometry 3 | 20 | 0° | ✚ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Test geometry 4 | 20 | 1° | ✚ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Test geometry 5 | 30 | 0° | ✚ | ✚ | ✗ | ✗ | ✗ | ✗ | ✗ | ✗ |
| Test geometry 6 | 30 | 1° | ✚ | ✚ | ✚ | ✗ | ✗ | ✗ | ✗ | ✗ |

Figure 78: Data sheet: Test geometries 1 – 6 – plaster of Paris moulding results (test)

Figure 78 reveals that test geometry 1 was unsuccessful and proved unsuccessful to release the plaster of Paris mould, resulting in the sides of the plaster mould having to be carved away using a chisel. Although the result of test geometry 2 was successful, it was also difficult to release the plaster of Paris mould. As discussed in Figure 55 (cf. Chapter 4.5.3.2) the changed moulding method yielded successful results for test geometries 3 to 6. It was decided to use the same moulding approach but to mix a softer plaster of Paris block for test geometries 5 and 6 in order to ascertain whether a lower density (1:1 water to plaster ratio) plaster block might result in easier releasing. The result in both cases was that the less dense (softer) plaster of Paris block crumbled into pieces when the slightest pressure was applied.

Figure 79 provides a data sheet for the plaster of Paris moulding re-test results of the six test geometries. As with the previous data sheets, a black addition symbol indicates that the extrusion broke off during the milling process and could not be tested during the casting process. A red cross indicates that the extrusion broke off during the moulding process.

| **Data sheet: Test geometries – moulding results (re-test)** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Extrusion height (mm) | Draft | Extrusion Width (mm) | | | | | | | |
| | | | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Test geometry 1 | 10 | 0° | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Test geometry 2 | 10 | 1° | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Test geometry 3 | 20 | 0° | ✚ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Test geometry 4 | 20 | 1° | ✚ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Test geometry 5 | 30 | 0° | ✚ | ✚ | ✗ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Test geometry 6 | 30 | 1° | ✚ | ✚ | ✚ | ✓ | ✓ | ✓ | ✓ | ✓ |

Figure 79: Data sheet: Test geometries 1 – 6 – plaster of paris moulding results (re-test)

For the re-test attempt it was decided to change the water-to-plaster ratio to 1:2 in order to achieve a more dense (harder) plaster geometry. Except for test geometry 5 where the 5 mm extrusion broke off, all the other test geometries yielded successful results. The test geometries with no draft were more difficult to release and in the case of test geometry 5 the extrusion was too thin to handle the pressure caused by the release process. From the moulding results it is clear that more dense plaster yielded better results. Since acceptable results were achieved with the re-test attempt, it was deemed unnecessary that further plaster density tests be conducted.

Figure 80 presents a table indicating the height-width release ratio with a difficulty-rating for the second plaster of Paris moulding attempt. On a scale from 1 to 5, 1 indicates extremely difficult release while 5 indicates easy release. Figures 79 and 80 indicate that a draft of at least 1° should be used on areas deeper than 10 mm to enable and facilitate a successful release.

| Release rating – re-test attempt | | | | | | |
|---|---|---|---|---|---|---|
| | **Block 1** 10 mm 0° | **Block 2** 10 mm 1° | **Block 3** 20 mm 0° | **Block 4** 20 mm 1° | **Block 5** 30 mm 0° | **Block 6** 30 mm 1° |
| **Release rating** | 4 | 5 | 2 | 3 | 1 | 2 |

Figure 80: Release rating – re-test attempt (1 indicates difficult release and 5 indicates easy release)

### 4.6.3 Slipcasting results for the test geometries 1 – 6

Figure 81 below provides a table reflecting the data analysis of the slipcasting results. A black addition symbol indicates that there was no result from which to obtain information because the extrusions broke off during the milling and or moulding process and a red cross indicates unsuccessful results obtained during the slipcasting process because the extrusion broke off.

| **Data sheet: Test geometries 1 – 6 – slipcasting results** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Extrusion height (mm) | Draft | Extrusion Width (mm) | | | | | | | |
| | | | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Test geometry 1 | 10 | 0° | ✘ | ✔ | ✔ | ✔ | ✔ | ✔ | ✔ | ✔ |
| Test geometry 2 | 10 | 1° | ✘ | ✔ | ✔ | ✔ | ✔ | ✔ | ✔ | ✔ |
| Test geometry 3 | 20 | 0° | ✚ | ✘ | ✔ | ✔ | ✔ | ✔ | ✔ | ✔ |
| Test geometry 4 | 20 | 1° | ✚ | ✘ | ✔ | ✔ | ✔ | ✔ | ✔ | ✔ |
| Test geometry 5 | 30 | 0° | ✚ | ✚ | ✚ | ✘ | ✔ | ✔ | ✔ | ✔ |
| Test geometry 6 | 30 | 1° | ✚ | ✚ | ✚ | ✔ | ✔ | ✔ | ✔ | ✔ |

Figure 81: Data sheet: Test geometries 1 – 6 – slipcasting results

Figure 81 indicates that during the slipcasting process the thinnest extrusion of most of the test geometries, with the exception of test geometry 6, broke off. The results of the slipcasting of the test geometries reveal that the solidification time is different between the thinner and thicker extrusions. The thinner extrusions dry faster than the thicker extrusions. In addition, the slip blocks had to be removed before the thicker extrusions were sufficiently dry to ensure that the other thin extrusions did not shrink too much and break off during the release process. The outcome was a slightly uneven (wobbly) shrinkage of the thicker extrusions, especially on the test geometries with an extrusion height of more than 10 mm. The 1° angle allowed for an easier release permitting the 6mm extrusion of test geometry 6 to release without breaking off. Furthermore the sharp 90° corners of the plaster of Paris moulds caused the edges of the ceramic body extrusions to chip. It is recommended that for moulding and casting purposes a fillet (rounding) is added to the edges of the prototype design to improve results. To obtain best results, it appears that the variation between extruding parts within a design should not substantially differ in thickness.

## 4.7 Design and production parameters

From the above test results the following design and production parameters are recommended:

- Design parts extruding 10 mm must be at least 4 mm wide
- Design parts extruding 20 mm must be at least 5 mm wide
- Design parts extruding 30 mm must be at least 7 mm wide
- Avoid sharp edges in the design
- Fillet (rounding) all edges within the design
- Avoid designing different extruded parts with substantial width differences in a single design
- Within the design a draft of at least 1° should be added to areas deeper than 10 mm
- A water-to-plaster ratio of 1:2 should be used
- Release the slipcast body early to ensure flexibility during release

## 4.8 Conclusion

The accuracy obtained on the CNC milled test geometries is of a high standard. Compared to traditional methods it would be almost impossible to achieve such accuracy using manual hand skills. Due to the precision achieved in the test geometries, precise and accurate plaster of Paris moulds could be made which resulted in a range of successful slipcasting results. This chapter reflects on the use of CNC milling as an accelerated manufacturing technology. In particular it addresses the benefits, limitations and the role of CNC milling as an optimal digital manufacturing technology available to the studio ceramicist. It has established relevant CAD design and CNC milling manufacturing parameters regarding the technical aspects that the studio ceramicist would need to familiarize him- or herself with. This chapter furthermore offered a practical evaluation on select materials and established Necurite 630 as a suitable cost-effective milling material. The aforementioned design and manufacturing parameters will further be applied to the development of a range of final vessel prototypes and the manufacture of plaster of Paris master moulds, the results thereof to be discussed in Chapter 5.

# Chapter 5

# Vessel prototype and master mould testing and analysis

## 5.1 Overview

Testing of a range of geometries has shown that the automated process of CAD and CNC milling can successfully be used to fulfil the studio ceramicist's design and manufacture intention to develop master moulds for the batch production of intricate ceramic vessel forms, thus replacing the current labour-intensive and time-consuming manual working processes. This chapter aims to batch test and analyse the design, prototyping and master moulding of vessel forms in order to determine cost-effectiveness, technical aspects and the overall product-to-market lead time cycle.

## 5.2 Introduction

In order to achieve high rigour and control throughout the study, SolidWorks® CAD software and the same 3-axis CNC milling machine (see Chapter 3.5 above) were used for the final application of the findings from the test results. A range of geometric vessel forms varying in degree of complexity were designed with the objective being to measure overall product development time to establish an alternative to traditional methods. Below examines the determining aspects and their impact on the accelerated manufacture of ceramic master moulds, i.e. flexibility, complexity, accuracy and scale. In this chapter the three secondary objectives of the study are collectively explored through the designing of four different vessel form geometries. Each vessel form will address one of the four aspects, i.e. flexibility, complexity, accuracy and scale. The action research steps, i.e. plan, act, observe and reflect, are used to individually explore each objective and related aspect. The chapter demonstrates the overall cost-effectiveness when utilizing the above-mentioned technologies through presenting findings that show a significant reduction in design and manufacturing time when integrating emerging technologies within ceramics studio practice. An addendum of additional design geometries is included at the end of the dissertation.

## 5.3 Vessel prototype development

### 5.3.1 Lofted vessel 1: Flexibility

**Plan**: With this prototype the objective is to apply SolidWorks® and CNC milling to determine to what extent CAD and CAM as design and manufacturing technologies support the ceramicist to make frequent and fast changes to a design. As previously mentioned, in a technology-driven market the ability to effect frequent changes to a design is an important aspect for the studio ceramicist wanting to batch produce a range of unique artefacts.

#### 5.3.2.1 3-D CAD design: Lofted vessel 1

**Act**: The original vessel form presented in Figure 82 was created by drawing 4 circles on different planes and by connecting each circle with four standard guide curves. The guide curves on the front and right plane is connected to the apex of each circle on the plane. The shape of the guide curves is parabolic and inwards to the centre of the design. The Lofted Boss/Base tool feature (see Figure 83) was used on the guide curves to form a round 3-D parabolic shape that connects the circles. Figure 82 illustrates the design for Lofted vessel 1 with measurements of 115 mm x 100 mm x 250 mm.

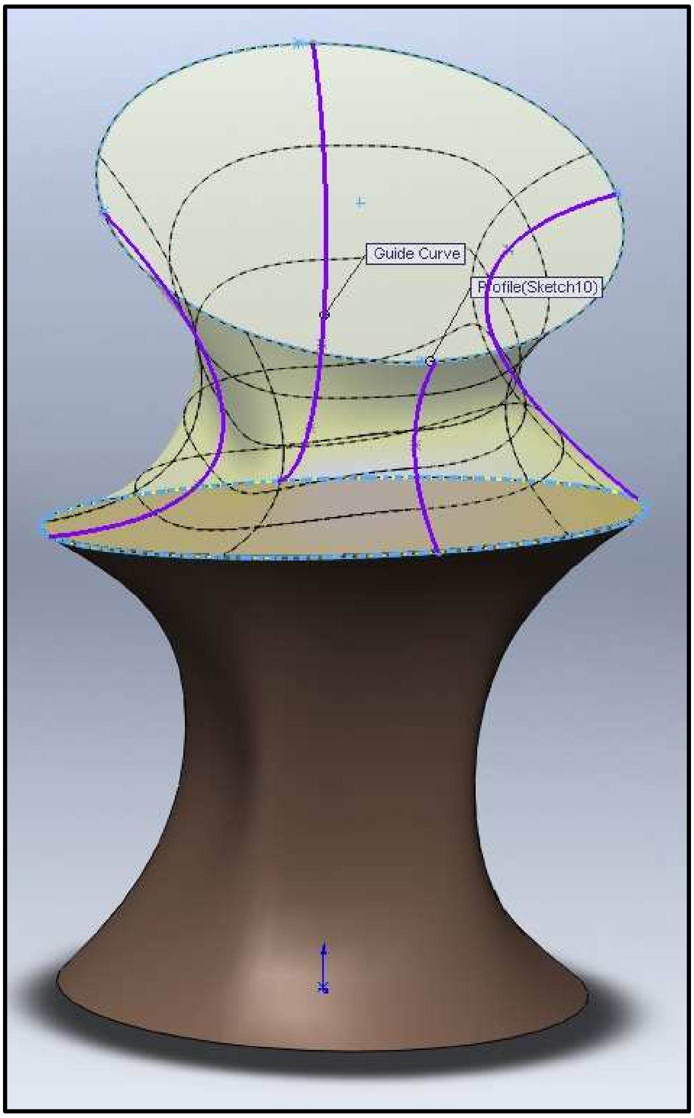


Figure 82: Lofted vessel 1: CAD design, 115 mm x 100 mm x 250 mm

To modify the design it was decided to use the 3-D sketching capability of SolidWorks®. The 3-D sketch capability allows the designer to modify a design using the mouse without changing exact measurements. It is possible for the designer to drag points on a plane to a different position without specifying specific X, Y and Z coordinates. The shape and form of the design will change visually while the points are dragged. This is especially useful for artists since an artist is normally concerned about the form and shape of an artefact, and not so much about the exact measurements that engineers normally require. This allows the designer to freely explore different shapes and forms by easily modifying existing designs. Features in SolidWorks® that ensure that a design is valid and that it does not have undercuts further allow for freedom of design since the designer does not have to technically analyse a design, but can test a design for correctness after visual creation. The feature to test for undercuts will be illustrated later in this chapter.

To achieve Modification 1 of the lofted vessel form, the 3-D sketch capability of SolidWorks® was used to drag each guide curve narrower (towards the centre line) on the right plane. It was planned to only modify the angle of the guide curves and not the size of the circles and their angle. Dragging the guide curves towards the centre line caused the lofted vessel form to narrow and create sharper angles and more pronounced edges while maintaining their parabolic shape. The same process was used to achieve the results for Modification 2. While the guide curves in Modification 1 was dragged narrower, towards the centre line, the guide curves were dragged away from the centre line in Modification 2 to create a round shape. Again the parabolic shape was maintained.


Figure 83: Diagram of shaped-based features

Below, Figures 86 and 87 illustrate design changes to the original design, referred to as Modification 1, and Figures 88 and 89 illustrate design changes to the original design, referred to as Modification 2.

