PERPUSTAKAAN UMP
0000096928

Computer N C) Machining for Rapid Manufacturing Processes

by

Muhammed Nafis Osman Zahid

A Doctoral Thesis

Submitted in partial fulfilment
of the requirements for the award of

Doctor of Philosophy
of
Loughborough University

SEPTEMBER 2014

Copyright 2014 Muhammed Nafis Osman Zahid

Abstract

The trends of rapid manufacturing (RM) have influenced numerous developments of technologies mainly in additive processes. However, the material compatibility and accuracy problems of additive techniques have limited the ability to manufacture end-user products. More established manufacturing methods such as Computer Numerical Controlled (CNC) machining can be adapted for RM under some circumstances. The use of a 3-axis CNC milling machine with an indexing device increases tool accessibility and overcomes most of the process constraints. However, more work is required to enhance the application of CNC for RM, and this thesis focuses on the improvement of roughing and finishing operations and the integration of cutting tools in CNC machining to make it viable for RM applications. The purpose of this research is to further adapt CNC machining to rapid manufacturing, and it is believed that implementing the suggested approaches will speed up production, enhance part quality and make the process more suitable for RM. A feasible approach to improving roughing operations is investigated through the adoption of different cutting orientations. Simulation analyses are performed to manipulate the values of the orientations and to generate estimated cutting times. An orientations set with minimum machining time is selected to execute roughing processes.

Further development is carried out to integrate different tool geometries; flat and ball nose end mill in the finishing processes. A surface classification method is formulated to assist the integration and to define the cutting regions. To realise a rapid machining system, the advancement of Computer Aided Manufacturing (CAM) is exploited. This allows CNC process planning to be handled through customised programming codes. The findings from simulation studies are supported by the machining experiment results. First, roughing through four independent orientations minimized the cutting time and prevents any susceptibility to tool failure. Secondly, the integration of end mill tools improves surface quality of the machined parts. Lastly, the process planning programs manage to control the simulation analyses and construct machining operations effectively.

Contents

List of Figures

List of Tables

List of Abbreviations

Acronyms	Definition
3DP	Three Dimensional Printing
ABS	Acrylonitrile Butadiene Styrene
Add-O	Additional Orientation
AM	Additive Manufacturing
API	Application Programming Interface
ArcHLM	Arc Hybrid-Layered Manufacturing
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CAPP	Computer Aided Process Planning
CAT	Computer Axial Tomography

Acronyms	Definition	Acronyms	Definition
CNC	Computer Numerical Control	RP	Rapid Prototyping
D	Dimension	RP&M	Rapid Prototyping & Manufacturing
EBM	Electron Beam Melting	RPTM	Rapid Prototyping, Tooling and Manufacturing
EDM	Electrical Discharge Machine	RT	Rapid Tooling
FDM	Fused Deposition Modelling	SiC	Silicon Carbide
GUI	Graphical User Interface	SLA	Stereolithography
HisRP	High Speed Rapid Prototyping	SLM	Selective Laser Melting
Ind-O	Independent Orientation	SLS	Selective Laser Sintering
IPW	In-process Workpiece	SPI	Society of the Plastics Industry
LENS	Laser Engineering Net Shaping	SRP	Subtractive Rapid Prototyping
MCS	Machine Coordinate System	STL	Standard Tessellation Language
MIG	Metal Inert Gas	TAV	Tool Access Volume
MRI	Magnetic Resonance Image	UAM	Ultrasonic Additive Manufacturing
MRR	Material Removal Rates	WEDM	Wire cut Electrical Discharge Machine
RDVC	Relative Delta Volume Clearance		
RM	Rapid Manufacturing		

List of Symbols

Symbols	Definition/Units	Symbols	Definition/Units
%	Percentage	mmpm	Millimetres per minute
µm	Micro metre	Ø	Diameter
^{0}	Angles	rpm	Revolutions per minute
mm	Millimetres	Θ	Range on visibility orientation
θ	Input angle		

