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Conventional machining methods for rapid prototyping and direct manufacturing

Zhi Yang
The Pennsylvania State University

Richard A. Wysk
The Pennsylvania State University

Sanjay Joshi
The Pennsylvania State University

Matthew C. Frank
Iowa State University, mfrank@iastate.edu

Joseph E. Petrzelka
Iowa State University

Abstract
The material and product accuracy limitations of rapid prototyped products can often prevent the use of rapid prototyping (RP) processes for production of final end-use products. Conventional machining processes are well-developed technologies with the capability of employing a wide range of materials in the creation of highly accurate components. This paper presents an overview of how conventional machining processes can be used for RP and direct manufacturing processes. The methodologies of computer numerical control machining for rapid prototyping (CNC-RP) and wire electronic discharge machining for rapid prototyping (WEDM-RP) are presented in this paper. A general discussion of selection criteria and cost comparisons among both current additive RP and conventional machining approaches to rapid manufacturing are also presented.

Keywords
rapid prototyping, RP, computer numerical control, CNC machining, CNC-RP, wire EDM, electronic discharge machining, WEDM-RP, direct manufacturing, selection criteria, cost comparison, rapid manufacturing

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Conventional Machining Methods for Rapid Prototyping and Direct Manufacturing

Zhi Yang
Richard A. Wysk
Sanjay Joshi
Department of Industrial and Manufacturing Engineering,
The Pennsylvania State University, University Park, PA 16802

Matthew C. Frank
Joseph E. Petrzelka
Department of Industrial and Manufacturing Systems Engineering,
Iowa State University, Ames, IA 50011

Abstract: The material and product accuracy limitations of rapid prototyped products can often prevent the use of Rapid Prototyping (RP) processes for production of final end-use products. Conventional machining processes are well-developed technologies with the capability of employing a wide range of materials in the creation of highly accurate components. This paper presents an overview of how conventional machining processes can be used for rapid prototyping and direct manufacturing processes. The methodologies of Computer Numerical Control machining for Rapid Prototyping (CNC-RP) and Wire Electronic Discharge Machining for Rapid Prototyping (WEDM-RP) are presented in this paper. A general discussion of selection criteria and cost comparisons among both current additive RP and conventional machining approaches to rapid manufacturing is also presented.

Keywords: Rapid Prototyping; CNC-RP; WEDM-RP

1 Background

Traditional Rapid Prototyping (RP) is commonly referred to as layered manufacturing or solid free form fabrication. It is used for the physical modeling of a new product design directly from computer aided design (CAD) data without the use of any special tooling or significant process engineering. This rapid procedure reduces the lead time required to produce a prototype of a product by eliminating much or all of the process engineering time and tooling requirements (Noorani 2006). The advantages of rapid prototyping have made a substantial contribution to the soaring global markets for quick-to-market, highly engineered products. The market for RP, consisting of all products and services globally, grew 16% to an estimated $1.141 billion in 2007, according to the Wohlers Report 2008. Successful RP application areas include quoting, ergonomic studies, rapid tooling, visual aid for engineering, and functional models (Noorani 2006).

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In spite of the dramatic technology developments in RP during the last two decades, a majority of RP products still cannot be used for producing end-use parts. Technologies like Rapid Tooling (RT) and Rapid Manufacturing (RM) attempt to overcome many of the current limitations in the production of final end-use parts using RP technologies (Hopkinson, Hague et al. 2006). One of the major advantages of RP/RT/RM is the ability to create parts rapidly. Rapid manufacturing can be defined as the ability to manufacture an object, directly from CAD data input, without significant human intervention or skill. This procedure of transforming CAD data directly into final product is also referred to as direct manufacturing. From the literature, the common limitations for current RM processes are material variety and properties, processing speed, dimensional accuracy, surface finish, repeatability, geometry capability, and cost effectiveness (Grimm and Wohlers 2001; Ruffo and Hague 2007).

From the manufacturing point of view, a large variety of processes are capable of producing RM products with one or several limitations mentioned above. Those processes include additive processes, such as stereolithography (SLA), Selective Laser Sintering (SLS), Fused Deposition Modeling (FDM), three-dimensional printing, Direct Metal Laser Sintering (DMLS), Laser Engineered Net Shaping (LENS) and Electron Beam Melting (EBM), and subtractive processes, such as CNC milling, CNC Wire EDM, etc. The limitations for current RM provide the general criteria for selecting manufacturing processes for RM applications. During the RM process selection procedure, the final product requirements are set as constraints for the process and the process efficiency/cost is set as the as the criterion for RM process candidates. Many RM processing candidates are eliminated because of they are incapable of meeting some of the common engineering product constraints, such as material, tolerance, and geometry.

It appears that there are no dominating processes for making rapid prototyping parts and no universal RP process for all RM applications (Bártolo and Bidanda 2007). Most additive processes present no geometry limitations. The ability to produce almost endless geometric shapes and features using additive processes makes them a desirable candidate for nearly any geometry. However, some of other limitations, such as: material limits, processing speed, dimensional accuracy, surface finish, and cost effectiveness impose severe limits for the use of additive processes. Generally speaking, parts to be made using additive processes are typically constrained by material and dimensional accuracy (Hopkinson, Hague et al. 2006). On the other hand, subtractive processes are commonly limited by the geometry they can produce, but are capable of manufacturing products using a variety of materials and can fabricate products of high dimensional accuracy.

In this paper, we present a variant of tradition subtractive manufacturing applications for CNC milling and CNC Wire EDM, and discuss how they can be utilized to obtain a part directly from Computer Aided Design (CAD) data without the use of any special tooling or significant process engineering. Section 2 provides a review of the literature on conventional machining process technologies for rapid prototyping. Section 3 provides details on methodologies for conventional machining processes for rapid prototyping. Section 4 discusses the RM process selection criteria and compares several processes as RM tools. Section 5 discusses the economics of using conventional machining processes for rapid manufacturing..

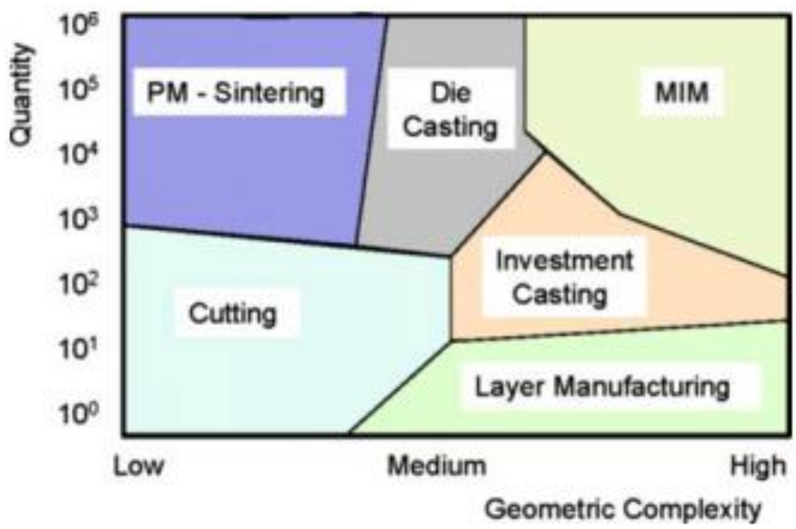
2 Literature Review

In this section, the importance of using conventional processes as RM tools is discussed, followed by an overview of previous research.