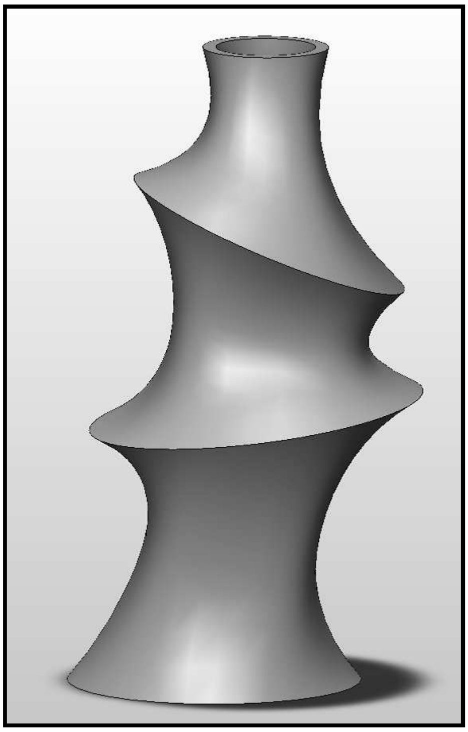

Figure 84: Lofted vessel 1 – original design – front view

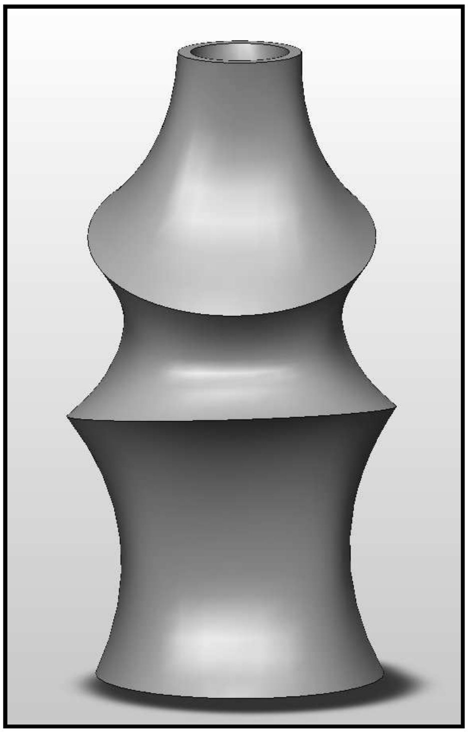

Figure 85: Lofted vessel 1 – original design – right view

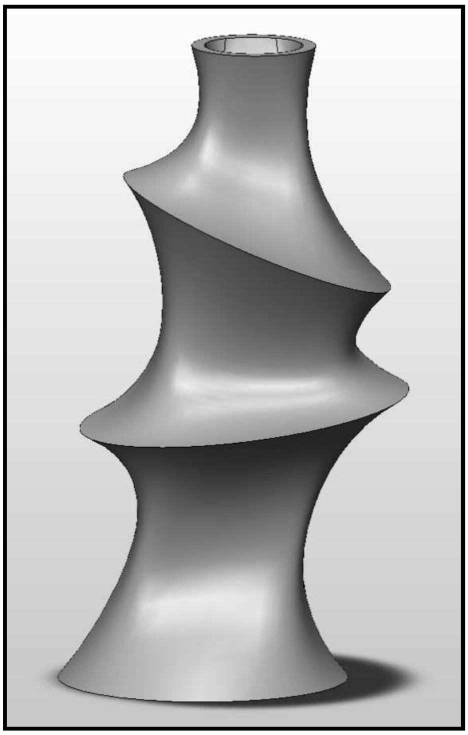

Figure 86: Lofted vessel 1 – modification 1 – front view

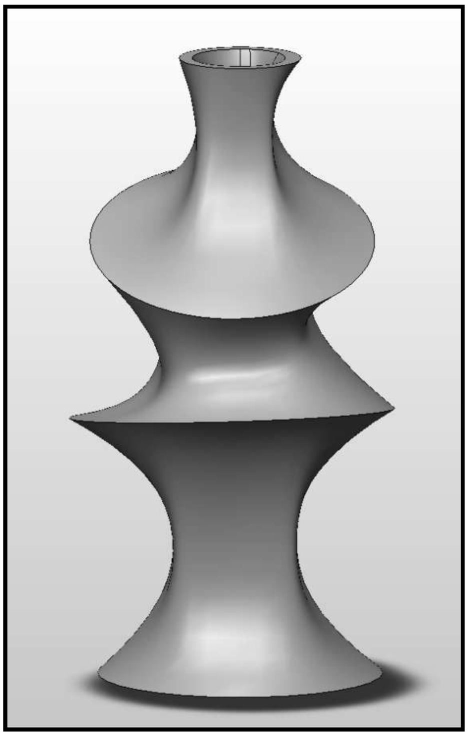

Figure 87: Lofted vessel 1 – modification 1 – right view

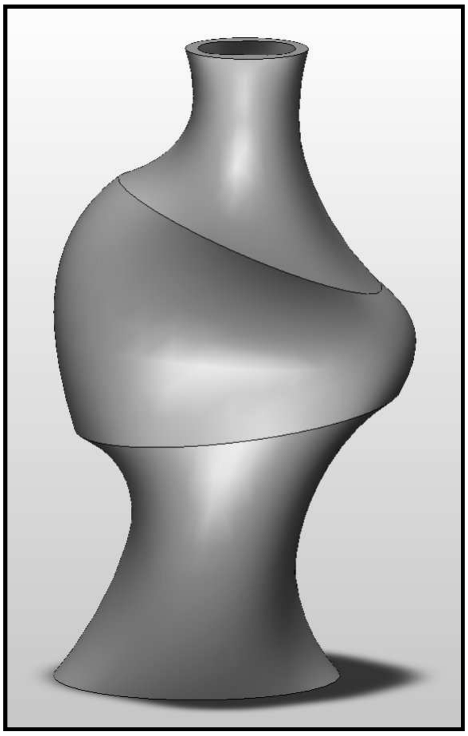

Figure 88: Lofted vessel 1 – modification 2 – front view

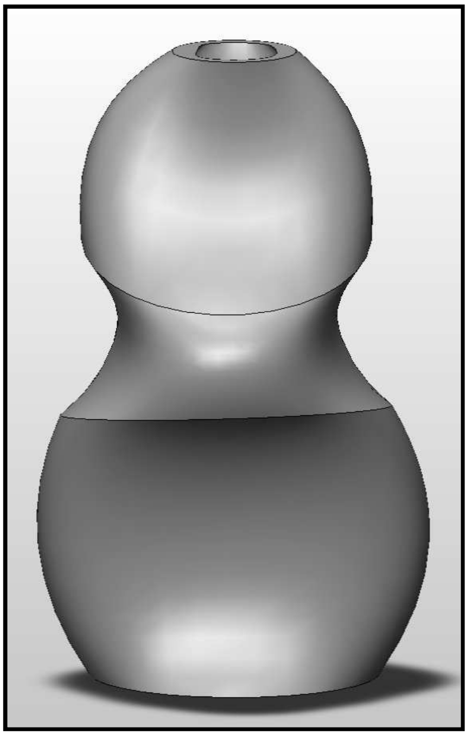

Figure 89: Lofted vessel 1 – modification 2 – right view

SolidWorks® facilitates the process to create a mould from the designed vessel form by allowing the designer to split the vessel form into two or more parts through parting lines. The general placement of the parting lines is normally in the middle of the vessel form, but it can be moved to eliminate undercuts and to ensure the optimal release of the artefact from the mould. To ensure no undercuts are formed or that the design parameters are maintained, SolidWorks® provides a draft analysis facility as mentioned earlier in this chapter. Within the software program, the steepness of the draft is highlighted by colour coding the gradient in comparison to the release angle of the mould. The colour code varies from green, which indicates easy release, to red, which indicates potential problems with release. If an analysis indicates red areas outside of the design parameters as determined in Chapter 4, the design will have to be modified to ensure effective release. A draft analysis of 1° was used in Figure 90. Only small areas of the prototype design had a draft between 0° and 1° as indicated in red. The design parameters that were determined in Chapter 4 using the test geometries showed that a draft of 0° will release if the area is not deeper than 10 mm. The design was not modified since it complied with the determined design parameters. Figure 90 is an example of a draft analysis that was done on the Lofted vessel 1 (Modification 1). Figures 91 and 92 show the prototype designs for the CNC milling of the prototypes for Lofted vessel 1 (Modification 1).

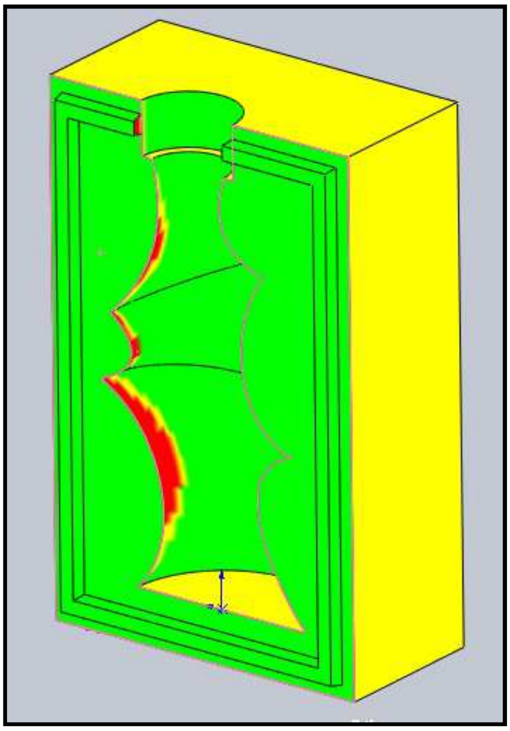

Figure 90: Draft analysis of design for Lofted vessel 1 (Modification 1)

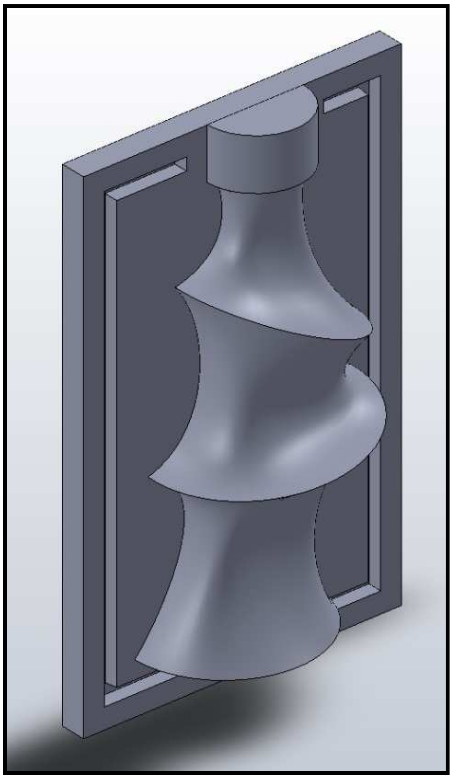

Figure 91: Lofted vessel 1 prototype design – Part 1

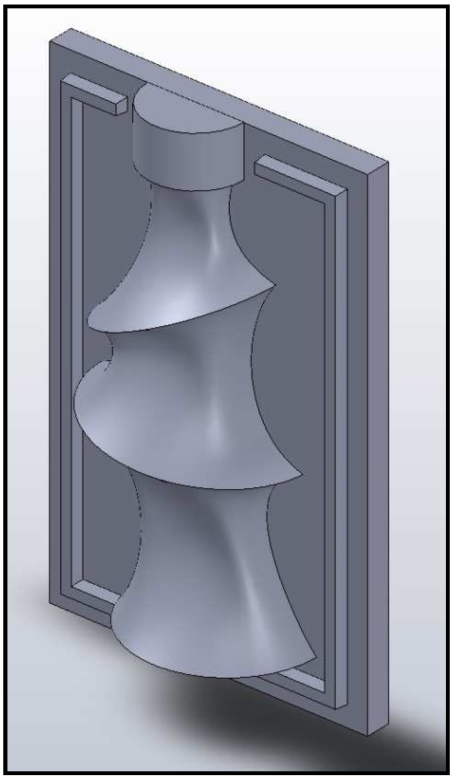

Figure 92: Lofted vessel 1 prototype design – Part 2

**Observe**: Figure 93 provides a table indicating the overall design time and costing for Lofted vessel 1. The evaluation reveals that a skilled SolidWorks® designer will be able to draft the original vessel form in thirty minutes. To change the design from the original to achieve Modification 1 takes approximately five minutes per modification. The time required to create Modification 2 also required five minutes, but only Modification 1 was taken through the entire process.

| Lofted vessel 1: Data sheet – Design time and cost | | |
|---|---|---|
| | **Time** | **Cost (ZAR)** |
| Original 3-D CAD design | 30 min | R 87.30 |
| Modification 1 | 5 min | R 14.55 |
| Prototype design – Lofted vessel 1 | 15 min | R 43.65 |
| **Total** | **50 min** | **R 145.50** |

Figure 93: Lofted vessel 1: Data sheet – Design time and costs

**Reflect**: Reflecting on the capabilities of SolidWorks® regarding fast changes within a design, Figure 93 clearly demonstrates the ability of SolidWorks® to assist the artist in this regard. Compared to the traditional method where a change in design requires the redrawing of the entire artefact on paper, it is evident that SolidWorks® adequately supports the design process by allowing for rapid changes. The advantage of being able to view the change in design in real time as the design is modified allows not only for quick changes, but dynamic changes as well.

#### 5.3.2.2 CNC prototype manufacturing: Lofted vessel 1

**Plan**: The next process is to manufacture the vessel prototype of Lofted vessel 1 from the SolidWorks® CAD prototype design using the CNC milling process to ascertain whether its capabilities support the development of vessel prototypes. Due to cost implications it was decided to manufacture the first modification since it is smaller in volume and thus will cost less to manufacture as was established in Chapter 4 by means of the test geometries.

**Act**: The prototype was milled using a DAHLI 720 3-axis milling machine that was available to the researcher (as indicated in Chapter 4). Since the design is not symmetrical, two separate parts had to be manufactured. Figure 94 shows the result from the CNC milling process.

Figure 94: Lofted vessel 1: CNC milled vessel prototype

Observe: Figure 95 provides a table displaying the time and cost for the milling procedures of the two prototype halves of Lofted vessel form 1. The table also indicates material cost.

| Lofted vessel 1: Data sheet – Manufacturing time and cost | | | | |
|---|---|---|---|---|
| | **Time** | | **Cost (ZAR)** | |
| | **Part 1** | **Part 2** | **Part 1** | **Part 2** |
| Programming time | 2h45 | 2h45 | R 480.15 | R 480.15 |
| Set-up time | 1h | 1h | R 100.00 | R 100.00 |
| Machine time | 11h30 | 11h30 | R 3 450.00 | R 3 450.00 |
| Finishing time | 0 h | 0 min | R 0.00 | R 0.00 |
| Material cost | - | - | R 466.94 | R 466.94 |
| Total | 15h15 | 15h15 | R 4 497.09 | R 4 497.09 |
| **Grand Total** | **30h30** | | **R 8 994.18** | |

Figure 95: Lofted vessel 1: Data sheet – Manufacturing time and cost

**Reflect**: The results from the CNC milled prototype (Figure 94) show that a 3-axis CNC milling machine adequately supports the milling of prototype vessel forms. The CNC milled vessel prototypes produced an exact replica of the SolidWorks® CAD design. The surface finish obtained was of a high quality and did not need any additional finishing and is consistent with the results achieved in Chapter 4.

#### 5.3.2.3 Master mould and slipcasting: Lofted vessel 1

**Plan**: Figure 96 shows the successful plaster of Paris master moulds result that was cast from the milled prototype, Lofted vessel 1. The results achieved with Lofted vessel 1 proved consistent with the results in Chapter 4 where it was determined that Necurite 630 is a suitable material for both milling and the casting process. The same release process as previously discussed was used to attain the results.

Figure 96: Lofted vessel 1: Plaster of Paris master mould

Figure 97 indicates the time and cost to manufacture the plaster of Paris master mould from the vessel prototype. The hourly rate and material cost was supplied by an experienced professional ceramicist.

| Lofted vessel 1: Data sheet – Master moulding time and cost | | |
|---|---|---|
| | **Time** | **Cost (ZAR)** |
| Master mould (@ 200/h) | 30 min | R 100.00 |
| Material cost | - | R 50.00 |
| **Total** | **30 min** | **R 150.00** |

Figure 97: Lofted vessel 1: Data sheet – Master moulding time and cost

**Act**: Production of the final vessel form was done according to the standardized slipcasting production process applicable to ceramic ware. To ensure reliability a commercial clay slip body was used to cast vessel forms. Figure 98 shows the successful result that was obtained. Figure 99 shows a batch production range of 5 out of 15 units and Figure 100 shows the full production range of 15 units.