CHAPTER 1

INTRODUCTION

1.1 Research overview

In recent years, the goals of manufacturing systems have become more intense due to global competition in product development. In order to reach the market quickly, products need to be manufactured within time frames that are commonly used to produce prototypes (Koren 2010). Consequently, this trend has attracted the attention of technology developers to improve the current manufacturing methods employed in making prototypes. Historically, rapid prototyping (RP) technologies were introduced in the 1980s and were used to quickly create prototypes in an automated manner. The main purpose of this group of technologies was to assist new product development particularly for analysis and evaluation processes. RP allows design changes at early phases of product development and confirms validity of the product before entering full scale production. As RP technologies have evolved, their role has expanded to produce finished parts or end-user products. Instead of being used just for conceptualization, the advancements of technology have empowered the process to produce high specification products such as moulds and tooling, customised parts and biomedical components (Yan et al. 2009, Eyers et al. 2010, Campbell et al. 2012). Hence, several new terminologies have been introduced to reflect the evolution of the technology which includes rapid manufacturing (RM), rapid tooling (RT) and rapid prototyping and manufacturing (RP&M).

In order to establish RP technology as a reliable manufacturing method, several different techniques have been developed and commercialized. Most of the techniques have been developed based on an additive mechanism that builds the part by stacking layers of material (liquid, powder or sheet) until the entire object is formed (Wohlers 2008). Further developments have invented some advanced techniques that are capable of processing metallic materials instead of just producing polymeric products. Using more powerful energy sources such as electron beams, the part is constructed by melting and joining layers of material, maintaining the additive mechanism. This is recognized as an additive manufacturing (AM) process which is intended to handle RM and RT applications. However, as the technology continues to evolve and process requirements become more complex, AM faces several difficulties in coping with the high demands of manufacturing end-user products. Currently, the process is still struggling to resolve several limitations that restrict its abilities. Even the technology capable of processing metallic materials, may not be able to fully cater for several important issues which include roughness, accuracy, manufacturing materials and final part properties (Campbell et al. 2012, Wong et al. 2012). Most research work has been only focused on improving AM processes or materials, neglecting other methods that could be adopted for RM applications.

On the other hand, direct manufacture of metal parts is one of the key indicators for the process to be used in RM applications. Qualitative assessment of various processes that are capable of producing metal parts is presented in Figure 1.1. According to this diagram, only two processes are capable of directly fabricating metal parts. The rest can be considered as indirect processes because they use other methods such as moulds and dies to actually produce the parts. Since the limitations of AM processes remain unsolved, alternative methods need to be considered for RM such as cutting operations. However, there is a limitation in terms of part complexity despite the capability to handle low to medium production quantities. This method of manufacturing is categorized under subtractive processes. Essentially, further investigation is required to explore the capability of this method in RM processes.

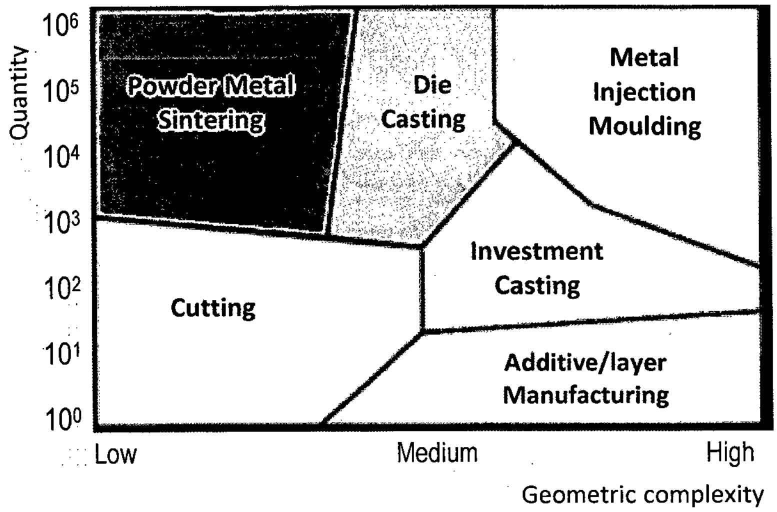

Figure 1.1: Qualitative assessment of different processes in producing metal parts (Levy et al. 2003)