2.1 The importance of conventional process as RP

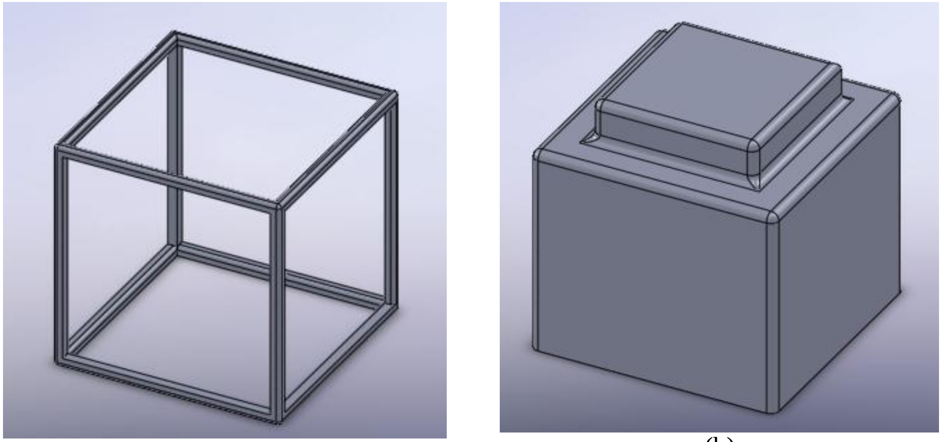
First of all, conventional machining processes are relevant to RP. RP technologies may be divided generally into additive processes and subtractive processes(Pham and Gault 1998). The RP research focuses on additive processes, whereas little efforts have been placed on using subtractive processes for RP. RM technologies have been introduced to ensure long-term consistent component use for the entire production life cycle, and one of the largest efforts is focused in the direct manufacture of metal parts (Bakkelund, Karlsen et al. 1997; Levy, Schindel et al. 2003). Six different RP principles are contenders for direct metal parts fabrication. Figure 1 illustrates the qualitative situations of the direct metal components production relative to the usual options. Cutting methodologies and layer manufacturing, i.e., the subtractive methodologies occupy a large portion of the graph when quantities are relative low. When considering a low volume of RP parts, they are normally used as customized parts for various early engineering or marketing applications.

Figure 1 Qualitative assessment of methods available for direct metal component production (Levy, Schindel et al. 2003)



Due to the nature of the manufacturing processes, whether subtractive or additive, different processes have their own innate advantages and disadvantages. Figure 2 illustrates an example of two parts with different mass volumes. The part in Figure 2 (a) would require an excessive amount of material removal to make the part from a block of stock. This would be reasonably efficient for an additive RP process. On the other hand, for the part in Figure 2 (b), an additive RP process would spend an excessive amount of time stacking simple layers, whereas the subtractive process would finish the part very quickly from a block of stock.

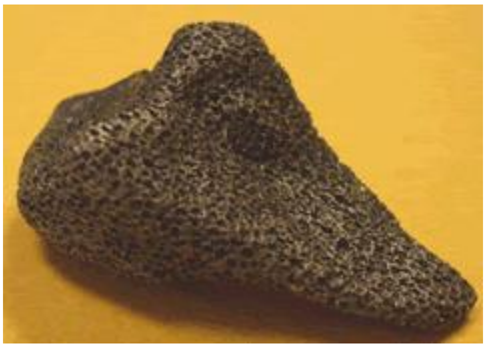
Figure 2 Example models with low (a) and high (b) mass/enclosed volume



(a) (b)

Conventional subtractive processes typically have good material processability. Subtractive processes have been used in industry for years and are able to machine a variety of materials in solid form. On the other hand, material processability is still a challenge for most of RP techniques. Each RP technique requires a specific form of material, such as powder, solid pellet or filament; therefore, some of the RP applications are limited by the choice of material. For example, a variety of RP technologies can be used to fabricate scaffolds in tissue engineering (Landers and Mülhaupt 2000; Lam, Mo et al. 2002; Zein, Hutmacher et al. 2002), but most of them have input material weakness, such as requiring rigid filaments or material in powder form (Yeong, Chua et al. 2004). Furthermore, the fabrication process is time consuming, and it is difficult to manufacture lattice structures using additive processes. It would be easier to subtract material from a scaffold block made by traditional processes, such as solvent casting or gas foaming. Figure 3 illustrates an example of a human tibia fragment (for reconstructive surgery) machined from Trabecular Metal™ with CNC-RP.

Figure 3 A machined Trabecular Metal™ human tibia fracture replica (image from (Frank 2009))



The attention paid to alternative processes for RP by the industrial community has differed from that of academe. According to Wohler's report in 2006, over the past few years the term "rapid manufacturing" has gained acceptance. About 10% of RP parts are made for rapid manufacturing purposes and an increase is expected in the coming years. Direct metal fabrication technologies are used in a wide variety of industries, from automotive and aerospace to electronics and dentistry. As the range of technologies and materials expands, the rapid manufacture of metal parts will become increasingly popular (Wohlers 2006).

2.2 Previous efforts

Conventional subtractive processes have been developed for years. The advantages of conventional subtractive processes are the accuracy and diversity of materials that can be used. Several challenges in using conventional subtractive process as RP are toolpath generation and fixture design and geometric issues such as accessibility for material removal.

The standard approach to planning parts for conventional machining is to define the "features" on the part, and match these features and tolerances to a set of processes that can create the required geometry to the specified accuracy. Current CAD/CAM software has the ability to generate toolpath automatically for simple geometries, and several software packages have made NC programming much easier and less labor-intensive. However, software still needs the user to select surfaces, features on the part and specify toolpath strategies one by one. In most cases, the time required planning the part, kit the required tooling, and setup the machine has limited the use of CNC for small quantities of parts.

The majority of the research on toolpath generation focuses on milling process. Dragomatz and Mann provide a literature review on NC milling path generation (Dragomatz and Mann 1997). They classify research papers into different categories according to their related topics, such as roughing path, tool positions, offset surface for approximation, 4 or five-axis toolpath generation, etc. Interestingly, while numerous research papers discussed automatic toolpath generation based on a specific geometry models, such as Boundary Representation (B-rep), feature based, or mesh models, only few discuss using milling processes for RP/RM applications. In recent years, some researchers have tried to generate toolpath from STL format, which is a commonly used RP input. While doing so, they try to recognize basic features (Qu and Stucker 2005), and generate toolpath for raster milling (Qu and Stucker 2006). These efforts have built an important foundation for using conventional processes as an RP tool.

2.3 CNC-RP

Several researchers have explored the use of CNC machines for rapid prototyping. Hassold introduces the possibility of applying CNC machines as a RP technique (Hassold 1995). He discusses the potential advantages and limitations that researchers may confront during application, as well as the issues such as safety, health, and cost. Chen and Song describe layer-based robot machining for rapid prototyping (Chen and Song 2001). They demonstrate a process using laminated slabs of plastic, machined as individual layers and glued to the previous layers. Another approach is to use CNC machining for prototyping dies, an area called Rapid Tooling (Radstok 1999). These approaches do not offer the flexibility or practicality of creating various parts; however they make short-run production possible using CNC machining, and become part of fundamentals of CNC-RP.