Figure 98: Lofted vessel 1: Final slipcasting vessel

Figure 99: Lofted vessel 1: Batch production range – 5 out of 15 units

Figure 100: Lofted vessel 1: Batch production range of 15 units

**Observe**: In order to measure the production lead time offered when using CNC milling compared to traditional mould manufacturing methods, information regarding time and cost related aspects for traditional manufacturing methods was used based on data provided by an experienced professional ceramicist. The traditional method used by the ceramicist to alter an existing design requires the ceramicist to rebuild the vessel form from start. This process normally involves the ceramicist carving or modelling an entire new prototype out of plaster of Paris or ceramic modelling clay. First a negative pattern and then a positive pattern are moulded from the prototype. A master mould is then moulded from the positive pattern. It is important to note that, as illustrated in Figure 14 (cf. Chapter 3.5), the utilization of CAD and CNC milling reduces the number of steps required in the manufacturing process of master moulds compared to the traditional method. Figure 101 shows a time and cost layout for the traditional manufacturing process in order to make a final comparison between the utilization of emerging technologies and traditional methods.

| **Lofted vessel 1: Data sheet – Traditional manufacturing time and cost** | | |
|---|---|---|
| | **Time** | **Cost (ZAR)** |
| Initial Prototype development with modification (@ R200/h) | 32h + 32 h | R12 800 |
| Manufacturing - negative pattern (@ R200/h) | 2 h | R 400 |
| Manufacturing - positive pattern (@ R200/h) | 2 h | R 400 |
| Manufacturing - master mould (@ R200/h) | 2 h | R 400 |
| Material cost | | R 660 |
| **Total** | **70 h** | **R 14 660.00** |

Figure 101: Lofted vessel 1: Data sheet – Traditional manufacturing time and cost

**Reflect**: Figure 102 below presents a summary table comparing the overall manufacturing time and costs for the manufacturing of the master moulds utilizing traditional methods against the utilization of CAD and CNC milling technologies. The total cost for all materials for the traditional and digital manufacturing approaches are reflected in the data sheets and therefore no hourly rate are allocated. This is applicable to all four vessel forms. In Lofted vessel 1 the results indicate that with SolidWorks® changes to a design can be made quickly, effortlessly and effectively within minutes compared to traditional methods of rebuilding a design by hand which may take days depending on size and complexity. The utilization of CNC milling supports the accelerated development of the vessel prototype. Due to the high quality of the milled prototype, to manufacture a second plaster of Paris master mould will only take thirty minutes and therefore a series of moulds for production can be manufactured adding to the accelerated production time of final artefacts. The overall manufacturing process took thirty eight hours and ten minutes less when utilizing the selected technologies compared to the traditional method. The most significant result from this example is that the modified prototype design can be manufactured directly from the CAD SolidWorks® design and there is no need to rebuild a prototype by hand. The traditional method would require that for the slightest modification the entire prototype would need to be rebuilt. The machine time (for this prototype) took 75% of the total manufacturing time which frees the artist to undertake and/or finish other tasks. Considering this and the advantage of absolute accuracy the studio ceramicist will benefit from incorporating the use these technologies.

| Lofted vessel 1: Data sheet – Summary time and cost comparison | | |
|---|---|---|
| | **CAD & CNC milling** | **Traditional method** |
| **Time** | 31h50 | 70 h |
| **Cost** | R 9 289.68 | R 14 660.00 |

Figure 102: Lofted vessel 1: Data sheet – Summary time and cost comparison

### 5.3.2 Swept vessel 2: Complexity

**Plan**: In this example the focus is to apply SolidWorks® and CNC milling to determine to what extent CAD and CAM as design and manufacturing technologies support the ceramicist to design very complex and innovative vessel forms. For slipcasting it is essential that moulds do not have excessive undercuts; this aspect puts a limitation on the level of design complexity. This, however, is not a limitation of CAD, but rather design criteria when producing artefacts from production moulds. The intent was to design a form that would be very complex to create through traditional methods.

#### 5.3.2.1 3-D CAD Design: Swept vessel 2

**Act**: Swept vessel 2 shows an example of a wave pattern that merges with an ellipse form. The external geometry forms an exact ellipse that is rounded on the outside and flat in the inside, while the internal geometry is formed by wave patterns in the form of sine waves. The sine wave patterns are not round, but have a slight oval shape. The wave forms are spaced evenly and are very delicate. The sine wave patterns smoothly merge with the external geometry binding the two geometries seamlessly as one. To build this vessel form by hand will require a great deal of skill and time. Figure 103 illustrates the design for Swept vessel 2 with measurements of 150 mm x 40 mm x 200 mm.

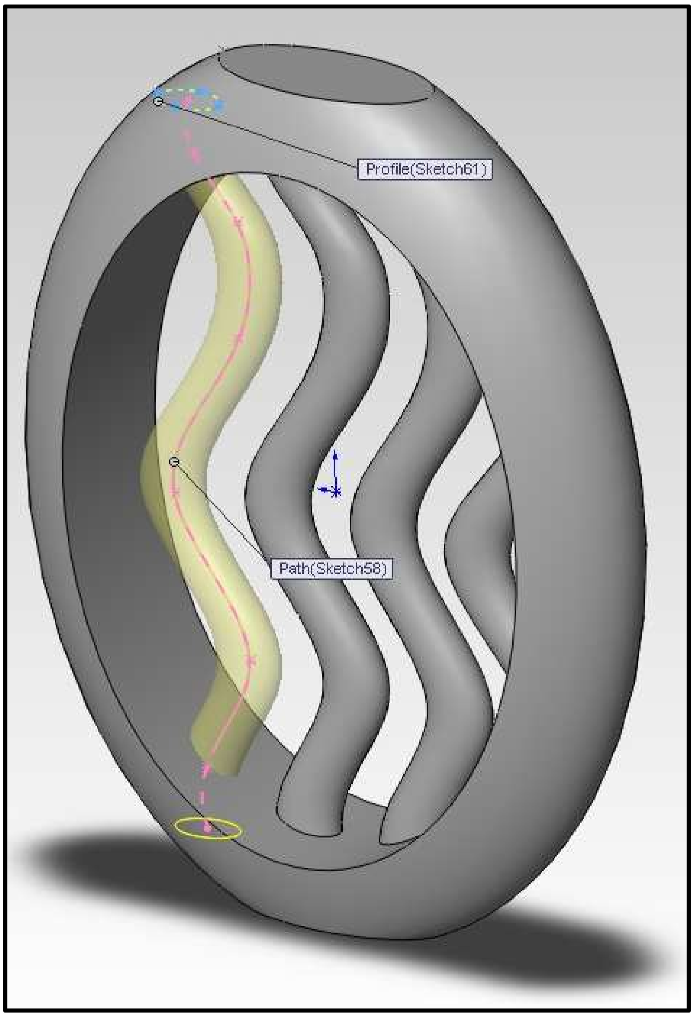


Figure 103: Swept vessel 2: CAD design, 150 mm x 40 mm x 200 mm

The design was created in SolidWorks® by adding large fillets to the outside of an ellipse shape that was formed with the Extrude Boss/Base feature (see Figure 104). An oval hole with the same shape as the outer oval was cut into the geometry using the Extrude Cut feature. The sine waves were formed using a small ellipse and the Swept Boss/Base feature to follow a sine guide curve to create the vessel form.


Figure 104: Diagram of shaped-based features

Figure 105 shows the 3-D CAD design of Swept vessel 2 in order to demonstrate the ability of SolidWorks® to create complex geometries.

Figure 105: Swept vessel 2: 3-D CAD Design

Figures 106 and 107 illustrate the prototype designs for the vessel form.  Four circular mould locators were added to ensure the mould stays in place during the slipcasting process.

Figure 106: Swept vessel 2 prototype design – Part 1

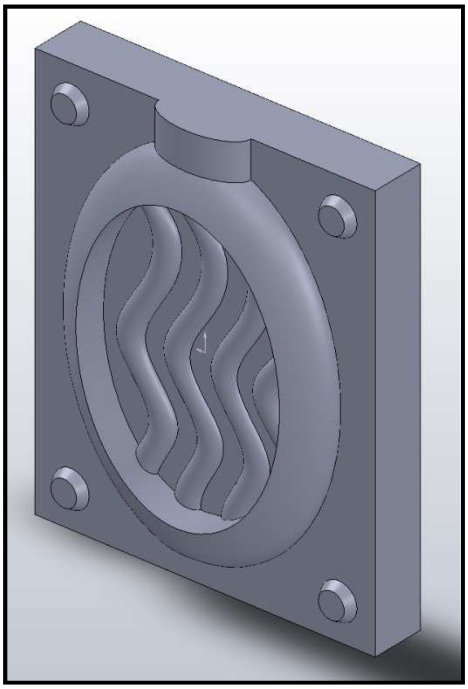

Figure 107: Swept vessel 2 prototype design – Part 2

**Observe:** Figure 108 provides a data sheet with a layout of the time and cost for the designing of Swept vessel 2. As indicated, a skilled SolidWorks® designer will be able to draft the complex vessel form in one and a half hours. The design is not symmetrical and therefore two prototype parts needed to be designed.

| **Swept vessel 2: Data sheet – Design time and cost** | | |
|---|---|---|
| | **Time** | **Cost (ZAR)** |
| 3-D CAD design | 1h30 | R 261.90 |
| Prototype design – Swept vessel 2 | 15 min | R 43.65 |
| **Total** | **1h45** | **R 305.55** |

Figure 108: Swept vessel 2: Data sheet – Design time and cost

**Reflect**: In this example, Swept vessel 2, SolidWorks® illustrates the ease with which very complex shapes and forms can be created within a very short time period. The complexity of the design is not limited to the capabilities of SolidWorks®, but rather by the limitations of the slipcasting process requiring the use of a mould where no undercuts may exist.

#### 5.3.2.2 CNC prototype manufacturing: Swept vessel 2

**Plan**: The manufacturing of a complex prototype is always a time-consuming aspect for the artist. In this example CNC milling will be utilized to test its ability to assist with the manufacturing of Swept vessel 2.

**Act**: Figure 109 illustrates the capability of CNC milling to assist in the manufacturing of very complex vessel prototype forms.

Figure 109: Swept vessel 2: CNC milled vessel prototype

**Observe**: Figure 110 provides a data sheet for the time and cost of the milling procedures of Swept vessel 2. The surface finish obtained on the milled vessel prototype was of a high quality requiring no additional finishing (cf. Chapter 4). Very good edge stability was obtained, i.e. no damage occurred on the sharp edges of the inner circle of the design.

| Swept vessel 2: Data sheet – Manufacturing time and cost | | | | |
|---|---|---|---|---|
| | Time | | Cost (ZAR) | |
| | Part 1 | Part 2 | Part 1 | Part 2 |
| Programming time | 1h30 | 1h30 | R 261.90 | R 261.90 |
| Set-up time | 1 h | 1 h | R 100.00 | R 100.00 |
| Machine time | 2h30 | 2h30 | R 750.00 | R 750.00 |
| Finishing time | 0 min | 0 min | R 0.00 | R 0.00 |
| Material cost | - | - | R 383.04 | R 383.04 |
| Total | 5h | 5 h | R 1 494.94 | R 1 494.94 |
| **Grand Total** | **10 h** | | **R 2 989.88** | |

Figure 110: Swept vessel 2: Data sheet – Manufacturing time and cost

**Reflect**: From the results of the milled vessel prototypes (Figure 109) it is clear that CNC milling supports the development of very complex designs. A 3-axis milling machine sufficiently supports the milling of complex vessel prototypes if design criteria are adhered too (i.e. the absence of undercuts). The resultant prototypes were furthermore an exact replica of the SolidWorks® design. Although smaller in size due to the shape of the design, less material had to be removed and therefore less time was required to mill Swept vessel 2 as compared to Lofted vessel 1. This again confirms that the time required for milling is mostly influenced by the amount of material that needs to be removed. The design of the mould locaters (place holders) was changed from a long interlocking riff to four smaller interlocking circles which contributed to reducing the machine time.

#### 5.3.2.3 Master mould and slipcasting: Swept vessel 2

**Plan**: Figure 111 illustrates the plaster of Paris master moulds manufactured from the vessel prototype form. The results obtained were again consistent with the results in the previous chapter where it was determined that Necurite 630 is a suitable material for both milling and the manufacturing of plaster of Paris master moulds. The plaster of Paris moulds released from the prototype without any difficulty.

Figure 111: Swept vessel 2: Plaster of Paris master mould

Figure 112 provides a data sheet with aspects related to the time and cost for the manufacturing of the plaster of Paris master mould.

| Swept vessel 2: Data sheet – Master moulding time and cost | | |
|---|---|---|
| | **Time** | **Cost (ZAR)** |
| Master mould (@ R200/h) | 30 min | R 100.00 |
| Material cost | - | R 50.00 |
| **Total** | **30 min** | **R 150.00** |

Figure 112: Swept vessel 2: Data sheet – Master moulding time and cost

**Act**: Figure 113 illustrates the final Sweep vessel 2 form produced by means of the slipcasting production technique. Excellent results were obtained. Figure 114 shows a batch production range of 10 out of 15 units and Figure 115 shows the batch production range of 15 units.

Figure 113: Swept vessel 2: Final slipcasting vessel

Figure 114: Swept vessel 2: Batch production range – 10 out of 15 units

Figure 115: Swept vessel 2: Batch production range of 15 units

**Observe**: Figure 116 presents a data sheet comparing time- and cost-related aspects when manufacturing a master mould employing the traditional method.

| Swept vessel 2: Data sheet – Traditional manufacturing time and cost | | |
|---|---|---|
| | **Time** | **Cost (ZAR)** |
| Prototype development (@ R200/h) | 16 h | R 3 200 |
| Manufacturing - negative pattern (@ R200/h) | 2 h | R 400 |
| Manufacturing - positive pattern (@ R200/h) | 2 h | R 400 |
| Manufacturing - master mould (@ R200/h) | 2 h | R 400 |
| Material cost | | R 470 |
| **Total** | **22 h** | **R 4 870** |

Figure 116: Swept vessel 2: Data sheet – Traditional manufacturing time and cost

**Reflect**: Figure 117 below provides a data sheet summarizing the overall time and cost aspects related to the manufacturing of the master mould for Sweep vessel 2 when comparing the utilization of CAD and CNC milling technologies against the traditional methods of master mould manufacturing.

| Sweep vessel 2: Summery time and cost comparison | | |
|---|---|---|
| | **CAD & CNC milling** | **Traditional method** |
| **Time** | 12h15 | 22 h |
| **Cost (ZAR)** | R 3 445.43 | R 4 870 |

Figure 117: Swept vessel 2: Summary time and cost comparison

Swept vessel 2 confirmed that with the aid of SolidWorks® very complex and innovative vessel forms can be created. Figure 109 demonstrates that CNC milling supports the development of complex vessel prototypes through the use of a 3-axis milling machine. The manufactured plaster of Paris master moulds were exact duplicates of the SolidWorks® design. As indicated in Figure 117, the traditional method takes almost twice as long for the manufacturing of the master mould. This time penalty to develop complex master moulds limits the feasibility of such designs through traditional methods.

### 5.3.3 Mesh vessel 3: Accuracy

**Plan**: Accuracy regarding the shape, form and symmetry of the designed vessel form, as well as the accuracy regarding the manufacturing of the master moulds, can be an important aspect for the production of artefacts which adhere to high standards. The following example will determine if the application of SolidWorks® and CNC milling technology assists the studio ceramicist in this regard.

#### 5.3.3.1 3-D CAD Design: Mesh vessel 3

**Act**: Figure 118 shows a sketch of the design intended to test the accuracy capability of CAD and milling. The external geometry enclosing the diamond mesh pattern forms an exact ellipse. The inner mesh flows seamlessly into the outer ellipse merging into a single artefact. The diamond mesh pattern is precisely spaced requiring very accurate measurements to ensure a consistent appearance to the design. To build this vessel form with the same accuracy by hand will be extremely difficult and time-consuming. Figure 118 illustrates the design for Mesh vessel 3 with measurements of 150 mm x 40 mm x 200 mm.

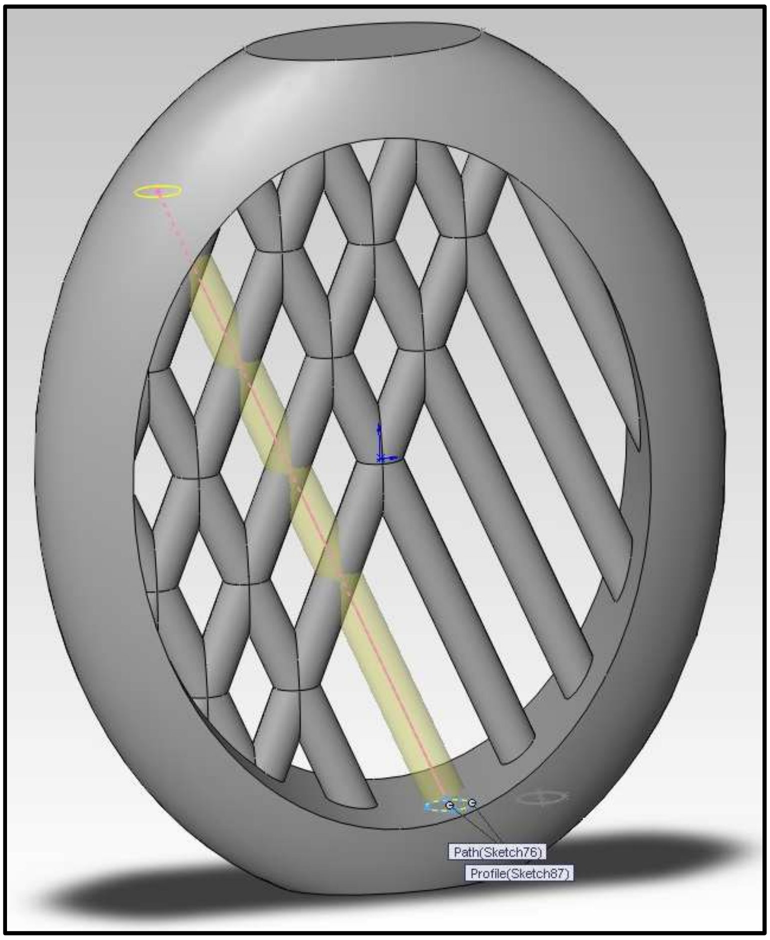


Figure 118: Mesh vessel 3: CAD design, 150 mm x 40 mm x 200 mm

The external geometry was created using exactly the same technique as described in the Swept vessel 2 example. The mesh pattern was created using a small circle and the Swept Boss/Base feature (Figure 119) that followed the path of the diagonal lines that was drawn with exact spacing.