Subtractive rapid prototyping (SRP) is a conventional technology that has been previously used to create prototypes. In general, the term subtractive means the process of removing material away from the workpiece to form physical objects (Burns 1993). Traditionally, the cutting process utilizes hand tools to shape the materials and produce the part. Later, the introduction of CNC technology has improved the process with the capability of performing different kinds of machining operations. This technology was developed before the introduction of various AM processes. However, due to the attractive features of AM processes namely their easy of operation, increased design freedom, high automation and speed of production, the development of CNC machining has been left behind and has not been fully considered for RM applications.

In terms of process capabilities, CNC machining employs a different mechanism in building the part which is totally opposite to AM processes. Cutting tools are used to penetrate and remove material from the workpiece. Hence, a great variety of denser and stronger materials such as pure metals can be directly machined. In addition, greater part accuracy and superior surface finish are among the interesting features promised by CNC machining processes. Unfortunately, all these benefits do not in themselves fully justify the implementation of CNC machining for rapid processes.

There are several factors that limit the ability of CNC machining to be incorporated in RM processes. The central issue relies on the absence of rapid machining systems to assist in the setup planning before executing cutting operations (Frank 2007). Unlike AM processes, CNC machining requires a proper process plan that primarily involves the development of cutting toolpaths. Many variables need to be defined in the planning stage including cutting parameters and tool sizes. A common solution is to leave all the decisions to the skilled machinist in order to develop an effective machining program. As a result, the planning tasks are highly dependent on human inputs and this restricts process automation which is an important part of the requirement for a rapid system. Another limitation can be seen in terms of the approach to fixturing and tooling. If the part possesses intricate and complex features, special tools and fixturing methods are required to develop the geometries. In the case of re-fixturing the part, the coordinate system must be setup again. These time consuming activities still limit the performance of CNC machining even though it is capable of surmounting many of the inherent limitations presented by AM processes.

Recent developments in the application of CNC machining for rapid processes have led to a renewed interest in adopting this technology. A novel approach known as CNC-RP manages to use the subtractive process in RP&M applications. The CNC-RP methodology utilizes a conventional 3-axis milling machine with two opposite 4th axis indexers and is able to machine parts from various cutting directions (Frank et al. 2002). Machining from different orientations is proven to expand the accessible regions and allows the creation of parts with complex shape. Since various materials can be machined with high precision and accuracy, this process is suitable for making ordinary prototypes, tools, customised parts or any components for small production runs. Prototypes that possess similar material properties as in full scale production will enable real validation and testing processes. But, the application of CNC-RP goes far beyond component testing. CNC machining is capable of fabricating tools that can be used for mass production. Similarly, it also can produce final parts especially for more demanding applications with tight requirements. The capability of CNC machining to produce parts directly from Computer Aided Design (CAD) models will bring the product to market sooner with minimum development cost (Rosochowski et al. 2000).

This thesis proposes and evaluates further improvements in CNC-RP methodology and is specifically focused on making the process compatible to RM applications. In the global market, other than producing new products with minimum cost and time, it is also necessary to achieve high quality (Lan 2009). Therefore, there are two crucial aspects that can be considered process requirements. First, the production time which includes both time spent in the process planning and part fabrication must be kept to a minimum. Thus, process automation and optimization are the key solutions to fulfil this requirement. RM processes are specifically used to produce final parts that will be directly delivered to the user. Hence, quality attributes become a major concern and must be enforced on the part produced. This can be seen in terms of accuracy and surface integrity. In order to propose the improvements, further investigations on the process methodology are carried out.