Frank et al. presents a methodology termed CNC-RP (Frank 2003). This methodology employs a plurality of layer-based toolpath from various orientations about an axis of rotation, in order to machine the entire surface of a part without refixturing. CNC-RP presents a method for "feature-free" CNC machining that requires little or no human-provided process engineering. This methodology is a purely subtractive process that can be applied to any material that can be milled on CNC machines. The method described herein was developed in response to the challenge of automating as much of the process engineering as possible. The ultimate goal is to generate both the NC code and an automatically executed fixturing system by the touch of a button, using only a CAD model and material data as input. The process is perfectly suited for prototypes as well as parts that are to be produced in small quantities.(Frank 2003; Frank, Wysk et al. 2004)

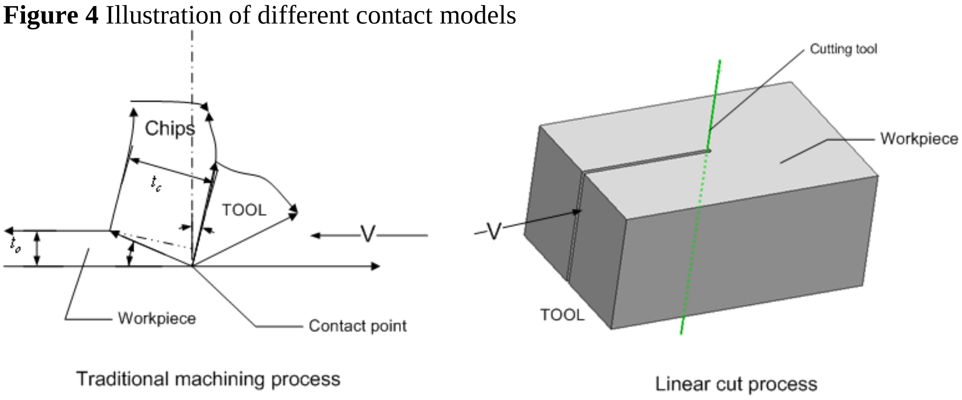
Research related to CNC-RP includes machinability analysis and setup orientation. McBreaty et al. discussed visibility analysis for CNC-RP(McBrearty 2005; McBrearty, Wysk et al. 2006). They developed a method that forms the basis for the selection of an axis of rotation for which the workpiece would be completely visible and a step in the automation sequence. Li and Frank discuss the general visibility problem for three-axis machining operations(Li and Frank 2006). They extended 2D visibility analysis for CNC-RP by extruding 2D slice and determining intersections. Frank et al. developed a method to determine setup orientations for CNC-RP(Frank, Wysk et al. 2006). They analyzed sliced 2½D geometry visibility and determined orientations that will minimize the number of rotations on CNC machine.

The use of traditional subtractive processes as RM tools is also found in some US patents. The inventions focus on using milling processes as rapid prototyping tools. Sachs described a method of fabrication complex part using CNC milling machines in his patent “Three dimensional model and mold making method using thick-slice subtractive fabrication (U.S. Pat. No. 6021358) (Sachs 2000).

2.4 Wire Electrical Discharge Machining (WEDM)-RP

As a non-traditional linear cutting process, Wire Electrical Discharge Machining (WEDM) is used to machine electrically conductive materials. It cuts by using precisely controlled sparks that occur between an electrode/wire and a work piece in the presence of dielectric fluid, regardless of the hardness of the material (Jameson 2001). Like other linear cut manufacturing systems, such as abrasive water jet and laser material processing, WEDM has a noticeable line contact characteristic with the part being produced. Unlike traditional manufacturing processes which involve point contact between the tool and the work piece, the contact mode in linear cut manufacturing processes is a linear surface. Figure 4 illustrates the contact models for traditional machining processes and linear cut manufacturing systems.

Figure 4 Illustration of different contact models



To achieve maximum utilization of the subtractive RP process and overcome the limitations associated with tool path generation, fixture design and tooling, research focusing on point contact mode using CNC-RP has been conducted for years with all of the reported work concentrating on milling processes (Hassold 1995; Frank 2003; Frank, Wysk et al. 2004; McBrearty, Wysk et al. 2006; Zhu and Lee 2007). In contrast, investigations in linear cut machining as an RP process have been limited.

Even though it is an important material category for medical and bio-application materials (Bártolo and Bidanda 2007), metal fabrication is not handled well in traditional RP process. Laser-based processes suffer either low density of the finished part or poor finishing surface and accuracy (Gebhardt 2003; Steen 2003). Even though some post-processes, such as metal casting, can make a traditional RP product with high accuracy, it is not suitable for mass customization type medical RP applications. A new rapid prototyping manufacturing process is needed to overcome the shortcomings of traditional RP processes for metal products and fit the mass customization requirement with low cost and short lead time.

A major advantage of WEDM is that there is zero cutting force regardless of material hardness. The only energy input into the process is used to sublimate the material. This advantage makes WEDM a popular process for medical applications such as medical devices and medical substitution parts. Some of these products have very complex shapes and are made from hard-to-machine materials. As a non-traditional manufacturing process, WEDM can process any electrical conductive part regardless of the hardness of the material. It normally produces 2D or 2½-D parts with reasonable complexity. The recent developments of WEDM machine, such as six-axis WEDM, combining the advantages of WEDM, such as high accuracy regardless of material hardness, and force free processing, has made the WEDM process desirable for the fabrication of more complicated parts with high hardness materials. However, WEDM process engineering for complex geometries has not been investigated in a manner to make it suitable for RP. Lee (Lee, Brink et al. 2003; Lee 2005) combined the wire EDM and rapid tooling conception together, and provided a NC code generation software-WirePath^{TM}, which is generally applied for injection model dies. Complex parts are separated into small slices, and each slice will be produced on WEDM machine and then assembled into a complete part.

Using WEDM as a rapid prototyping tool is discussed in U.S. Pat. No. 6627835 (Hung and Ramani 2003), where the inventors cut the three dimensional object into slices, use WEDM to fabricate each slice, and assemble the slices into the final product. This application analyzes the geometry of the object and generates the numerical control code to fabricate the object together.

3 Overview of CNC-RP and WEDM-RP

All existing processes for RM have some limitations falling into the seven common limitations for current RM, which are material variety and properties, process speed, dimensional accuracy, geometry, surface finish, repeatability, and cost effectiveness. A major problem for subtractive processes has been challenges stemming from tool path generation, fixture design and geometric issues of accessibility. The effort required to solve these problems as a case by case solution has increased the engineering cost associated with producing them significantly. A general cost model is presented in following equation:

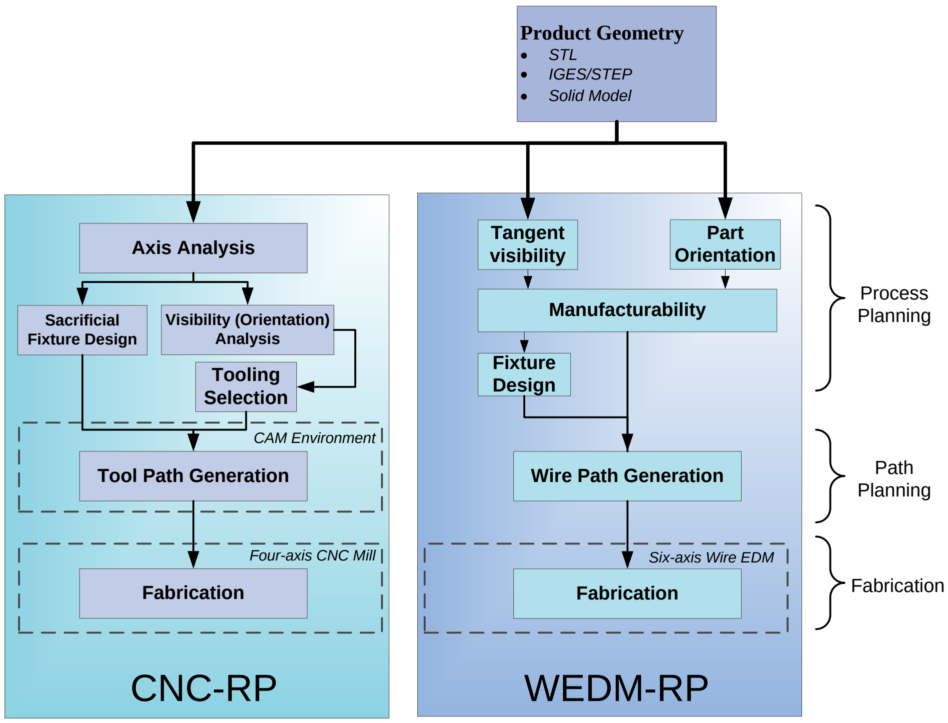
$$Total\ Cost = Engineering\ Cost + Material\ Cost + Manufacturing\ Cost$$