Figure 119: Diagram of shaped-based features

Figure 120 illustrates the 3-D CAD design of Mesh vessel 3 in order to test SolidWorks® for its capability for the designing of accurate geometries.

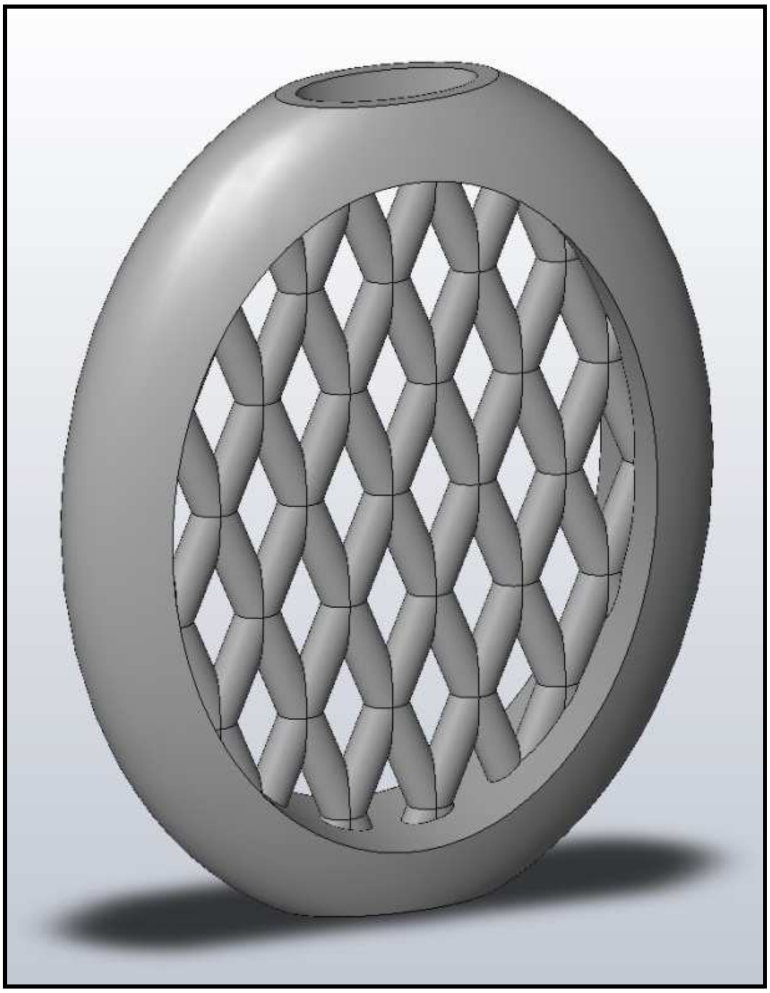

Figure 120: Mesh vessel 3: 3-D CAD Design

The symmetrical mirror shape of the design in Figure 120 allows for only a single vessel prototype to be manufactured. This greatly reduces the time and cost required for the milling process. A disadvantage of creating only one mould is that mould locaters cannot be added since the locaters require male and female connectors causing the design to be asymmetrical. To ensure the master mould is stable during the slipcasting process, mould locaters will have to be added manually to the plaster of Paris master mould after it has been created. Figure 121 illustrates the prototype design of Mesh vessel 3 for CNC milling.

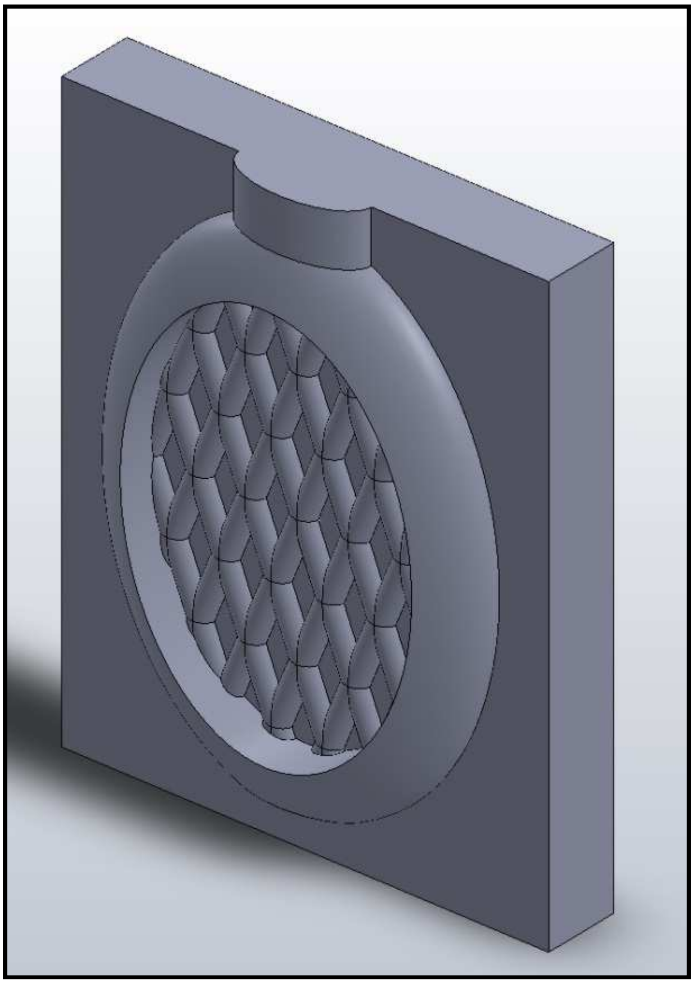

Figure 121: Mesh vessel 3: Prototype design

**Observe**: Figure 122 provides a data sheet indicating the time and cost as well as the prototype design time for the design of Mesh vessel 3. An experienced designer will be able to draft the vessel form in one and a half hours. Time and cost was also saved since only a single mould without mould locators was created.

| **Mesh vessel 3: Data sheet – Design time and cost** | | |
|---|---|---|
| | **Time** | **Cost (ZAR)** |
| 3-D CAD design | 1h30 | R 261.90 |
| Prototype design – Mesh vessel 3 | 5 min | R 14.55 |
| **Total** | **1h35** | **R 276.45** |

Figure 122: Mesh vessel 3: Data sheet – Design time and cost

**Reflect**: In this example SolidWorks® illustrates the ease with which accurate forms can be created within a very short time period. SolidWorks® has the ability to design to an accuracy of micrometres. Achieving similar accuracy by hand is highly unlikely.

#### 5.3.3.2 CNC prototype manufacturing: Mesh vessel 3

**Plan**: In this example the intention is to test the capability of CNC milling to assist with the manufacturing of accurate vessel prototypes. The design of Mesh vessel 3 forms a mirror image meaning that the back and front are the same. Therefore the manufacturing of the vessel prototype requires only one milled half from which two plaster of Paris master moulds will be manufactured in order to construct a hollow form for slipcasting.

**Act**: Figure 124 below illustrates the capability of CNC milling to assist in the manufacturing of very accurate vessel prototypes. The CNC milling result was a near exact duplicate of the CAD design. Very small ridges on the mesh pattern remained after the milling process. These ridges could have been removed by another milling pass or finishing round using a smaller milling drill point, but this would have increased the cost and it was therefore decided to not complete another pass. Figure 123 illustrates where the ridges were removed by lightly sanding the prototype by hand.

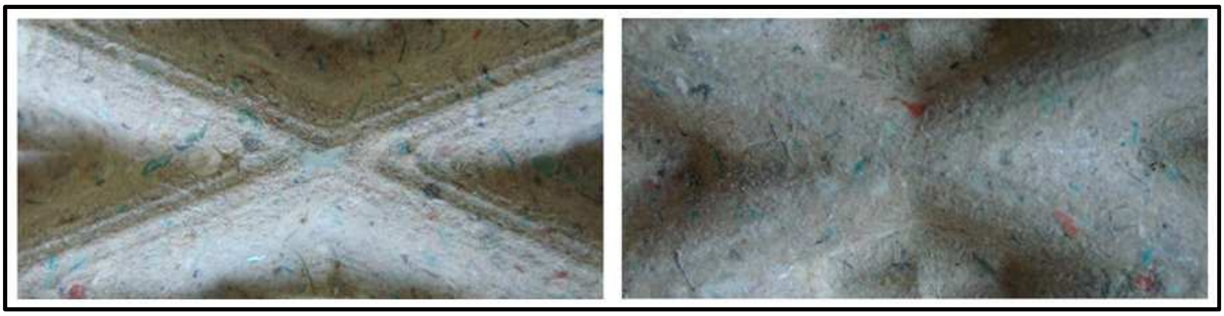

Figure 123: Ridges before and after sanding

Figure 124: Mesh vessel 3: CNC milled vessel prototype

**Observe**: Figure 125 provides a data sheet with the time and cost layout, including material cost, for the milling of Mesh vessel 3.

| **Mesh vessel 3: Data sheet – Manufacturing time and cost** | | |
|---|---|---|
| | **Time** | **Cost (ZAR)** |
| Programming time | 1h30 | R 261.90 |
| Set-up time | 1 h | R 100.00 |
| Machine time | 4h20 | R 1 300.00 |
| Finishing time | 0 min | R 0.00 |
| Material cost | - | R 383.04 |
| **Total** | **6h50** | **R 2 044.94** |

Figure 125: Mesh vessel 3: Data sheet – Manufacturing time and cost

**Reflect**: From the results of the milled vessel prototype (Figure 124) it is clear that CNC milling supports the development of very accurate forms. The prototype was a near exact replicate of the SolidWorks® design. An exact replicate could have been achieved through another milling pass.

#### 5.3.3.3 Master mould and slipcasting: Mesh vessel 3

**Plan**: Figure 126 shows the plaster of Paris master mould manufactured from the vessel prototype, Mesh vessel 3. Locaters were added manually to the plaster mould. The same process was followed as with the previous examples. The plaster of Paris mould released from the prototype without experiencing any difficulties.

Figure 126: Mesh vessel 3: Plaster of Paris master mould

Figure 127 provides a data sheet of the time and cost aspects for manufacturing the plaster of Paris master mould of Mesh vessel 3.

| Mesh vessel 3: Data sheet – Master moulding time and cost | | |
|---|---|---|
| | **Time** | **Cost (ZAR)** |
| Master mould | 30 min | R 100.00 |
| Material cost | - | R 50.00 |
| **Total** | **30 min** | **R 150.00** |

Figure 127: Mesh vessel 3: Data sheet – Master moulding time and cost

**Act**: Figure 128 illustrates the final vessel form of Mesh vessel 3 produced through the use of the slipcasting production technique. Excellent results were obtained. The accuracy of the mesh pattern was very good. Figure 129 illustrates a batch production range of 5 out of 15 units and Figure 130 shows a production range of 15 units of Mesh vessel 3 that were cast from the master mould.

Figure 128: Mesh vessel 3: Final slipcasting vessel

Figure 129: Mesh vessel 3: Batch production range – 5 out of 15 units

Figure 130: Mesh vessel 3: Batch production range of 15 units

**Observe**: Figure 131 compares time- and cost-related aspects when manufacturing a master mould following the traditional methods.

| Mesh vessel 3: Data sheet – Traditional manufacturing time and cost | | |
|---|---|---|
| | **Time** | **Cost (ZAR)** |
| Prototype development (@ R200/h) | 24 h | R 4 800 |
| Manufacturing - negative pattern (@ R200/h) | 2 h | R 400 |
| Manufacturing - positive pattern (@ R200/h) | 2 h | R 400 |
| Manufacturing - master mould (@ R200/h) | 2 h | R 400 |
| Material cost | | R 490 |
| **Total** | **30 h** | **R 6 490** |

Figure 131: Mesh vessel 3: Data sheet – Traditional manufacturing time and cost

**Reflect**: Figure 132 provides a data sheet of the overall time and cost for the manufacturing of the master mould for Mesh vessel 3 when comparing the utilization of CAD and CNC milling technologies against the traditional methods of master mould manufacturing. The consulted ceramicist indicated that a similar vessel form can be built by hand, but nevertheless pointed out that to achieve the same accuracy of the mesh pattern that can be obtained when using the utilized technologies would be extremely difficult if not impossible.

The overall manufacturing cost and time required to produce Mesh vessel 3 was significantly less than for the Swept vessel 2 since only one part had to be manufactured. Due to the very complex diamond pattern the manufacturing of this part alone was more time-consuming than a single part of the previous example, Swept vessel 2. SolidWorks® and CNC milling are mainly used in the engineering field where accuracy is critical. Accuracy of millimetres cannot be achieved by hand, no matter the skill level of the artist. The Mesh vessel 3 design revealed that with the aid of SolidWorks® very accurate vessel prototypes can be created. It was established that CNC milling can produce an accurate prototype from the SolidWorks® design through a 3-axis milling machine as the vessel prototype was a near exact replica of the SolidWorks® design. The accurate plaster of Paris master moulds that were manufactured from the prototype assisted in the manufacturing of a very complex final vessel form as indicated by the result presented in Figure 126. The final vessel form was an exact duplicate of the SolidWorks® design in shape but was smaller in size due to solidification shrinkage as discussed in the previous chapter. A solidification shrinkage of 3% occurred with the slipcasting body that was used. Compared to traditional hand manufacturing, producing a vessel form of such accuracy would be extremely difficult and time-consuming. Solidification shrinkage will occur when using either the traditional or technology method and is not a limitation of the introduction of technology but is a slipcasting characteristic. Figure 132 indicates a difference of twenty one hours and five minutes to complete the process using the traditional method. Figure 132 below provides a data sheet summarizing the overall time and cost aspects related to the manufacturing of the master mould for Mesh vessel 3 when comparing the utilization of CAD and CNC milling technologies against the traditional methods of master mould manufacturing.

| Mesh vessel 3: Summery time and cost comparison | | |
|---|---|---|
| | **CAD & CNC milling** | **Traditional method** |
| **Time** | 8h55 | 30 h |
| **Cost (ZAR)** | R 2 471.39 | R 6 490 |

Figure 132: Mesh vessel 3: Summary time and cost comparison

### 5.3.4 Solid mesh vessel 4: Scale

**Plan**: The ability to design a single vessel form and to then rapidly change its size according to new requirements is a significant advantage for the studio ceramicist. The Solid mesh vessel 4 example will investigate if rapid changes to size are possible using SolidWorks® and CNC milling.

#### 5.3.4.1 3-D CAD Design: Solid mesh vessel 4

**Act**: A symmetrical design was created to lower the manufacturing cost while still fulfilling the objective. It was decided to manufacture a smaller replica of Solid mesh vessel 4 to keep costs down. Figure 133 is a sketch illustration of the design for Solid mesh vessel 4 with measurements of 150 mm x 40 mm x 200 mm.