1.2 A glimpse of CNC-RP

Generally, three distinct developments based on cutting orientations, toolpath planning and fixturing approaches have succeeded in establishing rapid machining using CNC processes. The use of indexing devices allows the workpiece to be rotated to various angles. In order to determine sufficient cutting orientations, visibility analysis is performed on the part prior to the machining processes (Frank et al. 2006). The output of the analysis is a minimum set of orientations that allows the cutting tool to reach the entirety of the part surfaces. Hence, all geometries that are visible from at least one of the orientations can be completely machined. Within each cutting orientation, roughing and finishing operations are performed one after another (Frank 2007). Several requirements need to be obeyed during cutting operations that are basically related to cutting levels and machining sequences. Once completed, the workpiece is rotated to the next orientation that reveals new surfaces to be machined. During this process, the workpiece remains on the indexing device and thus preserves the original coordinate system, hence eliminating the rework of further setups. The processing steps in CNC-RP are visualized in Figure 1.2.

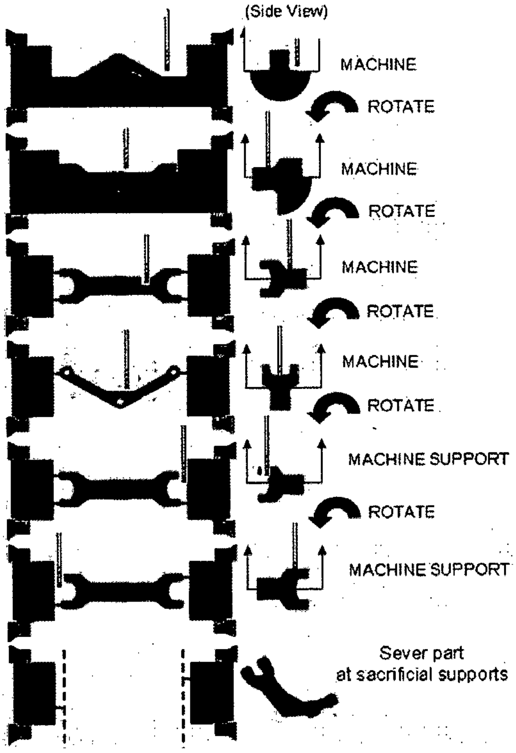

Figure 1.2: Processing steps in CNC-RP (Wysk 2008)

CNC-RP employs a feature free approach which does not consider any features that may be present on the part. Therefore, universal toolpath planning is adopted that simply machines all surfaces on the part. The smallest tool diameter is selected in finishing operations with the aim of reaching all part geometries (Frank 2003). Most of the cutting parameters are standardized for both roughing and finishing operations. Some of the decisions may not be the most favourable for machining operations, but, it allows the rapid generation of toolpaths and fulfils the requirements for RM processes. The fixturing method employs the addition of small diameter cylinders parallel to the axis of rotation at both ends of the part. These supports are machined simultaneously with the part and remain connected to the workpiece once machining has been completed. These sacrificial supports must be then removed during later post processing. Most of the tasks performed in CNC-RP are assisted by customised algorithms that are incorporated in commercial Computer Aided Design/Computer Aided Manufacturing (CAD/CAM) packages.

1.3 Problem statement

Implementation of CNC machining in RM processes requires different approaches that contradict common practice. The nature of machining processes involves considerable human input to control and run the operation. This is different from other RM tools such as AM processes that tend to have less human involvement and are fully automated during production. In order to incorporate CNC machining in RM processes, new approaches have been developed which manage to adopt extensive levels of automation in the processing steps. However, there are several issues with current implementations that cause inefficiency and limitations to the process. In general, this can be perceived from three different perspectives that relate to cutting orientations, tooling approach and process planning.