Engineering cost includes product design costs, process planning costs and production setup costs. Additive rapid prototyping has small or no engineering costs because there is no need for process plan and production setup. On the other hand, the engineering costs for conventional processes can be significant. This noteworthy costs could be compromised by large volume production, because the engineering costs only consist of one time costs for product design, process plan and production setup. If the engineering time can be reduced to a trivial level, conventional subtractive processes can be profitable for low volume RM application. The methods of CNC-RP and WEDM-RP intend to decrease the engineering cost by decreasing human interaction significantly.

As conventional subtractive processes, CNC and WEDM have some similarity as general approaches to RP. Both processes need product geometry preparation, model analysis and preparation, toolpath generation and fabrication preparation, and fabrication of the final product.

Figure 5 summarizes the steps in the general approach for CNC-RP and WEDM-RP.

Figure 5 General approach for using conventional machining as RM tools



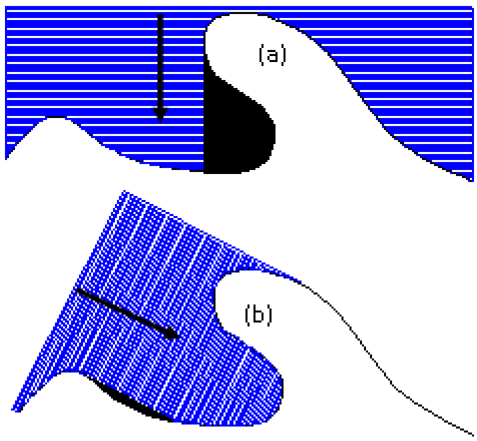
3.1 CNC-RP

This section presents a general overview of the current methodology for CNC-RP as developed by Frank et al (Frank 2003; Frank, Wysk et al. 2004; Frank, Wysk et al. 2006). Methods have been developed to cover all aspects of process planning for rapid machining, including toolpath planning, choosing tool geometries, calculating setup orientations, and a concept for a universal approach to fixturing.

With regard to general toolpath planning, the CNC-RP method borrows from layer-based RP technologies. The basic concept is to machine the visible surfaces of a part from each of a plurality of orientations. In order to simplify the problem from both a process and fixture-planning standpoint, only rotations about one axis for orientations of the stock material during processing are used. This not only reduces the problems associated with process planning, but it assures the absolute collision-free nature of the approach. From each orientation, some, but not all of the part surfaces will be visible. The goal is to machine the part from enough orientations, such that, after all toolpaths are complete, all surfaces have been fully machined from at least one orientation. For each orientation, there is no particular plan for a set of feature machining operations; rather, geometry is machined using simple 2½D layer-based toolpaths. Unlike the existing rapid prototyping methods, CNC machining is a subtractive process; therefore, one can only remove the material around the periphery of a part (visible cross section of the part).

The process plan stage includes axis analysis, visibility (orientation) analysis, sacrificial fixture design, and tooling selection. Visibility (orientation) analysis is a challenging problem for CNC-RP process planning. A desired goal is to machine the part with the fewest number of orientations or setups. The critical data required for processing a part using this method is the number and orientation of the two-and-a-half-dimensional (2½-D) toolpaths necessary to machine all the surfaces (Frank, Wysk et al. 2006). The feature-free nature of this method suggests that it is unnecessary to have any surface be completely machined in any particular orientation. In the first operation (Figure 6 a) much of this surface is visible from the first orientation; however, the dark areas under the overhanging surface are not visible. In the second operation, this originally "shadowed" region of the same surface is now visible (Figure 6 b). This approach avoids the problem of feature recognition and feature-based process planning. At least two, but more likely numerous orientations will be required in order to machine all the surfaces of a part about one axis of rotation. (Even a simple part like a sphere requires two orientations).

Figure 6 Free-form surface being machined from two orientations(Frank 2003)

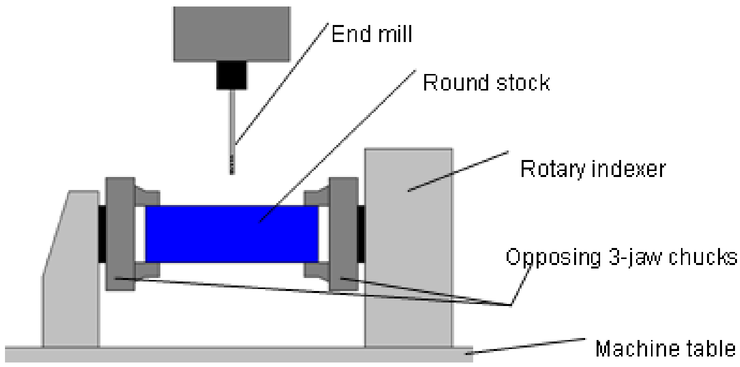


One would note that if all the visible surfaces of a part from numerous orientations were machined completely, then at some point the part would simply fall from the stock material. Therefore, this method employs a fixturing approach that is similar in concept to the sacrificial supports used in many existing additive rapid prototyping processes. However, in CNC-RP the supports are not added to the physical model during processing, rather, they are added to the CAD model prior to toolpath planning; hence they emerge as extra features extending from the ends of the component. The sacrificial supports are currently implemented as small diameter cylinders added to the solid model geometry parallel to the axis of rotation. During processing, the supports are created incrementally, along with the rest of the part surfaces. Upon completion, the finished part is left secured to the round stock material by these supports.

The rapid machining process is based on a setup strategy whereby a rotary device is used to rotate round stock material that is fixed between two opposing chucks. Rotating the stock using an indexer eliminates the inherent problem of retaining reference coordinates associated with re-clamping a part in a conventional fixture. For each orientation, all visible surfaces are machined and the sacrificial supports keep it connected to the uncut ends of the stock material. Once all operations are complete, the supports are severed (sawed or milled) in a final series of operations, and the part is removed. Post-processing is performed to finish the minimal support contact patches on the part.

The setup and steps to this approach are shown in Figure 7 and Figure 9, respectively. As an example in Figure 9, a component is being machined using sacrificial supports to retain the part at its ends along the axis of rotation. CNC-RP employed this setup and process planning strategy in previous work as a method for rapid machining. Sacrificial support fixtures have been designed manually and used in several proof-of-concept parts. This method of using one axis of rotation for indexing between setups is obviously not capable of machining all parts of extremely complex shape. Parts with severely undercut features or complex features on three or more mutually orthogonal faces may not be machinable with this approach. In particular, this setup strategy assumes that some axis of rotation exists such that all surfaces are visible.