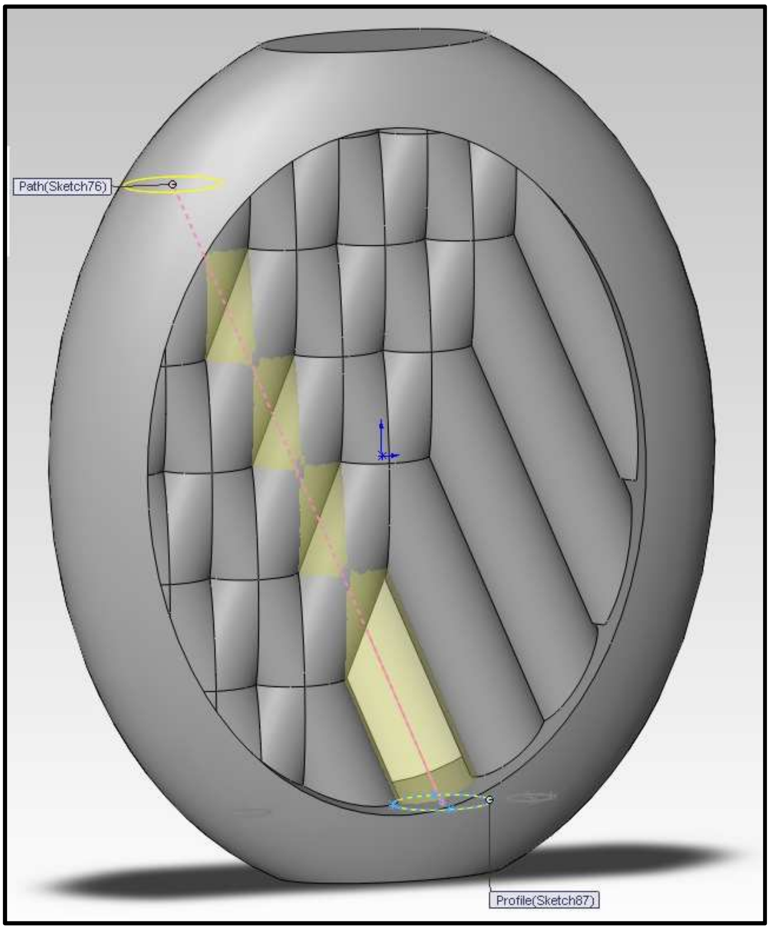


Figure 133: Solid mesh vessel 4: CAD design, 150 mm x 40 mm x 200 mm

To create the design (Solid mesh vessel 4) in SolidWorks®, similar steps as the previous example was used except for increasing the diameter of the small circles used by the Swept Boss/Base feature (see Figure 134). This caused the size of the diagonal lines to increase and merge with each other forming a solid body with a pattern.


Figure 134: Diagram of shaped-based features

When using SolidWorks® to change the scale of the design is a simple process which allows for the change of a single coefficient value regarding the dimensions of the object. In this example the design was decreased by 50% in scale taking approximately 1 minute to do. The coefficient value of the object's size was changed from 1 to 0.5. All measurements of the design then instantly changed and decreased the objects size by 50%. Figure 135 shows the small 3-D CAD design of Solid mesh vessel 4 with measurements of 75 mm x 20 mm x 100 mm.

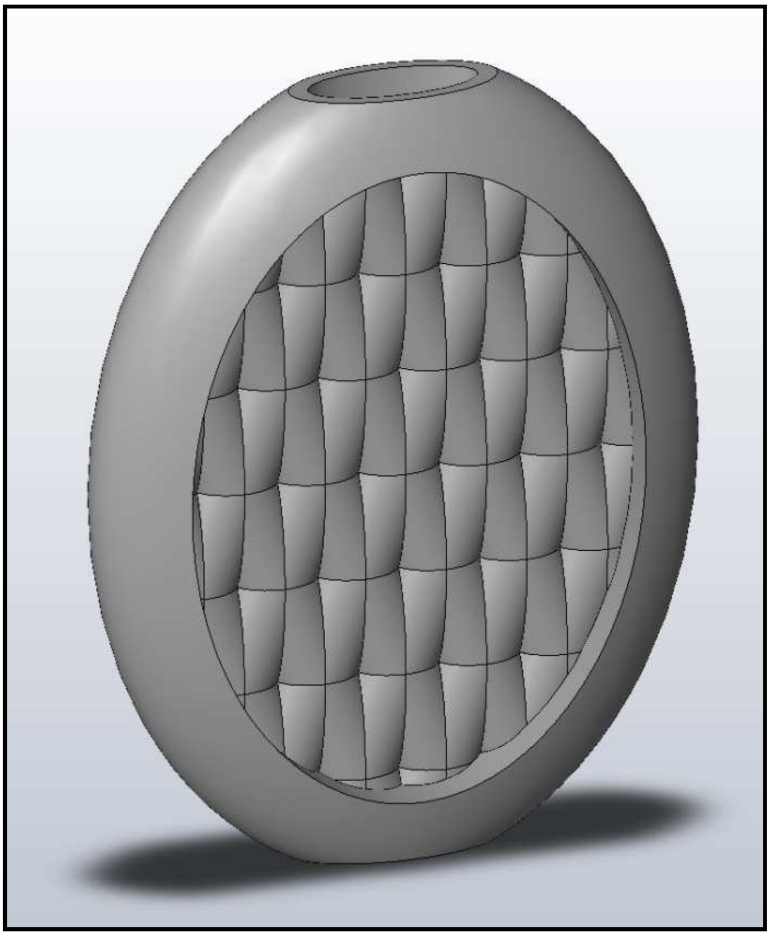

Figure 135: Solid mesh vessel 4: 3-D CAD Design, 75 mm x 20 mm x 100 mm

As previously mentioned, the symmetrical shape of the design portrayed in Figure 135 requires that only a single master mould needs to be manufactured. This greatly reduces the time and cost required for the prototype milling process. Figure 136 demonstrates the prototype design created for the milling of the prototype for Solid mesh vessel 4.

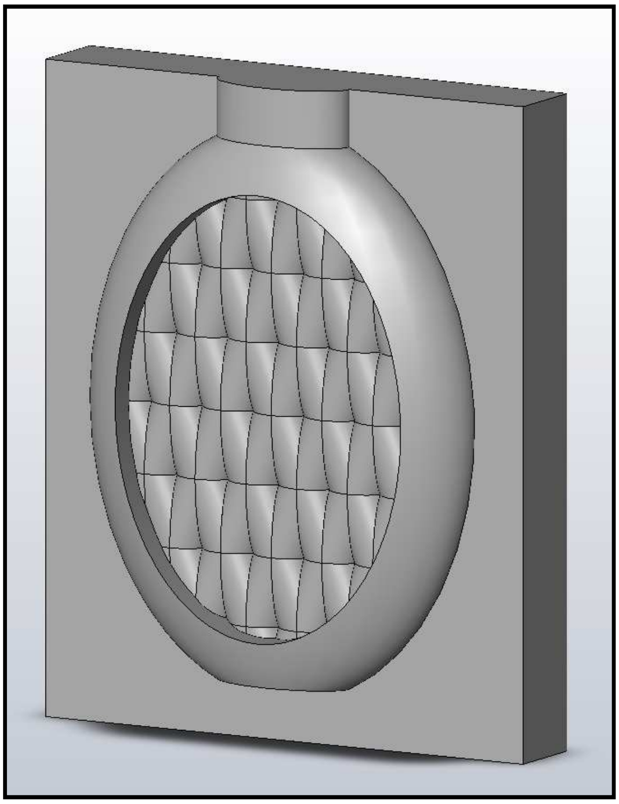

Figure 136: Solid mesh vessel 4: Prototype design

**Observe**: Figure 137 provides a data sheet indicating the time and cost as well as the prototype design time for the designing of the vessel form Solid mesh vessel 4. A skilled SolidWorks® designer will be able to draft the vessel form in ninety minutes from start to finish. It took 1 minute to modify the scale of the design. Similar to the previous example, it took five minutes to design the CAD prototype since no mould locaters were added to ensure a symmetrical design and only one part for each size had to be manufactured.

| **Solid mesh vessel 4: Data sheet – Design time and cost** | | |
|---|---|---|
| | **Time** | **Cost (ZAR)** |
| Original 3-D CAD design | 1h30 | R 261.90 |
| Modify size | 1 min | R 2.91 |
| Prototype design – Solid mesh vessel 4 | 5 min | R 14.55 |
| **Total** | **1h36** | **R 279.36** |

Figure 137: Solid mesh vessel 4: Data sheet – Design time and cost

**Reflect**: In this example SolidWorks® illustrates the ease with which the scale of any vessel form can rapidly be altered by changing a single parameter. Changing the scale of a design traditionally requires that the vessel form be rebuilt by hand. This is a very repetitive and time-consuming task and compels artists to limit changes in scale as far as possible.

#### 5.3.4.2 CNC prototype manufacturing: Solid mesh vessel 4

**Plan**: With Solid Mesh vessel 4 it was the intention to ascertain the ability of CNC milling, as a manufacturing technology, to assist the ceramicist to alter the scale of an object more frequently.

**Act**: Figure 138 illustrates the capability of CNC milling to assist in the manufacturing of prototypes with different sizes. The milled vessel prototypes were measured with a vernier calliper; results reflect that the two moulds are proportionate to one another with the smaller prototype measuring 50% less than the larger prototype.

Figure 138: Solid mesh vessel 4: CNC milled vessel prototypes

**Observe**: Figure 139 provides a data sheet with a layout of the time and cost implications for the milling procedures of the two parts. The smaller vessel form took less time to mill because less material had to be removed. The surface finish obtained for the prototypes was of a high quality requiring no additional finishing.

| Solid mesh vessel 4: Data sheet – Milling time and cost | | | | |
|---|---|---|---|---|
| | Time | | Cost (ZAR) | |
| | Small | Large | Small | Large |
| Programming time | 45 min | 1h30 | R 130.95 | R 261.90 |
| Set-up time | 1 h | 1 h | R 100.00 | R 100.00 |
| Machine time | 3 h | 5h | R 900.00 | R 1 500.00 |
| Finishing time | 0 min | 0 min | R 0.00 | R 0.00 |
| Material cost | - | - | R 66.88 | R 383.04 |
| Total | 4h45 | 7h30 | R 1 197.83 | R 2 244.94 |
| **Grand Total** | **12h15** | | **R 3 442.77** | |

Figure 139: Solid mesh vessel 4: Data sheet – Manufacturing time and cost

**Reflect**: From the results of the milled vessel prototypes (Figure 138) it is clear that CNC milling supports modifications to the scale of an artefact. In both examples the milled prototype was an exact replica of the SolidWorks® design and also showed accuracy of form.

### 5.3.4.3 Master mould and slipcasting: Solid mesh vessel 4

**Plan**: Figure 140 illustrates the plaster of Paris master moulds manufactured from the prototypes. As mentioned, mould locators were added to the plaster of Paris master moulds after they were manufactured. The same procedure as in the previous examples was used to manufacture the plaster of Paris master moulds. As with the previous examples, the plaster of Paris mould released easily from the milled vessel prototypes.

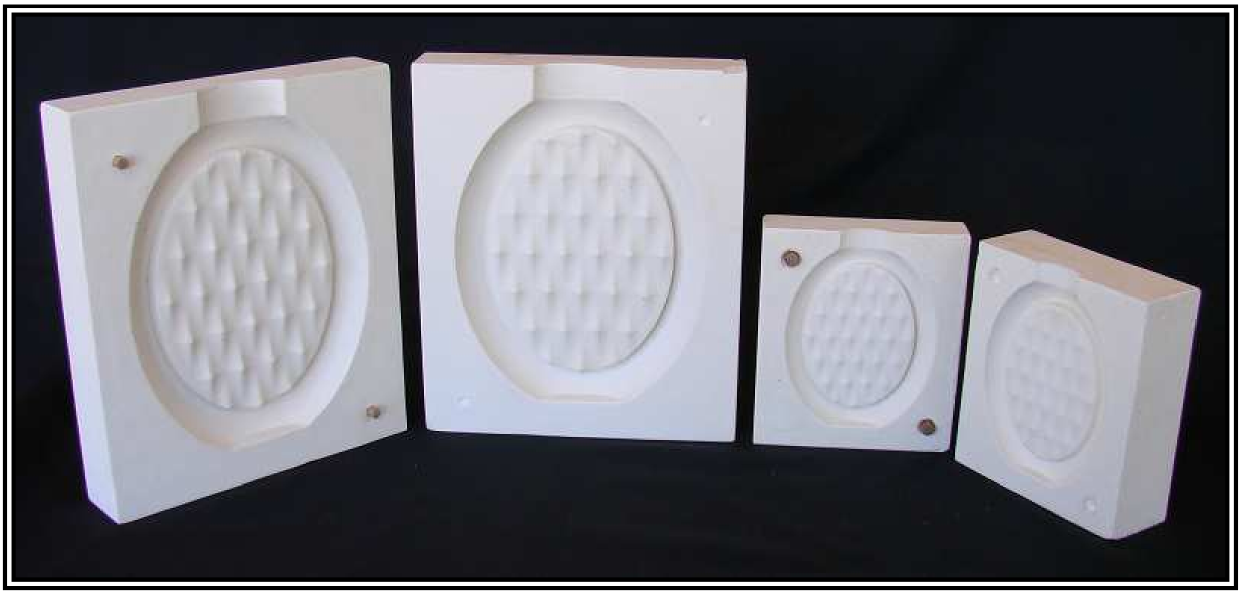

Figure 140: Solid mesh vessel 4: Plaster of Paris master moulds

Figure 141 presents a data sheet with the time- and cost-related aspects for the manufacturing of the master mould for the original and reduced scale example of Solid mesh vessel 4.

| Solid mesh vessel 4: Data sheet – Master moulding time and cost | | | | |
|---|---|---|---|---|
| | **Time** | | **Cost (ZAR)** | |
| | **Small** | **Large** | **Small** | **Large** |
| Master mould | 20 min | 30 min | R 66.60 | R 100.00 |
| Material cost | - | - | R 25.00 | R 50.00 |
| Total | 20 min | 30 min | R 91.60 | R 150.00 |
| **Grand Total** | **50 min** | | **R 241.60** | |

Figure 141: Solid mesh vessel 4: Data sheet – Master moulding time and cost

**Act**: Figure 142 illustrates the final vessel forms of Solid mesh vessel 4. The same slipcasting production technique was used as in previous examples to create the final vessel forms. Figure 143 shows a range of 5 out of 15 units that was taken during the casting process. Figure 144 shows the batch production range of the full- and half-sized units.

Figure 142: Solid mesh vessel 4: Final slipcasting vessel

Figure 143: Solid mesh vessel 4: Batch production range – 5 out of 15 units

Figure 144: Solid mesh vessel 4: Batch production range of full- and half-sized units

**Observe**: Figure 145 compares time- and cost-related aspects following the traditional method for both the small and large Solid mesh vessel 4.

| Solid mesh vessel 4: Data sheet – Traditional manufacturing time and cost | | |
|---|---|---|
| | **Time Small and Large** | **Cost (ZAR) Small and Large** |
| Prototype development (@ R200/h) | 30 h | R 6 000 |
| Manufacturing - negative pattern (@ R200/h) | 3 h | R600 |
| Manufacturing - positive pattern (@ R200/h) | 3 h | R 600 |
| Manufacturing - master mould (@ R200/h) | 3 h | R 600 |
| Material cost | | R 560 |
| **Total** | **39 h** | **R 8 360** |

Figure 145: Solid mesh vessel 4: Data sheet – Traditional manufacturing time and cost

**Reflect**: Figure 146 provides a data sheet on the overall time and cost for the manufacturing of the master mould for Solid mesh vessel 4 when comparing the utilization of CAD and CNC milling technologies against the traditional methods of master mould manufacturing. To achieve the exact depth of pattern for Solid mesh vessel 4, according to the consulted professional ceramicist, will also be very difficult to obtain accurately, if not impossible.

To alter the scale of a master mould, the artist was traditionally required to rebuild a new vessel form from the beginning which included the subsequent manufacturing of a new master mould.  However, the capability of SolidWorks® to instantly scale the size of a vessel form makes this process a viable option.  In this example the utilization of SolidWorks® and CNC milling showed that to alter the scale of a design took significantly less time compared to the traditional method.

| Solid mesh vessel  4: Summery time and cost comparison | | |
|---|---|---|
| | **CAD & CNC milling** | **Traditional method** |
| **Time** | 14h41 | 39 h |
| **Cost (ZAR)** | R 3 963.73 | R 8 360 |

Figure 146: Solid mesh vessel 4: Summary time and cost comparison

## 5.4 Overall reflection and interpretation of results

Figure 147 provides a data sheet summarizing the overall **time** required for the different design and prototype manufacturing processes of the various vessel forms.