The integration of a 3-axis milling machine and 4th-axis indexers for CNC-RP preserves some flexibility in the system to rotate the workpiece to various orientations. As illustrated in Figure 1.3, different cutting directions possess different levels of accessibility. Therefore, an algorithm is developed to assess the surface visibility of the part from different directions (Frank et al. 2006). Basically, the main purpose of visibility analysis is to determine the necessary cutting orientations to fully machine the part. Hence, the orientations proposed are meant to be effective during the last stage or in finishing operations that guarantee tool accessibility to all surfaces (Renner 2008). In early developments, only a single operation is performed within each cutting orientation. Later development introduced separated operations where a rough cut is performed first followed by a finishing process within the same orientation. So, instead of removing the bulk of the material, the finish cut just needs to remove the remaining material not accessible to the roughing tool.

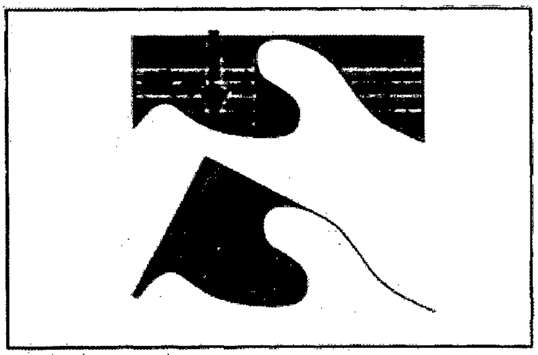

Figure 1.3: Cutting tool accessibility (Frank et al. 2004)

During roughing operations, the cutting tool needs to remove a large amount of material and penetrate the workpiece until the maximum cutting depth is reached and this is dependent on the tool length. The condition of this machining is visualized in Figure 1.4. This is a part of the requirement to prevent the formation of thin material (thin webs) during the subsequent cutting orientations which is an undesirable situation in machining. Another method to avoid this problem is by machining with at least three cutting directions.

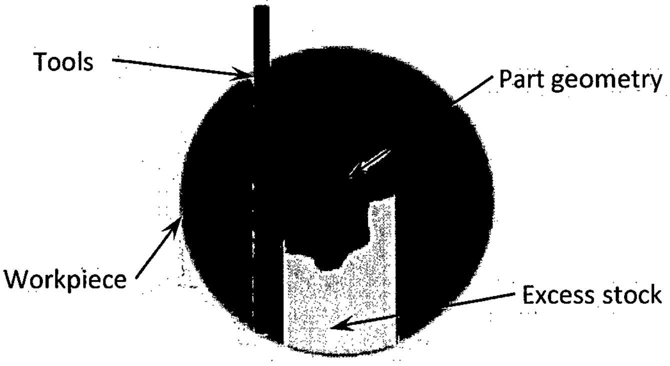

Figure 1.4: Long cutting depth adopted by CNC-RP (Frank 2007)

There are two issues that can be investigated based on current implementations. First, constraining roughing operations to cutting orientations also used for finishing processes tends to limit the possibility of optimising the process. Therefore, instead of relying on the orientations proposed by visibility analysis, roughing operations can be performed at different angles that aim for high volume removal and minimum machining time. So far, however, no research has been found that attempts to optimise the roughing operation in order to improve overall process efficiency. Since the process is highly dependent on part geometries, this serves as an alternative approach to cutting the workpiece from various orientations.

The second issue is related to the cutting level employed in the roughing operation. The drawbacks of this decision can be seen in terms of tool usage and selection. Cutting operations involve physical contact between the tool and workpiece. One of the factors that effects tool performance is the contact length which will influence flank wear and tool temperature (Sadik et al. 1995). Hence, a long tool contact length can easily cause a deflection due to the cutting forces generated. Without appropriate control of machining parameters, the cutting tool is subjected to bending, distortion and chatter during machining. All these phenomena directly affect the quality of the machined part. In CNC-RP, process continuity between each orientation is paramount. Any tool breakage will interrupt the coordinate system including tool location and leads the whole operation to fail. One of the tool requirements for this operation is to have sufficient flute length to keep the tool close to the part and excess stock. This tends to cause restrictions in the selection of a tool as a long cutting tool is not commonly used and available. Therefore, the determination of cutting levels in this process needs to be revised. However, far too little attention has been paid to minimizing the cutting levels due to the requirement of thin web avoidance rules.