Figure 7 Set up for CNC-RP(Frank 2003)



Several samples parts machined using CNC-RP are illustrated in Figure 8

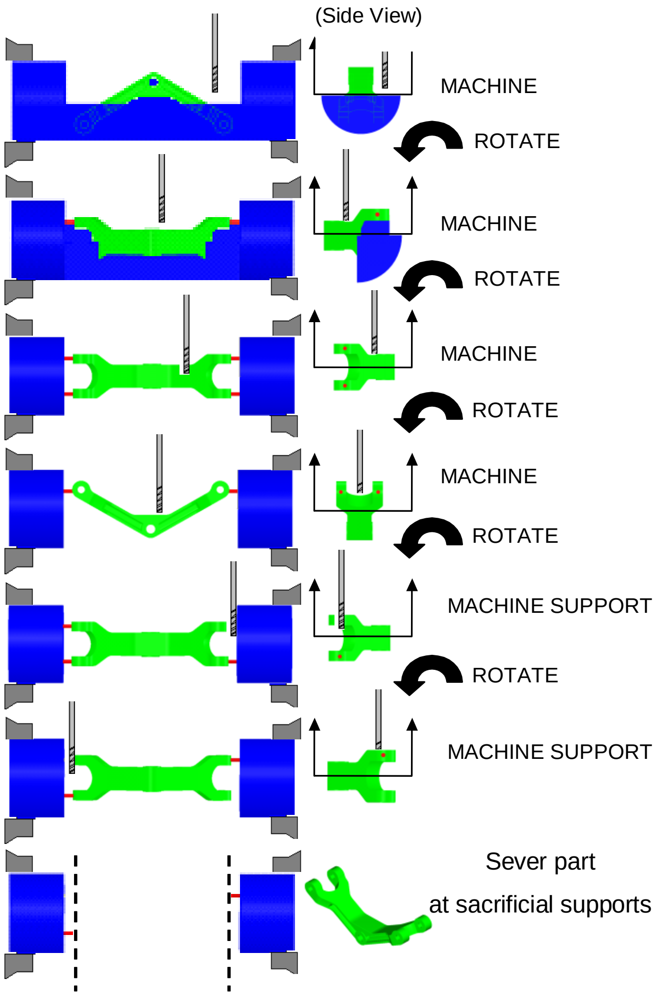
Figure 8 Sample parts made by CNC-RP (image from (Frank 2009))

(a) Bike suspension component
Material: Steel

(b) Human femur
Material: Delrin

(c) Toy jack
Material: Aluminum

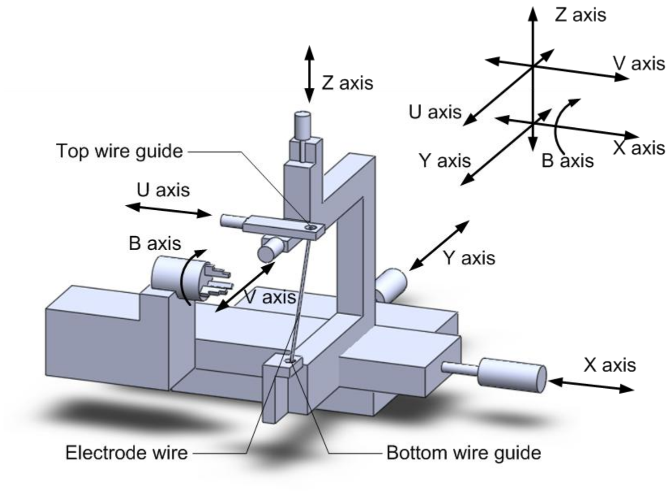
Figure 9 Process setups for CNC-RP (image from (Li and Frank 2006))



3.2 WEDM –RP

This section presents a general overview of the current methodology for WEDM-RP. WEDM subtracts material using a linear contact model. Figure 10 illustrates the design of a six-axis WEDM. The electric wire in Figure 10 is the cutting tool for WEDM, and will be kept straight during fabrication. Due to the uncommon fabrication approach of WEDM, the toolpath planning for WEDM-RP is not a layer-based approach.

Figure 10 Six-axis Wire Electrical Discharge Machining Design

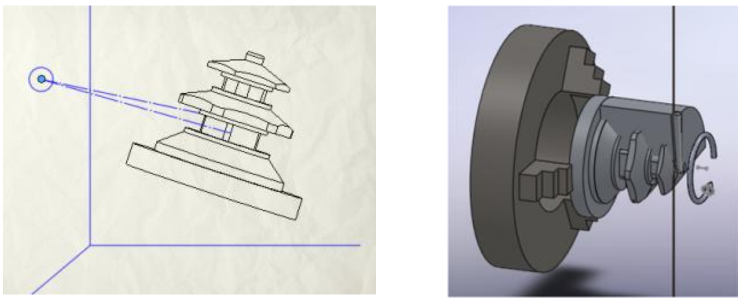


The entire process for WEDM-RP is illustrated in Figure 12 and can be summarized as the following important contents:

1. *Facet Visibility*: Because of the uncommon fabrication approach of WEDM, the visibility problem is different from the normal visibility problem. Figure 11 illustrates the difference between conventional visibility and WEDM visibility. This step takes STL as input format, and generates tangent visibility for each facet in STL file.

2. *Part Orientation*: This part of the problem intends to find an orientation such that it maximizes the machinable surface area. The STL file will be used as the input to this step.

Figure 11 Different visibility problems

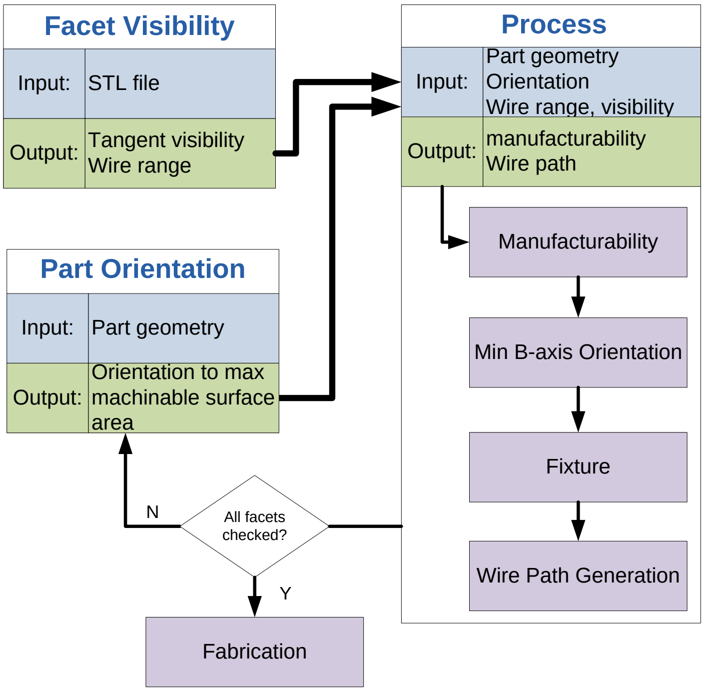


(a) Conventional visibility. Visibility from a point, such as visibility for milling process

(b) WEDM visibility,a straight line to access the surface.

3. *Model Process and wire path generation*: Based on facet visibility and part orientation results, the algorithms analyze the manufacturability of the given part and generate the wire path. In detail, the model geometry will be analyzed and manufacturability will be determined for the given part orientation.