**Data Sheet: Summary – Design and manufacturing time**

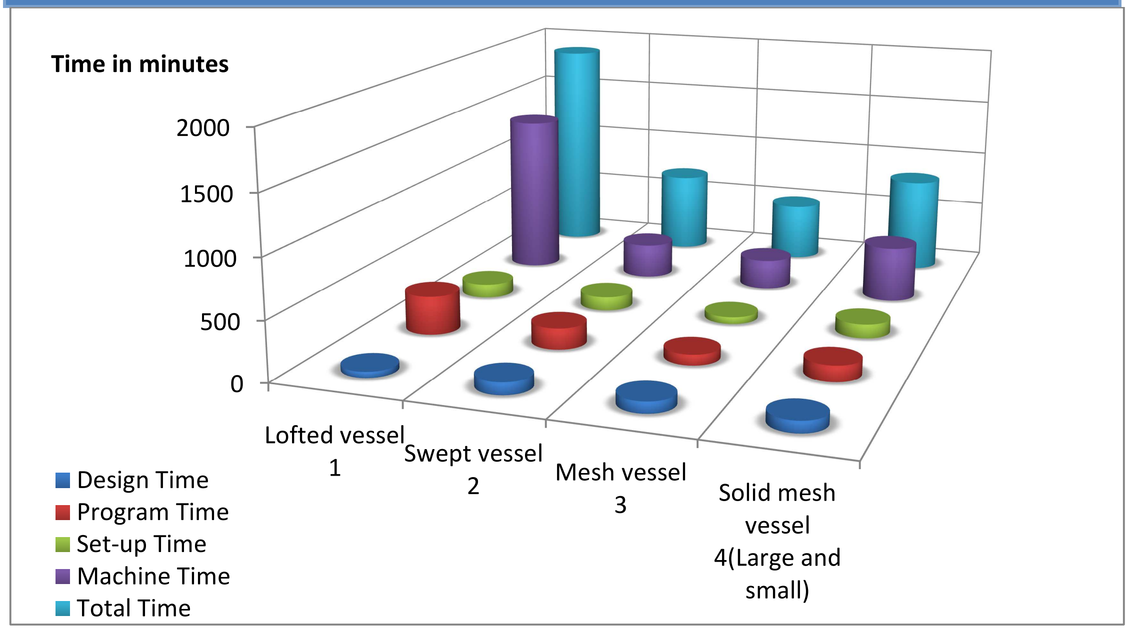


Figure 147: Data sheet: Summary – Design and manufacturing time

Figure 148 provides a data sheet summarizing the overall **costs** for the different design and prototype manufacturing processes for the vessel forms. Figure 148 indicates that cost is directly related to manufacturing time as can be seen by the correlation of Figures 147 and 148.

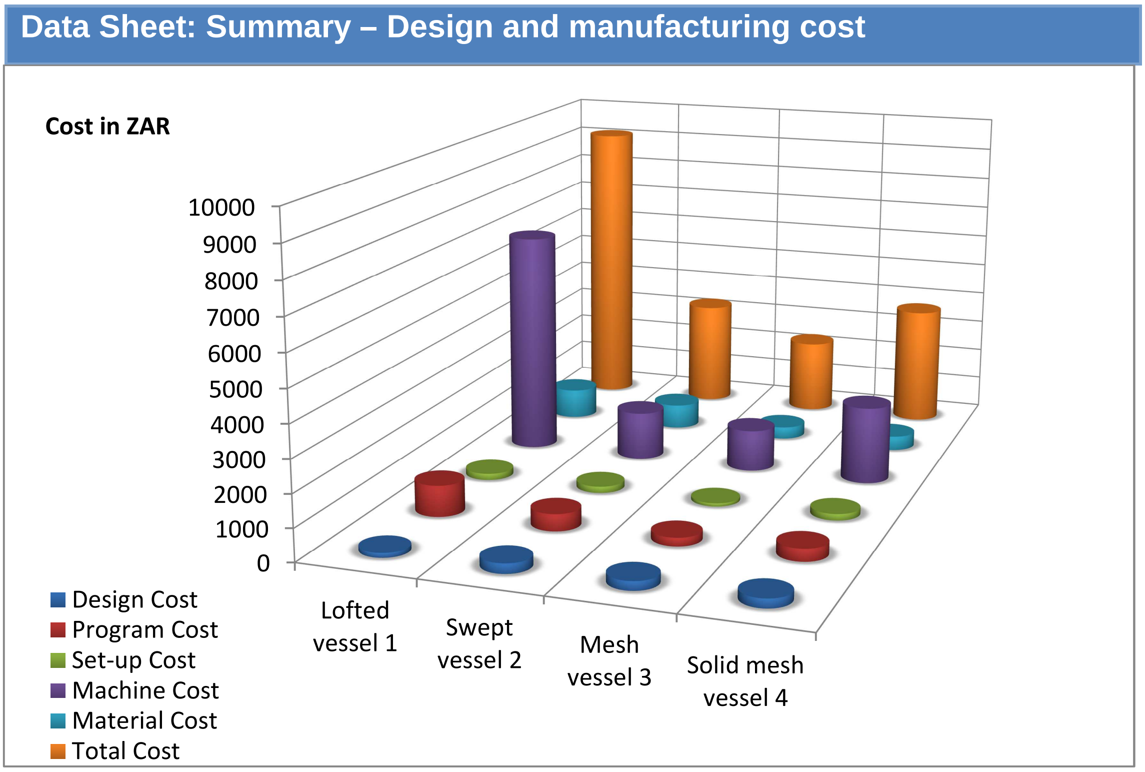


Figure 148: Data sheet: Summary – Design and manufacturing cost

Even though SolidWorks® is an engineering design software program and particularly intended for the designing of engineering components, it is suitable for application in the designing of ceramic artefacts since the features and parameters of SolidWorks® suit the requirements for designing ceramics artefacts. Figure 147 reveals that SolidWorks®, as a 3-D CAD design technology, significantly improves the overall efficiency and functionality of the design process compared to the overall manufacturing process. A significant conclusion is that the design time is influenced not only by the scale of the designed artefact, but also by complexity. Alterations within a design and can also be brought about quickly and easily as seen from Lofted vessel 1 and Solid mesh vessel 4. SolidWorks® is suitable for the prototype design development of the prototype vessel forms destined for CNC milling and is able to adequately translate the required data for the CAM process. The utilization of a 3-axis CNC milling machine as a manufacturing technology accelerates the development of prototype vessel forms that supports the manufacturing of plaster of Paris master moulds to be used for the batch production of studio-based ceramic artefacts. Machine time is mostly influenced by the scale of the object as seen from Swept vessel 1, but it is also influenced to a lesser extent by the accuracy of the design as seen from Mesh vessel 3. The machine time for the single prototype of Mesh vessel 3 is nearly the same as the machine time of two prototype parts for Swept vessel 2. In all the applicable examples the utilization of SolidWorks® and CNC milling for the manufacturing of prototypes indicates acceleration when compared to the traditional method as seen in figures 149 and 150 below. These figures compare the total manufacturing time and cost, including material, of each of the four examples compared to the traditional method of manufacturing.

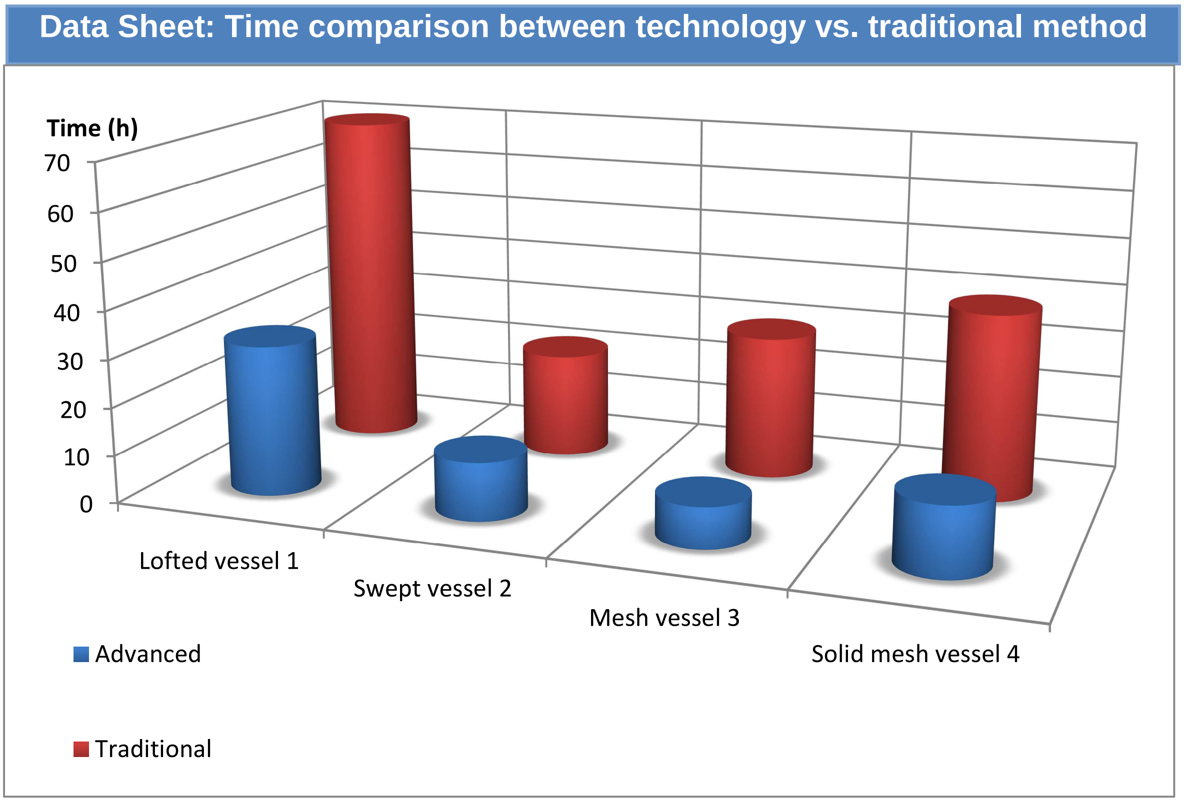


Figure 149: Data sheet: Time comparison between technology vs. traditional method

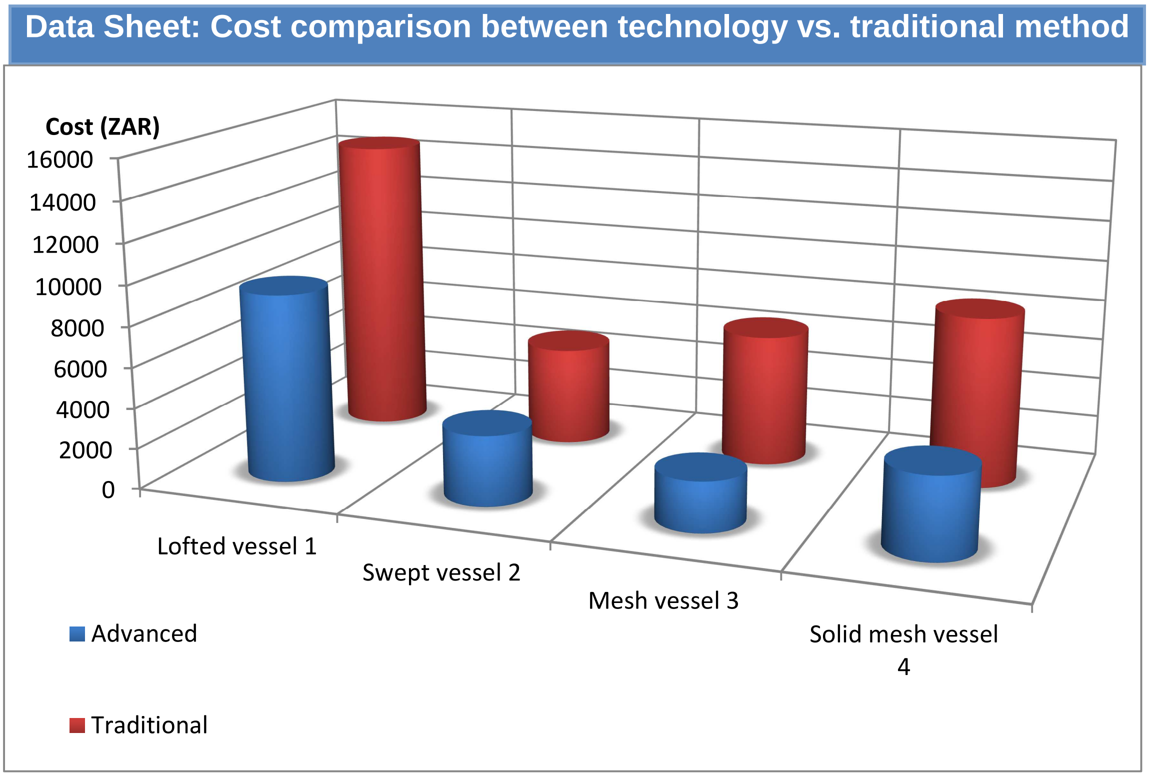


Figure 150: Data sheet: Cost comparison between technology vs. traditional method

## 5.5 Conclusion

Compared to traditional methods, the advantages of integrating technology – as seen in the examples presented in this chapter – are a clear indication that an interdisciplinary approach between ceramics and the use of engineering-based technology can be successfully implemented. The integration of relevant technology has the ability to accelerate and improve on the overall product-to-market lead time cycle for the batch production of studio-based ceramic artefacts. The utilization of SolidWorks® and CNC milling as emerging technologies furthermore assists the ceramicists to effortlessly improve on the aesthetics of their production by being able to design very accurate and complex artefacts.

# Chapter 6

# Conclusion

## 6.1 Summary

Technology has come a long way to gain wide acceptance for its value within certain sectors of the artistic community. For the artist CAD software and CAM applications such as CNC milling, 3-D printing, laser and water jet cutting play a vital role in today's studio practice environment. In addition to the exploration of CAD this research project has investigated the utilization of CNC milling as an emerging technology relevant to the field of ceramics. This study has specifically set out to determine if the utilization of SolidWorks® as a 3-D CAD design technology will reduce the design development time frame for the batch production of studio-based ceramic artefacts. It has also explored CNC milling as a manufacturing application to reduce the time-consuming process of manually producing plaster of Paris master moulds. Overall the interdisciplinary manufacturing approach that has been explored bridges the disciplines of ceramics and engineering, thereby impacting on the overall product-to-market lead time cycle for the cost-effective production of ceramic artefacts.

A significant finding that emerged from the literature review undertaken in Chapter 2 is the positive approach towards the utilization of emerging technologies within the arts. The perception has changed from a resistance during Modernism towards recognition of the advantages, possibilities and potential that these technologies have to offer the artist in a Post-modern age. In Chapter 3 the advantages of 3-D CAD was investigated. Operational features and design parameters of SolidWorks® were explored and include the designing of six test geometries. The results concerning the investigation of 3-D CAD design show that SolidWorks® is an applicable software program to be applied by the studio ceramicist for the designing of vessel forms. Chapter 4 provides a brief background on the advantages of CNC milling and technical aspects regarding milling machines and the milling process. It is important to understand the basic aspects and procedures of CNC milling because it influences the approach taken when designing and especially as far as production mould manufacturing is concerned. Through the manufacturing of six test geometries Necurite 630 was identified as a suitable milling material for the development of prototype vessel forms. The height-width release ratio for moulding and casting purposes were also tested. From the results obtained a set of design and production parameters was established (cf. Chapter 4.7). These design parameters assist in the designing of vessel forms by way of guiding and indicating design restrictions regarding height, width and depth. The design parameters provide guidelines towards the limitations for 3-D prototype and mould manufacturing purposes to assist the designer in eliminating possible production problems. The test geometries also indicate that CNC milling will be able to support the manufacturing of master moulds. From Chapter 5 the following findings emerged: The vessel form examples confirm that SolidWorks® allows for easy and flexible modifications within the design process, it allows the ceramicist to experiment with increased complexity, to achieve accuracy regarding form and symmetry and effect fast changes to the scale of a designed vessel. The overall technical analysis and cost- effectiveness of the vessel forms produced using the manufactured master moulds revealed the successful implementation of CAD and CNC milling as alternative technologies to traditional manufacturing methods in ceramics.