The tooling approach in CNC-RP is quite straightforward. Originally, the selection of cutting tools is just based on the smallest diameter available for the predetermined length that depends on workpiece size (Frank et al. 2002). Hence, the depth of cut is set at a minimum to achieve the required surface finish. However, neglecting some important parameters has resulted in inefficiency during the machining operations. For example, using a single tool size simplifies the toolpath development but the trade-off of this decision is a slow rate of material removal. Therefore, roughing operations are proposed to counter this inefficiency problem. The tool size is selected based on a linear relationship with the workpiece diameter. In addition, a flat end mill is commonly used to machine the part since the process relies on 2D cross sectional slices of the model (Frank 2003). Therefore, a staircase effect is developed on part surfaces as can also commonly be seen in AM processes. But, the capability of CNC machining to cut at very shallow depths minimizes the appearances of stepping.

In CNC machining, the development of cutting toolpaths is carried out by a CAD/CAM system. It is undeniable that these systems are capable of assisting in toolpath generation but the task of determining the type and size of cutting tool is usually overlooked (Veeramani et al. 1997). Recent developments have succeeded in proposing an optimum tool size combination by using several optimization tools (Renner 2008). However, to date, there are no clear guidelines to integrate different types of cutting tools into the process. This integration is important since in one cutting orientation, different kinds of surfaces are presented on the 3D object. Hence, using a flat end mill to machine non-flat surfaces is not really efficient as it obviously causes a staircase appearance as shown on Figure 1.5.

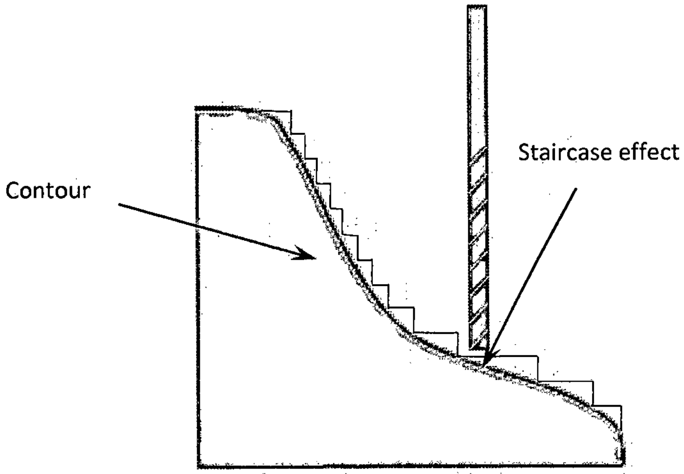

Figure 1.5: Staircase effect on contoured surfaces

Process planning in CNC machining deals with large amounts of data and requires support tools to optimise the operation. This is one of the factors that make some consider CNC process planning to be primarily a manual task (Anderberg et al. 2009). The planning task in CNC machining is crucial and directly correlated to the time, skill and cost to machine discrete parts (Frank 2007). Therefore, an efficient machining plan is usually developed through experience by skilled CAM operators (Frank et al. 2006, Relvas et al. 2004). From a production perspective, it is important to minimize the time spent in producing parts. However, from the perspective of rapid processes, the time spent on both planning and production must be kept to a minimum. Therefore, the generation speed of toolpaths and faultless machining codes needs to be increased. This is a key indicator that will determine the applicability of CNC machining in RM processes (Qu et al. 2001). The existence of Computer Aided Process Planning (CAPP) systems manages to minimize the time allocated for planning tasks. However, CAPP systems need to be developed correctly in order to produce effective machining operations. Previously, CNC-RP has preserved a certain level of automation in process planning. Hence, most of the tasks executed in the planning stage are well-assisted and established as a rapid machining system. In accordance with the automation requirement, any new approaches introduced to improve the machining operation must definitely be equipped with the planning tools to assist the development stage.