Figure 12 infrastructure of WEDM-RP



4. *Fabrication*: After analysis of all the facets in the STL file, the wire path will be sent to a 6-axis WEDM machine for fabrication the prototyping model.

An example part for fabrication on 6-axis WEDM is a pagoda, which is illustrated on Figure 13. The pagoda is a symmetric part without any cavity geometry and can be fully fabricated on six-axis WEDM in one setup using several discrete rotations about the axis.

Figure 13 An illustrative part – a model pagoda

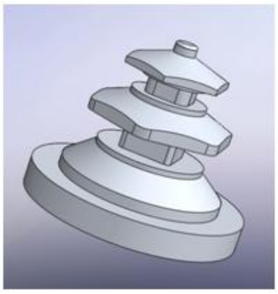
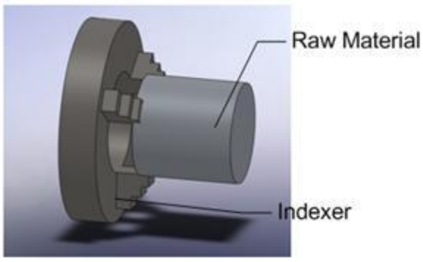
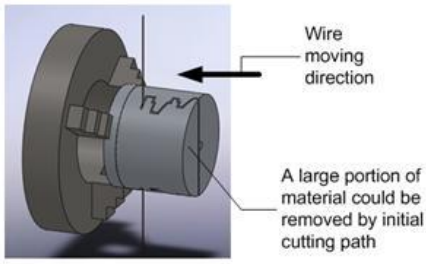


Figure 14 illustrates how the WEDM-RP process can be used to fabricate a complex part like the pagoda.

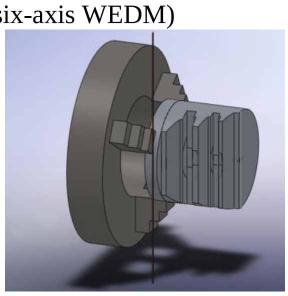
Figure 14 illustration of fabrication a pagoda on WEDM



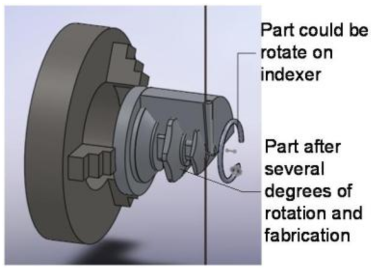
(a) raw material on an indexer (or B-axis on six-axis WEDM)



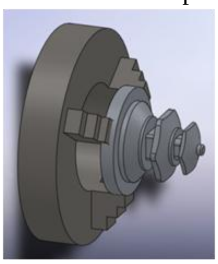
(b) Initial fabrication setup



(c) Part after first cut path



(d) Part after several rotations on indexer



(e) Finished part

4 RM process selection

When choosing any RM process, the selection is based on identifying as many feasible candidates as possible and then identifying the most cost effective process to manufacture final product directly from CAD data. General process selection criteria include technological feasibility, quality of conformance and manufacturing cost. Combining the seven common limitations of current RM mentioned in section 1, the criteria of RM process selection include:

1. Geometric capability
2. Accuracy
3. Material Flexibility
4. Manufacturing Cost

In this section, we focus on the first three criteria. The cost issue will be addressed in Section 5.

Additive processes generally have no limitations in geometric capabilities. Layers can be added through the use of some support structure, which nearly eliminates the typical challenges of undercuts and even hollow geometry in some cases. Since their commercialization in the late 1980s orders of magnitude level improvements have been made with respect to accuracy and ease of use, along with some considerable improvements in materials. However, materials is a very difficult challenge to overcome, due mainly because one needs to apply/cure/fuse small layers together. Hence, the layer based approach of conventional RP systems has both enabled their use in rapid prototyping, but hinders their use in direct manufacturing. There are several methods that have seen limited use in rapid and direct manufacturing, and we will discuss a notable few below.

Considered the first commercial RP technology, Stereolithography (SLA) is an additive RP process that was originally designed as a laser based approach with a liquid resin. The UV laser cures layers of resin in a vat, with sacrificial support structures serving as the "scaffolding" to support overhanging features. In terms of rapid manufacturing, SLA is significantly limited in terms of component production; however, there has been successful use of SLA as a rapid tooling process for subsequent molding operations. Later derivatives of SLA include the ink-jet technology based systems from Objet (polyjet systems), which produce significantly accurate layers with very small layer depths (typically down to 16 microns). This level of layer depth control is almost unique among additive RP systems, the exception being the Solidscape jewelry manufacturing systems that utilized an additive/subtractive approach. Material choices in SLA and SLA derivatives have expanded to include some basic elastomeric materials and even dual material systems. However, the materials are somewhat specialized for the requirement of the RP process itself and therefore are not common manufacturing materials. These systems will likely continue as excellent rapid prototyping and perhaps rapid tooling systems, but true rapid manufacturing of components is less likely.

Fused Deposition Modeling (FDM) involves modeling by application of melted material. The advantages of this process are not only the vast range of material, including ABS plastic, and the ability to use various colors, but also the fact that the material used can be changed during the process. FDM has achieved ±0.005" accuracy level in recent technology development. FDM has very good geometric capability as other additive processes, and has relatively higher accuracy comparing to other additive processes, but it cannot handle any metallic product.

Selective Laser sintering (SLS) uses a high power laser to fuse powder materials, primarily plastic or resin coated metals and sand. SLS plastic parts have been used for direct prototyping while sand systems are used for metal casting. The coated metal powders were an attempt to make metal parts with SLS, but this only produced a "green" part that would require full sintering in a secondary furnace. Direct Metal Laser Sintering (DMLS) is simply the use of higher power laser systems, which allows for the direct production of metal sintered components. As with any powder metallurgy process, the parts are not 100% dense after sintering and require a subsequent metal (typically bronze) infiltration process. Another development in powder based metal systems was Electron Beam Melting (EBM), which uses an electron beam in a vacuum build chamber instead of a laser system. The electron beam is sufficient for melting; hence fully dense components of steel and Titanium are commonly created. The accuracy of SLS and DMLS are dependent on the laser beam diameter and the accuracy is commonly found to be around ±0.02 inch (Gebhardt 2003). In SLS, DMLS or EBM, the powder material can be a challenge with respect to surface finish and the finish on the bottom side of overhanging surfaces. Of the three technologies, DMLS is most well suited for RM of metal components; however, SLS in plastics is a viable option for polymeric components.

The major limitations are whether 1) the material properties will be suitable replacements of virgin plastics or the metal alloys for the design and 2) whether the dimensional or surface characteristics are sufficient for fit and functional use.

The two processes being developed in the laboratory can be compared and contrasted against the brief list of process discussed above. The difference is that both CNC-RP and WEDM-RP are being developed for rapid manufacturing firstly. In most cases of rapid prototyping the additive methods are superior; however, we contend that modified conventional methods will have the advantage of a starting point much closer to functional parts by their very nature, similar to the layer based nature of additive RP and its ability to create prototypes.

CNC-RP uses three-axis CNC milling with 4^{th} axis indexing; hence it is a conventional subtractive fabrication process, albeit with a rapid approach to process planning. Unlike the additive processes, the geometric capability of CNC milling is limited by surface accessibility. Hidden portions of geometry cannot be manufactured by CNC-RP. On the other hand, CNC milling can fabricate a large variety of materials. It can handle the majority of metals, and some plastics and ceramics. As a mature manufacturing process, CNC milling can easily achieve ±0.002 inch accuracy in many materials.