Conclusions regarding the specific objectives of this research project were as follows: Objective 1 was to investigate if 3-D computer-aided design (CAD) can assist with the development of vessel prototypes and master mould design to reduce the design development time for the batch production of studio-based ceramic vessel forms. In order to meet objective 1 SolidWorks® was tested to determine if it allows for flexibility regarding frequent changes within a design, the complexity of form, the degree of accuracy within geometries and the rapid variable size adjustment of designs. SolidWorks® excelled in all these areas and met all the requirements of objective 1.

Objective 2 investigated the possibility of utilizing CNC milling technology for the manufacturing of vessel prototypes and master moulds for the batch production of studio-based ceramic artefacts. The CNC technology was capable of manufacturing all the required vessel forms to an acceptable standard which fulfilled objective 2.

Objective 3 focused on the testing and analysis of the developed vessel prototypes and master moulds in order to determine the cost effectiveness and the time required when utilizing CAD and CNC milling as emerging technologies to serve as an alternative to traditional manufacturing methods. A decrease in cost and the overall product-to-market lead time were achieved when using the emerging technologies compared to the traditional method of manufacturing.

## 6.2 Significance and development relevance

This study contributes towards strengthening emerging technology-integration suited to economic development. This study furthermore confirms that a significant amount of manufacturing time can be saved within the product-to-market lead time cycle. For the South African studio ceramicist the application of these technologies will contribute towards incubating an increased output of high-quality innovative products. SolidWorks® and CNC milling indicate that they both reduce the time-consuming process of manufacturing master moulds. Together, these two findings imply that the overall product-to-market lead time cycle for the manufacturing of ceramic artefacts is improved significantly. This research study namely reveals an acceleration of 231% in the overall product-to-market lead time for the four examples compared to the traditional manufacturing method. In a market environment cost-related aspects are always important and this study reveals that 173% was saved as far as costs are concerned.

This study contributes to existing knowledge of mould manufacturing by providing parameters and information regarding CAD and CNC milling for the manufacturing of master moulds for the production of ceramic artefacts. The findings from this research study make a contribution to the current literature by exploring an interdisciplinary approach between ceramics engineering through the utilization of emerging technologies. The most significant contribution and conclusion from this research study is that 3-D CAD and CNC milling can successfully be utilized as alternative production technologies when compared to traditional manufacturing methods.

## 6.3 Recommendations

This study has brought forward some aspects for further investigation. This research project was limited to the investigation of only one 3-D CAD design software program, namely SolidWorks®. Further investigation on other design programs can be undertaken in order to explore the best suitable design program for art students. Only a single milling material was examined, namely Necurite 630. Further studies on the development of different materials that will be suitable to be milled directly as master moulds will help to broaden knowledge in this field. Design parameters that were established are based on only six test geometries; these provide effective but nonetheless broad specifications. Further investigation in order to provide additional and more refined specifications will contribute towards the establishment of more exact design parameters. Research was furthermore undertaken using only a 3-axis milling machine and as such additional research concerning 5-axis milling machines can certainly be undertaken in this field. Industry requires further emphasis on stimulating an interdisciplinary co-creational approach between arts practice and engineering technologies which is crucial for keeping up with current developments within the contemporary art milieu.

## 6.4 Concluding comments

For the researcher this research project confirmed that the introduction of new technologies, in this case specifically 3-D computer-aided design and CNC milling, bring inspiring advantages into the field of traditional ceramic production, specifically within the educational environment. It categorically revolutionizes the tedious process of mould-making. SolidWorks® offers impressive design capabilities and CNC milling reduces manufacturing time in the development of accurate prototypes with a high degree of complexity. In a fully integrated computer process these two technologies offer ground-breaking and exciting possibilities for the studio ceramicist and particularly to the contemporary ceramic industry and market. Artistic value can be re-introduced into batch and possibly mass produced ceramic ware and in this manner technology more frequently associated with engineering may positively contribute to the artistic possibilities available to the studio ceramicist.

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# Addendums

**Addendum 1:** Necurite 630 - material information data sheet

# NECURITE® 630

## Data Sheet

1/2

**Characteristics:**

- Made of recycled polyurethane
- large volume board material based on PU
- good edge stability
- good scratch-resistance
- dimensionally stable
- paintable
- compatible with silicone

**Applications:**

- master and copy models
- cubing and data models
- styling and design models
- wind tunnel and water channel models
- architectural models
- general modelling

**Technical data:**

| | |
|---|---|
| Colour | beige |
| Coefficient of thermal expansion: | variable |
| Temperature resistance: | approx. 48 °C |
| Shore D | approx. 71 |
| Compressive strength: | approx. 8 - 10 N/mm² |
| Flexural strength: | approx. 6 - 8 N/mm² |
| Density: | approx. 0,625 g/cm³ (+/-0,025) |
| Abrasion resistance (at defined parameters) | approx. 3680mm³ (2,3 g/5 min.) |
| Fire protection classification | B2 |
| Thermal conductivity | approx. 0,060 – 0,080 W/mk |

- manufactured fluorocarbohydrate-free
- physiolgically harmless

**Measurements:**

| | | | |
|---|---|---|---|
| 1500 | 500 | 50 | mm |
| 2000 | 1000 | 50 | mm |

Surface machined parallel, other dimensions on request

**Storage/Transport:**

NECURITE®-boards should be stored on a flat underground and in a dry space at a temperature between 18℃ and 25℃.
Variations in temperature should be avoided during the transport and storage.

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# NECURITE® 630

## Data Sheet

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**Processing:**

| Adhesive / Putty | Colour | Mixture ratio A to B (by weight) | Pot life In minutes at 20°C | Curing time at 20°C in hours |
|---|---|---|---|---|
| NECURON® K6 | brown | 1:1 | 2-3 | 0,5 |
| NECURON® K8 | colourless transparent | 1:1 | 10 | 4-6 |
| NECURON® S6 | brown | 1:1 | 10-12 | 6-8 |

Or usual and compatible patternmaking adhesives/resins
We recommend that boards are plane-parallel to ensure good glue joints.

**Machining:**

Machining temperature: 20°C - 25°C
Tools: metal-cutting tools

**Milling parameters:**

| | Roughing | Finishing |
|---|---|---|
| Type of tool | Finishing tools d=80mm | Finishing tools d=80mm |
| Tool diameter [d] (mm) | 80 | 80 |
| Cutting speed.[Vc] (m/sek) | 50 | 50 |
| Speed [n] (1/min) | 12000 | 8000 |
| Feed speed (m/min) | 10 | 7,5 |
| Tooth speed [fz] (mm) | 0,21 | 0,21 |
| Number of teeth [z] | 4 | 4 |
| Cutting depth [$a_e$] (mm) | 4 | 0,5 |
| Cutter mark lenght [$f_{zeff}$] (mm) | 38 | 5 |

**NECURITE® 630**

This material does not contain any fillers that release harmful dust during machining. Nevertheless the dust content in the air should not rise above 6 mg/m³. Safety procedures recommended by the vocational co-operative of the chemical industry should be complied with. The article is not a regulatory product according to ICC regulations. In accordance with general local and national regulations waste is to be disposed by incineration in authorised places or conveyed to authorised tips (EAK 120105).

Technical statements and recommendations refer to current standard of technique and are based on our own experience. Further developments and improvements are reserved. Due to the variety of processing possibilities own experiments are recommended to optimise results.

© NECUMER-PRODUCT GmbH – Bruchheide 16 - D-49163 Bohmte Tel +49 (0) 5471/95020 - Fax +49 (0) 5471/950299
E-Mail: info@necumer.de - Internet www.necumer.de Version: 04 March 2010

Addendum 1: (http://www.amtcomposites.co.za/products/tooling-materials/necuron-tooling-boards/necurite-630)

**Addendum 2:** Fastcast Polyurethane F19 data sheet

AXSON TECHNOLOGIES

# F 19

**FASTCAST POLYURETHANE**
**CAN BE FILLED**
***POT LIFE : 7 MIN - VERY LOW SHRINKAGE***

## APPLICATIONS

- *Negatives, molds, masters and mock-ups using the unfilled product or filled with RZ 30150 mineral filler in order to limit exotherm and to get easy machining.*
- *Thermoforming molds using the product filled with RZ 209/6 aluminium powder in order to increase its thermal conductivity.*

## PROPERTIES

- *Very low shrinkage*
- *Low viscosity*
- *Easy-to-use mix ratio (1:1 by weight)*
- *High filler content possible while retaining a low viscosity*

| PHYSICAL PROPERTIES | | | | | |
|---|---|---|---|---|---|
| | | PART A | PART B | UNFILLED MIXING | MIXING FILLED WITH RZ 30150 |
| Composition | | POLYOL | ISOCYANATE | | |
| Mixing ratio by weight | | 100 | 100 | - | 360 |
| Aspect | | liquid | liquid | liquid | liquid |
| Color | | off-white | dark amber | beige | beige |
| Brookfield LVT viscosity at 25°C (mPa.s) | - | 100 | 55 | 78 | 2,600 |
| Density of parts before mixing<br>Density of cured mixing | ISO 1675-85<br>ISO 2781-88 | 0.93 - 0.99<br>- | 1.05 - 1.11<br>- | -<br>1.04 – 1.10 | -<br>1.66 – 1.72 |
| Pot life at 25°C on 200g (min) | - | | | 6 - 8 | 8 - 10 |

| MECHANICAL PROPERTIES AT 23°C (1) | | | | |
|---|---|---|---|---|
| | | | UNFILLED MIXING | MIXING FILLED WITH 360% OF MIXING RZ 30150 |
| Hardness | ISO 868-85 | Shore D1 | 72 | 79 |
| Flexural modulus of elasticity | ISO 178-93 | MPa | 1,200 | 4,100 |
| Flexural strength | ISO 178-93 | MPa | 50 | 41 |
| Compressive strength | ISO 604-93 | MPa | 48 | 55 |
| Charpy impact resistance | ISO 179/1eU-93 | kJ/m² | 16 | - |

(1) : Average values obtained on standardized specimens / Hardening 16 hours at 80°C



**AXSON France**
BP 40444
95005 Cergy Cedex
FRANCE
Tél. (++33) 1 34 40 34 60
Fax (+33) 1 34 21 97 87
Email : axson@axson.fr

**AXSON GmbH**
Dietzenbach
Tél. (++49) 60 74 407110

**AXSON ITALIA**
Saronno
Tel. (++39) 02 96 70 23 36

**AXSON IBERICA**
Barcelona
Tel. (++34) 93 225 16 20

**AXSON UK**
Newmarket
Tel. (++44) 1638 660 062

**AXSON Central Europe**
Zlate Moravce
Tel. (++421) 376422526

**AXSON MEXICO**
Mexico DF
Tel. (++52) 5552644922

**AXSON SHANGHAI**
Shanghai
Tel. (++86-21) 58683037

**AXSON NA USA**
Eaton Rapids
Tel. (++1) 517 6638191

**AXSON JAPAN**
Okazaki city
Tel.(++81) 564 262591

**AXSON MIDDLE EAST**
Info.middleeast@axson.com

**AXSON INDIA**
Pune
Info.india@axson.com

**AXSON KOREA**
Seoul
Info.korea@axson.com

# F 19

**FASTCAST POLYURETHANE**
**CAN BE FILLED**
***POT LIFE : 7 MIN - VERY LOW SHRINKAGE***

| THERMAL AND SPECIFIC PROPERTIES (1) | | | | |
|---|---|---|---|---|
| | | | UNFILLED MIXING | MIXING FILLED WITH 360% OF MIXING RZ 30150 |
| Glass transition temperature | T.M.A.-Mettler | °C | 100 | |
| Linear shrinkage<br>- thickness : 10 mm<br>- thickness : 60 mm | | mm/m | 0.8<br>- | -<br>0.7 |
| Coefficient of thermal expansion [+20, +70]°C | T.M.A.-Mettler | $10^{-6}K^{-1}$ | - | 80 |
| Can be demolded at 25°C after<br>- thickness : 10 mm<br>- thickness : 60 mm | - | min.<br>min. | 90<br>- | -<br>150 |

## PROCESSING CONDITIONS

*Before use part A (polyol) must be mixed until both color and aspect become homogeneous. Both parts (polyol and isocyanate) must be mixed at a temperature above 18°C according to the mix ratio indicated on this technical data sheet. For casting thicknesses between 5 mm and 60 mm maximum it is recommended to add a filler as follows:*

| *Part A* | *Part B* | *RZ 30150* | *RZ 209/6* |
|---|---|---|---|
| *100* | *100* | *360* | *380* |

*For bigger casting thicknesses please contact our Customer Service.*

## STORAGE CONDITIONS

*Shelf life of both parts is 12 months in a dry place and in their original unopened containers at a temperature between 15 and 25°C. Any open can must be tightly closed under dry nitrogen.*

## HANDLING PRECAUTIONS

*Normal health and safety precautions should be observed when handling these products :*

- *ensure good ventilation*
- *wear gloves, safety glasses and clothes.*

*For further information, please consult the product safety data sheet.*

## PACKAGING

| *Polyol (Part A)* | *Isocyanate (Part B)* |
|---|---|
| *1 x 4.5 kg* | *1 x 4.5 kg* |
| *1 x 18.0 kg* | *1 x 18.0 kg* |

## GUARANTEE

*Information of our technical data sheet is based on our present knowledge and the result of tests conducted under precise conditions. It is the responsibility of the user to determine the suitability of AXSON products for his application under his own conditions. AXSON refuses any guarantee about the compatibility of a product with any particular application. AXSON disclaims all responsibility for damage from any incident which results from the use of these products. The guarantee conditions are regulated by our general sale conditions.*

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Addendum 2: (http://www.amtcomposites.co.za/products/casting-resins-foams/urethane-plastics/f19)

**Addendum 3:** Supawood – material information data sheet

**PG BISON** PANEL PRODUCTS

ALRODE
PO Box 123948, Alrode, 1451, South Africa
Tel +27 11 389 2000 Fax +27 11 908 3546
Date: May 2007

DATA SHEET
TECHNICAL DATA
SUPAWOOD M.D.F
Superfine

SUPA WOOD

| PROPERTY | TEST METHOD | UNITS | SABS 540-1:1991 | | | | |
|---|---|---|---|---|---|---|---|
| THICKNESS | | mm | 12 | 16 | 18 | 22 | 32 |
| Thickness Tolerance: Sanded (within and between boards) | SABS 1174 | mm (max) | - 0.3 | | | | |
| Thickness Tolerance: Unsanded | SABS 1174 | mm (max) | ± 0.5 | ± 0.5 | ± 0.7 | ± 0.7 | ± 1.0 |
| Length & Width Tolerance | SABS 1174 | mm/m (max) | Length: -3 to +12; Width: -3 to +5 | | | | |
| Edge Straightness Tolerance | SABS 970 | mm/m (max) | 1.0mm per 1200mm | | | | |
| Edge Squareness Tolerance | SABS 817 | mm/m (max) | 1.5 | | | | |
| Moisture Content | EN 322 | % (max) | NS | | | | |
| Density variation within board | SABS 1175 | % (max) | ± 10 | | | | |
| Density | SABS 1175 | $Kg/m^3$ | 550 - 940 | | | | |
| Flatness Tolerance | SABS 969 | mm/m (max) | NS | NS | NS | NS | NS |
| Bending Strength (MOR) | SABS 1015 | MPa (min) | 30 | 30 | 30 | 30 | 25 |
| Modulus of Elasticity (MOE) | SABS 1015 | MPa (min) | 2500 | 2500 | 2500 | 2000 | 2000 |
| Internal Bond Strength | SABS 1016 | MPa (min) | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 |
| Surface Soundness | EN 311 | MPa (min) | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 |
| Thickness Swelling (24hr) | SABS 1012 | % (max) | 12 | 12 | 12 | 12 | 12 |
| Water Absorption (24hr) | SABS 1012 | % (max) | 8 | 8 | 8 | 8 | 8 |
| Internal Bond after cyclic test | EN 321 | MPa (min) | NS | | | | |
| Thickness Swelling after cyclic test | EN 321 | % | NS | | | | |
| Screw Holding - Face | SABS 1018 | N (min) | 1100 | 1100 | 1100 | 1100 | 1100 |
| Screw Holding - Edge | SABS 1018 | N (min) | 900 | 900 | 900 | 900 | 900 |
| Formaldehyde Potential | EN 120 | mg/100g | Either Class E1 or Class E2 | | | | |
| Toluene Run Test | BS EN 382-1:1993 | mm (min) | NR | | | | |
| Fire Rating | SABS 0177 | Class | NS | | | | |
| Weight of BOARD per square meter | Factory STD | Kg/m3 | NS | | | | |