1.4 Aims and objectives

The aim of this research is:

"To strengthen the implementation of CNC machining in RM processes (CNC-RM) by improving the machining and tooling approach at the same time establishing a rapid machining system"

Further investigation of current implementations of CNC machining in rapid processes has revealed several inefficiencies in the methodology. The problems discussed in section 1.3 have clarified the gaps found in the present approaches. Hence, there are two main objectives formulated to tackle the issues raised.

Objective 1: Investigate a different strategy to improve roughing operations by manipulating cutting orientations.

1.4.1 Rationale of objective 1

Roughing operations are performed in CNC machining to remove the bulk of material from the workpiece and to generate the profile of the part. In the metal cutting industry, roughing operations are considered to be time consuming processes and can take up to 50% of the total machining time depending on the size of workpiece and part (Kuragano 1992). Since roughing and finishing operations are directly correlated, removing the bulk of the material in the first place will assist the rest of the cutting processes in finishing operations. This justifies the need to develop a proper plan for an optimum material removal process during the roughing stage. Nevertheless, a common practice in rough cutting is still employed using larger tool sizes and aggressive cutting parameters to shape the part.

Particularly in RM application, the roughing operation is supposed to be executed in the orientations that provide maximum removal volume rather than maximum surface areas. The orientation proposed by visibility analysis is totally concerned with achieving maximum surface areas so that all features are accessible by the cutting tools. Hence, finishing operations are the most likely suitable process for these orientations. On the other hand, establishing other orientations for roughing operations might be useful to improve the machining efficiency. This approach tends to increase the number of orientations which contradicts previous studies that prefer to have minimum orientations (Frank et al. 2006). But, considering an automatic indexing device is used, the rotation task can be controlled directly from the machining code. The key parameters to validate the approach are time spent to machine the part and also the effectiveness of the sequence of operations. In order to generate these parameters, virtual machining simulation is utilized to handle the analysis. An approach to determining orientations is required that possesses maximum roughing time, minimum cutting time and fulfils the cutting condition requirements.

Objective 2: Investigate the influence of different cutting tools and formulate the integration approach to be implemented in CNC-RM processes

1.4.2 Rationale of objective 2

Improving part quality in RM processes has become a major concern for manufacturers. The parts produced must exhibit the same properties and dimensional tolerances as those produced by conventional manufacturing methods such as CNC machining (Zhao et al. 2000). Previous developments that adapted CNC machining for rapid processes were capable of fulfilling this requirement. However, limited tool selection during finishing operations has restricted the ability of this process to fabricate superior quality products. Aiming for process planning simplification, there is no clear method developed to integrate different cutting tools in finishing operations. In 3-axis machining, a flat end mill possesses the capability to machine flat regions that can be represented as horizontal or vertical surfaces. However, due to the limitations in machining axes, this tool is not suitable for machining other kinds of surfaces such as free form or sculptured surfaces. As the flat end mill is the tool most likely to be adopted, the staircase appearance will be present on the machined part and this affects surface quality. This situation leads to the investigation of implementing different types of cutting tools in CNC-RM processes. Primarily, the implications can be observed through the excess volume and surface roughness of the machined parts.

A variety of tools are available in CNC machining to allow the process to handle different part surfaces. Additionally, this technology is equipped with automatic tool changing systems which can be controlled directly from coded instructions. So, incorporating different cutting tools in the machining operations would not be a problem to the system. Nevertheless, in the CNC-RM application, critical attention is required in assisting the cutting area selection within and between each of the orientations. The aim is to provide flexibility in cutting tool selection and at the same time meet the automation requirement in the planning stage. However, the nature of machining processes requires different tools to effectively machine different part features. Therefore, a universal approach needs