WEDM-RP uses six-axis wire EDM as a fabrication process. The material is removed by spark discharges created between the workpiece and wire electrode. This cutting approach limits the material flexibility of wire EDM to electrically conductive material. Furthermore, the geometric capability of wire EDM is limited by tangent visibility and process accuracy of wire EDM is moderate. On the other hand, wire EDM also has several advantages. Wire EDM is the capability to cut any electrical conductive material regardless of the hardness of the material and the cutting force is negligible. These advantages make wire EDM a RM candidate for manufacturing metals like titanium, stainless steel, and cobalt alloys.

The comparison of different processes for various engineering constraints: geometric capability, accuracy, and material flexibility, are summarized in Table 1.

Table 1 comparison of different process

RP/RM Technology	Geometric capabilities	Accuracy	Material flexibility
SLA	Good, supports can be difficult to remove	Good, but Limited in z direction	Resin, limited set of materials
SLA/Polyjet	Excellent, easy to remove supports	Very Good to Excellent, small layer depths	Resin, limited set of materials, but includes multi-materials and some elastomers
FDM	Very Good, limited if not water soluble supports	Good, limited by large layer depths	Good plastic choices
Solidscape	Very Good, easy to remove supports	Very Good to Excellent	Limited to low melt plastics,waxes
SLS	Very good, some issues in power removal	Good to very good	Mostly plastics, coated metals and sand

RP/RM Technology	Geometric capabilities	Accuracy	Material flexibility
DMLS	Very good, some issues in power removal	Good to very good	Metals, but limited to brown PM part quality with porosity
LENS	Limited to 2-1/2 D	Limited to Moderate	Good, steels and titanium, good density
EBM	Very good, some issues in power removal	Moderate to Good	Very good, steels and titanium, good density
CNC- RP	Limited by sight visibility about and axis of rotation	Excellent	Excellent, any machinable material
WEDM-RP	Limited by tangent visibility	Very Good	Moderate, any electric conductive material

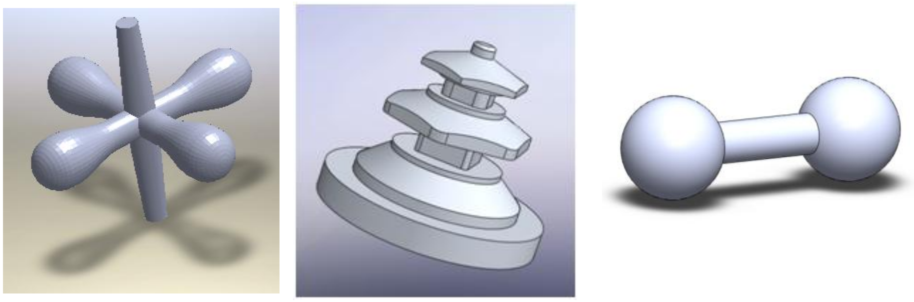
5 Economic Comparison

With the success of RP in reducing time and cost in the development cycle, the industry's attention has turned to downstream processes that promise an even greater impact on time and cost (Grimm 2004). However, the research on economics of rapid manufacturing is limited. Several researchers focus on cost model for additive RM processes. Hopkinson and Dickens studied the cost of RM in 2003(Hopkinson and Dickens 2003), and Hopkinson updated some of the results in his book Rapid Manufacturing in 2006(Hopkinson, Hague et al. 2006). In their research, the authors broke down the costs into machine costs, labor costs, and material costs. Their model is built upon the assumption that the machine was producing only copies of the same part and using a constant production time. Approximate cost analysis for injection molding, stereolithography, fused deposition modeling, and selective laser sintering are also discussed in their research.

A common cost comparison should include the head-to-head cost comparison of manufacturing the same product with different processes. However, it is difficult to compare several RM processes by evaluating the manufacturing cost for same part. Because the geometric capability, accuracy and material flexibility vary dramatically among different RM process, it is not reasonable to calculate the exact manufacturing cost for an aluminum part on CNC milling, and compare it to the cost for an ABS part fabricated on FDM. Instead, the cost range and magnitude comparison will make more sense considering the lack of common comparison ground. Several parts are selected to estimate the manufacturing cost for different processes and illustrated in Figure 15. The cost range summary is listed in Table 2. WEDM-RP is still in the development stage, it is difficult to get accurate estimation on processing time, so we will not consider this process into the cost comparison.

The following results can be observed in Table 2: (1) the cost range of CNC-RP, SLS, and FDM are on the same order of magnitude; (2) there is a significant cost change from conventional machining to CNC-RP. For subtractive process, such as CNC milling and CNC wire EDM, the advantages of those conventional processes are the well-developed methodology and low material and manufacturing costs. However, the high engineering costs consume the cost efficiency of conventional processes for low volume manufacturing. The methods of CNC-RP and WEDM-RP intend to solve this problem by creating automatic process planning, tooling and production setup plans and decrease the human interaction as much as possible. As a result, engineering costs become trivial after decreasing human interaction in process planning. This significant reduction in engineering cost makes CNC-RP fall into the same cost magnitude with additive RP processes, such as SLS and FDM.

Figure 15 Cost estimation parts



A toy jack A model pagoda A model dumbbell

Table 2 Cost range for different manufacturing processes for unique products in quantity of one production.

Process	Material	Cost Range
SLS[1]	DuraForm PA	[127,383]
FDM[2]	Rigid ABS	$248
Conventional Machining [3]	Aluminum 6061	[$800, $1000]
CNC-RP [4]	Aluminum 6061	$41.74

Notes:

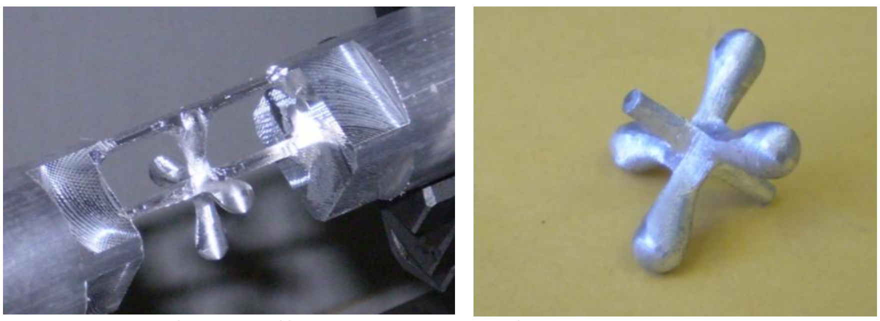
1.The data is obtained from quickparts.com for single part

2.The data is obtained from quickparts.com for one toy jack

3.Estimated cost. Considering the long engineering time and tool preparation

4.Real production cost for toy jack. Total machining time is 87 minutes to machine the toy jack from a round aluminum bar. The finished CNC part is illustrated in Figure 16

Figure 16 CNC machined Toy jack



(a) Toy jack before cut off (b) finished toy jack

6 Conclusion

CNC-RP and WEDM-RP provide the possibility of using conventional processes, such as CNC milling and WEDM, as RM tools. One of the advantages for conventional subtractive process is their material processability. Additive processes have difficult in manufacturing full density part or parts with lattice structures. It will easier to subtract material from a block of material than to build lattice structures layer by layer. The better material processability also provides conventional subtractive processes better adaptability for new material.