NOTES: NS = NOT SPECIFIED IR = INTERNAL REQUIREMENT CLASS E1 ≤ 8mg/100g CLASS E2 ≤ 40mg/100g

*Application Type: General Purpose Board for use in dry conditions*

A MEMBER OF STEINHOFF INTERNATIONAL

**PG BISON** PANEL PRODUCTS

ALRODE
28 Dan Jacobs Street, Alrode, Gauteng, 1428
PO Box 123948, Alrode, 1451, South Africa
Tel +27 11 389 2000 Fax +27 11 908 3546
Date: May 2007

**DATA SHEET**

**SUPAWOOD**

| | |
|---|---|
| **BRANDNAME** | **SUPAWOOD** |
| **GENERIC NAME** | Medium Density Fibreboard (MDF) Supawood |
| **PRODUCT DEFINITION** | Medium Density Fibreboard is a panel product consisting of wood fibre that is bonded together with a synthetic resin under heat and pressure. |
| **SPECIFICATION** | SABS 540-1 : 1991. *Fibreboard products. Part 1: Uncoated Fibreboard* |
| **ATTRIBUTES** | High density, smooth surface, good screw holding, low dimensional movement, low tool wear, low dimensional tolerances, high strength, low deviation to flatness, high internal bond strength, excellent machinability, good creep resistance when surfaced, good moisture resistance, excellent paintability, availability and price advantages. |
| **APPLICATIONS** | Furniture and fitments in the domestic, office and building industry.<br>Substrate for Formica HPL,<br>Veneers,<br>Foils (Vinyl and Paper) Printing and Painting (See typical application list.) |
| **LINKED TO** | Supalam (Supawood with decorative Melamine impregnated surface).<br>Supaply (Supawood with natural Veneer surface).<br>Supadecor (Supawood with Melamine coated paper foil surfaces).<br>Board 13 Composite Board (Supawood with Formica HPL or Deccon CPL surfaces). |
| **FABRICATION** | Similar to solid wood. |

NOTES:

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Addendum 3: (www.pgbison.co.za/downloads/Product%20Spcifications%202008.pdf)

**Addendum 4:** Taegu Tec ChaseMill TE90AX series dimensions

| D | d | L | *l* |
|---|---|---|---|
| 10 | 10 | 80 | 25 |
| 10 | 10 | 80 | 25 |
| 12 | 12 | 80 | 25 |
| 12 | 16 | 80 | 25 |
| 14 | 12 | 80 | 25 |
| 16 | 16 | 90 | 30 |
| 16 | 16 | 145 | 30 |
| 16 | 16 | 90 | 30 |
| 18 | 16 | 90 | 30 |
| 18 | 16 | 90 | 30 |
| 20 | 20 | 170 | 30 |
| 20 | 20 | 110 | 30 |
| 20 | 20 | 90 | 30 |
| 22 | 20 | 110 | 30 |
| 22 | 20 | 110 | 30 |
| 25 | 25 | 210 | 40 |
| 25 | 20 | 110 | 30 |
| 25 | 25 | 110 | 30 |
| 25 | 20 | 110 | 30 |
| 30 | 25 | 130 | 30 |
| 30 | 25 | 130 | 32 |
| 32 | 32 | 250 | 32 |
| 32 | 25 | 130 | 32 |
| 32 | 25 | 130 | 32 |
| 40 | 32 | 250 | 32 |
| 40 | 32 | 130 | 32 |
| 40 | 32 | 130 | 32 |

Figure 151: ChaseMill TE90AX dimensions

**Addendum 5:** Somta Carbide End Mill 2 flute long series dimensions

| d | l2 | l1 |
|---|---|---|
| 3 | 19 | 57 |
| 4 | 19 | 57 |
| 5 | 25 | 64 |
| 6 | 28 | 76 |
| 8 | 29 | 76 |
| 10 | 32 | 102 |
| 12 | 51 | 102 |
| 14 | 57 | 127 |
| 16 | 57 | 127 |
| 18 | 57 | 127 |
| 20 | 57 | 127 |
| 25 | 57 | 127 |

Figure 152: Somta Carbide End Mill 2 flute long series dimensions

**Addendum 6:** Additional designs

Figure 153: Additional design 1

Figure 154: Additional design 2

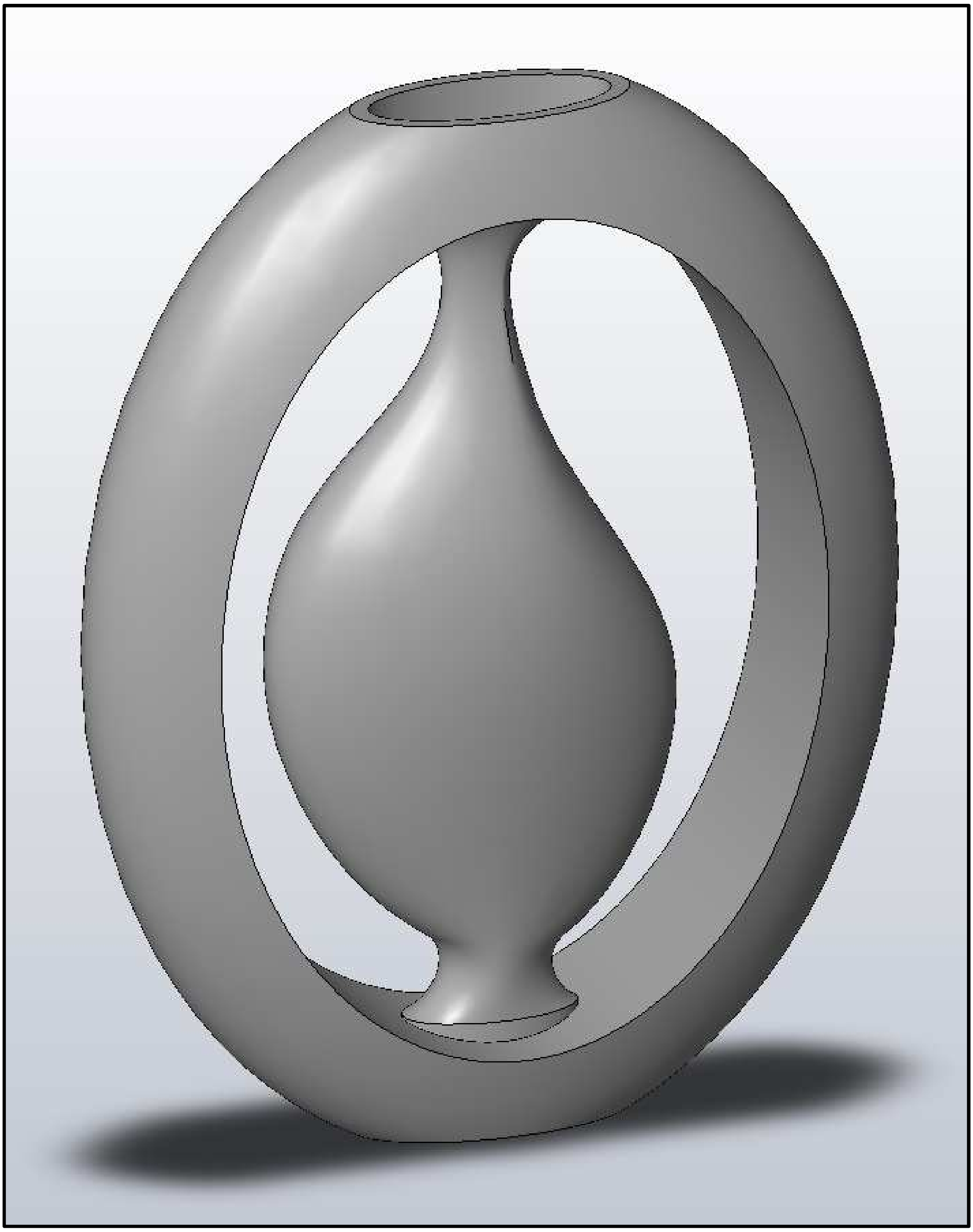

Figure 155: Additional design 3

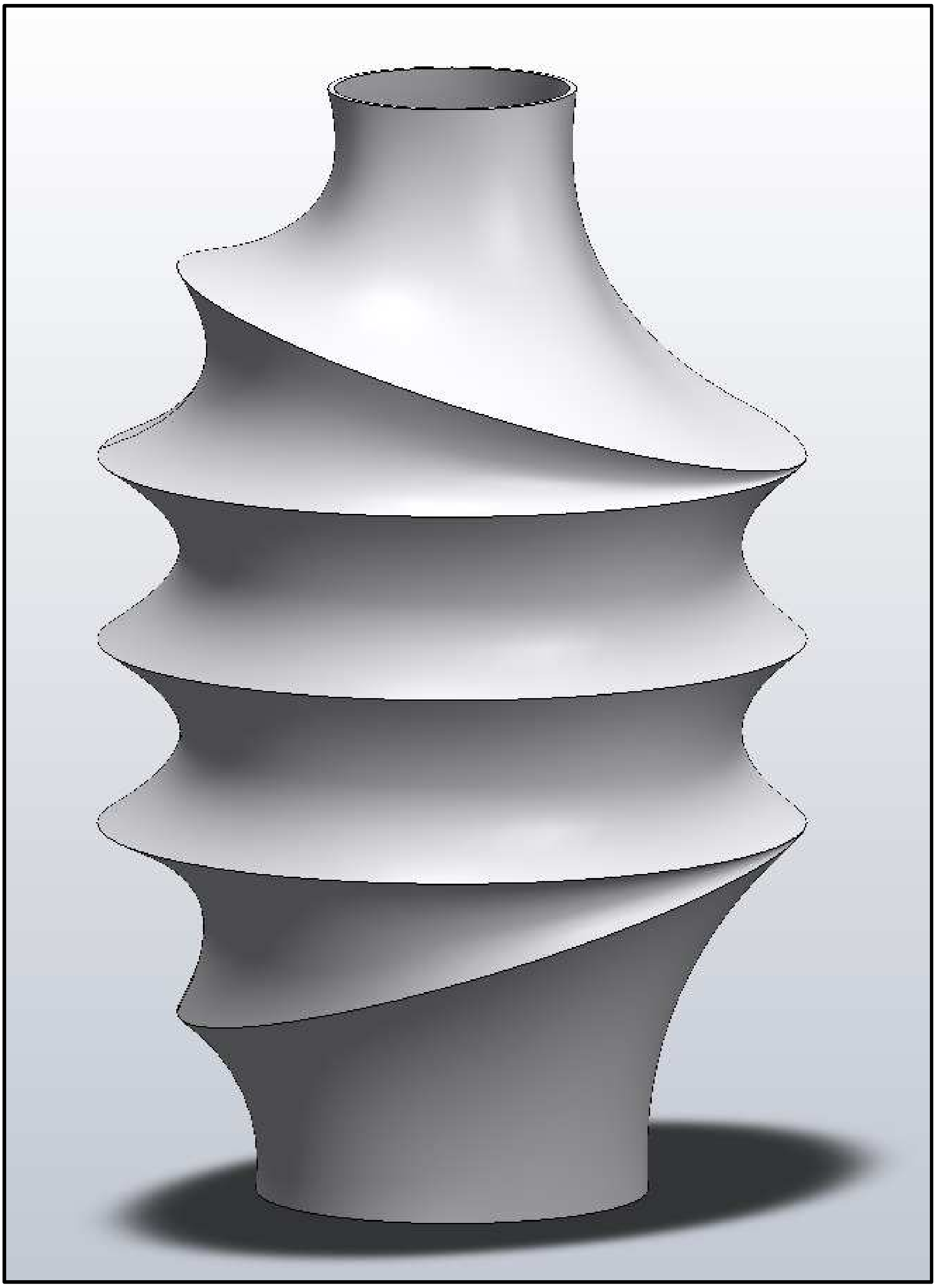

Figure 156: Additional design 4

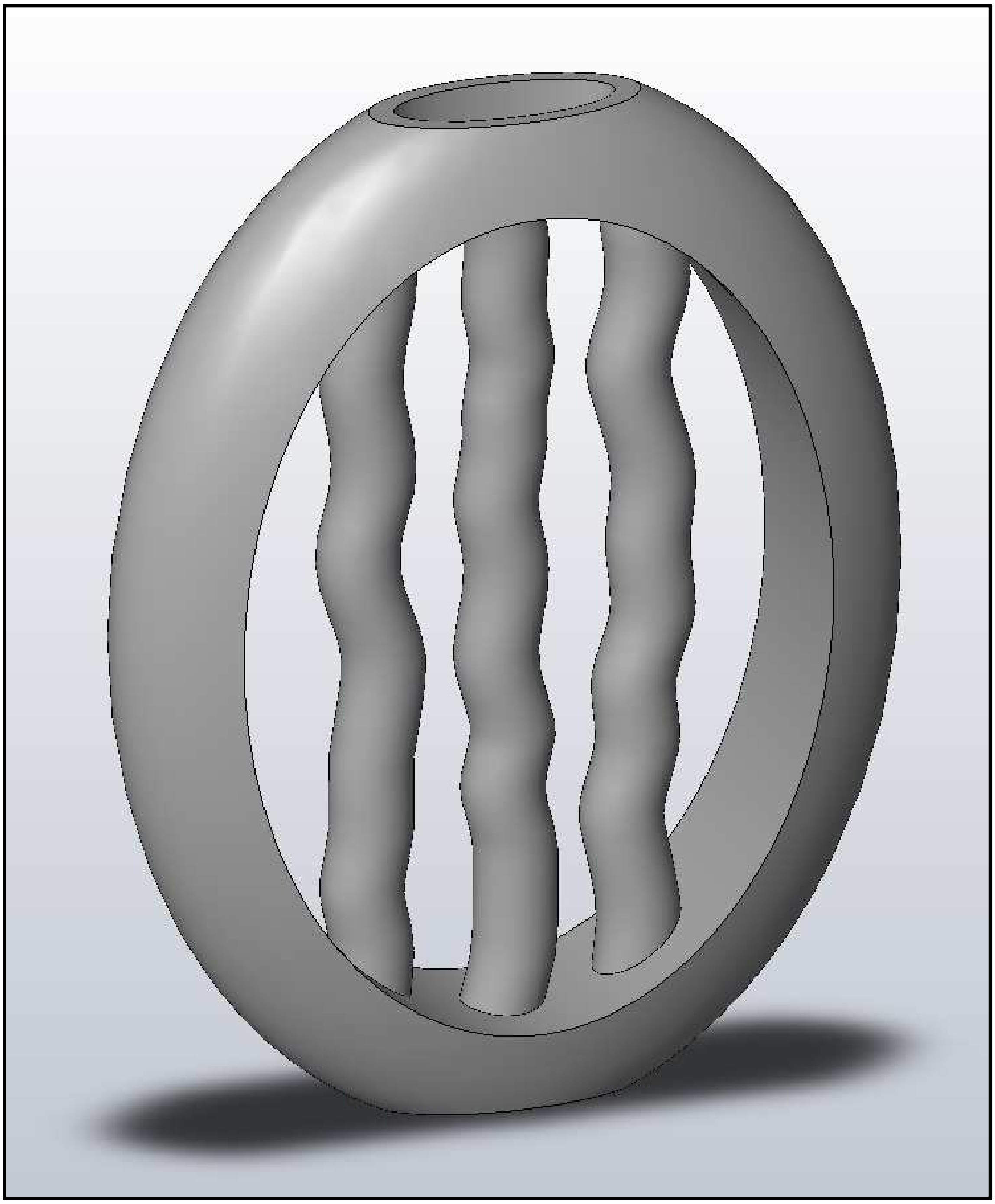

Figure 157: Additional design 5