It is impossible to select one process as the single best solution for all RM applications. RM process selection can be based on the following criteria: geometric capability, accuracy, material flexibility, and manufacturing cost. The various RM processes vary dramatically in those criteria. Additive processes generally have good geometric capabilities, but are limited in material flexibility and accuracy. Conventional subtractive processes are capable of manufacturing variety of materials with good accuracy, but limited in geometric capabilities. Therefore, there is no unique answer for RM process selection.

With the systematic approaches provided by CNC-RP and WEDM-RP, engineering time is decreased substantially. These methods decrease the total engineering time by automatically generating process plans and decreasing human interaction. The unit cost range for CNC-RP decreases by an order of magnitude compared to conventional machining processes and is on the same order of magnitude as commercial additive RP processes. Furthermore, CNC and WEDM can provide higher accuracy products than normal additive rapid prototyping processes. These advantages make conventional processes competitive candidates for RM applications.

7 Reference

Bakkelund, J., R. Karlsen, et al. (1997) "Fabrication metal objects using layer manufacturing technology and powder metallurgy science", *CIRP Annals - Manufacturing Technology*, Vol.46, No. 1, pp.135-138.

Bártolo, P. and B. Bidanda (2007) *Bio-Materials and Prototyping Applications in Medicine*, New York, Springer.

Chen, Y. H. and Y. Song (2001) "The development of a layer based machining system", *Computer-Aided Design*, Vol.33, No. 4, pp.331-342.

Dragomatz, D. and S. Mann (1997) "A classified bibliography of literature on NC milling path generation", *CAD Computer Aided Design*, Vol.29, No. 3, pp.239-247.

Frank, M. C. (2003) "The development of a rapid prototyping process using computer numerical controlled machining", the Pennsylvania State University. Ph.D. dissertation**:** 146 leaves.

Frank, M. C. (2003) "Subtractive Rapid Prototyping: Creating a Completely Automated Process for Rapid Machining". *Rapid prototyping : principles and applications*. C. K. Chua, K. F. Leong and C. S. Lim. Singapore ; New Jersey, World Scientific**:** 165-196.

Frank, M. C. (2009) "The Rapid Manufacturing and Prototyping Laboratory (RMPL)." from http://www.ie.imse.iastate.edu/rmpl/default.aspx.

Frank, M. C., R. A. Wysk, et al. (2004) "Rapid planning for CNC milling-A new approach for rapid prototyping", *Journal of Manufacturing Systems*, Vol.23, No. 3, pp.242-255.

Frank, M. C., R. A. Wysk, et al. (2006) "Determining setup orientations from the visibility of slice geometry for rapid computer numerically controlled machining", *Journal of Manufacturing Science and Engineering, Transactions of the ASME*, Vol.128, No. 1, pp.228-238.

Gebhardt, A. (2003) *Rapid prototyping*, Cincinnati, Hanser Gardener Publications.

Grimm, T. (2004) *User's guide to rapid prototyping*, Dearborn, Michigan, Society of Manufacturing Engineers.

Grimm, T. and T. Wohlers. (2001) "Rapid Production: Key Barriers to Growth." from http://www.tagrimm.com/publications/perspectives-apr2001-p.html.

Hassold, R. (1995) "CNC machining as a rapid prototyping technique", *Modern Machine Shop*, Vol.68, No. 5, pp.68-73.

Hopkinson, N. and P. Dickens (2003) "Analysis of rapid manufacturing - Using layer manufacturing processes for production", *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, Vol.217, No. 1, pp.31-40.

Hopkinson, N., R. J. M. Hague, et al. (2006) *Rapid manufacturing : an industrial revolution for the digital age*, Chichester, England ; Hoboken, NJ, John Wiley.

Hung, C. W. and K. Ramani (2003) "Three dimensional object fabrication techniques ". U. S. P. a. T. Office. the United States of America. B1**:** 29.

Jameson, E. C. (2001) *Electrical discharge machining*, Dearborn, MI, Society of Manufacturing Engineers.

Lam, C. X. F., X. M. Mo, et al. (2002) "Scaffold development using 3D printing with a starch-based polymer", *Materials Science and Engineering: C*, Vol.20, No. 1-2, pp.49-56.

Landers, R. and R. Mülhaupt (2000) "Desktop manufacturing of complex objects, prototypes and biomedical scaffolds by means of computer-assisted design combined with computer-guided 3D plotting of polymers and reactive oligomers", Vol.282, No. 1, pp.17-21.

Lee, A. (2005) "Wire-PATH(TM): Modular and flexible tooling for rapid product development", School of Mechanical Engineering, Purdue University. PH.D**:** 179.

Lee, A., J. Brink, et al. (2003) "Wire path rapid tooling process and supporting software development", Proceedings of DAC2003: 29th Design Automation Conference, Chicago, Illinois.

Levy, G. N., R. Schindel, et al. (2003) "Rapid Manufacturing and Rapid Tooling With Layer Manufacturing (Lm) Technologies, State Of The Art And Future Perspectives", *CIRP Annals - Manufacturing Technology*, Vol.52, No. 2, pp.589-609.

Li, Y. and M. C. Frank (2006) "Machinability analysis for 3-axis flat end milling", *Journal of Manufacturing Science and Engineering, Transactions of the ASME*, Vol.128, No. 2, pp.454-464.

McBrearty, K. (2005) "Visibility analysis and considerations for computer numerical controlled rapid prototyping", Pennsylvania State University. M.S. Thesis**:** 48 leaves.

McBrearty, K., R. A. Wysk, et al. (2006) "Visibility for determining rotational axis CNC rapid prototyping and rapid manufacturing", Proceedings of 2006 ASME International Design Engineering Technical Conferences and Computers and Information In Engineering Conference, DETC2006, Philadelphia, PA, United States.

Noorani, R. (2006) *Rapid prototyping : principles and applications*, Hoboken, N.J., Wiley.

Pham, D. T. and R. S. Gault (1998) "Comparison of rapid prototyping technologies", *International Journal of Machine Tools & Manufacture*, Vol.38, No. 10-11, pp.1257-1287.

Qu, X. and B. Stucker (2005) "Circular hole recognition for STL-based toolpath generation", *Rapid Prototyping Journal*, Vol.11, No. 3, pp.132-139.

Qu, X. and B. Stucker (2006) "Raster milling tool-path generation from STL files", *Rapid Prototyping Journal*, Vol.12, No. 1, pp.4-11.

Radstok, E. (1999) "Rapid tooling", *Rapid Prototyping Journal*, Vol.5, No. 4, pp.164-168.

Ruffo, M. and R. Hague (2007) "Cost estimation for rapid manufacturing - Simultaneous production of mixed components using laser sintering", *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, Vol.221, No. 11, pp.1585-1591.

Sachs, G. A. (2000) "Three dimensional model and mold making method using thick-slice subtractive fabrication ". U. S. P. a. T. Office.

Steen, W. M. (2003) *Laser material processing*, New York, Springer.

Wohlers, T. T. (2006) *Rapid Prototyping and Manufacturing State of the Industry Annual Worldwide Progress Report*, Wohlers Associates.

Yeong, W.-Y., C.-K. Chua, et al. (2004) "Rapid prototyping in tissue engineering: challenges and potential", *Trends in Biotechnology*, Vol.22, No. 12, pp.643-652.

Zein, I., D. W. Hutmacher, et al. (2002) "Fused deposition modeling of novel scaffold architectures for tissue engineering applications", *Biomaterials*, Vol.23, No. 4, pp.1169-1185.

Zhu, H. and K.-W. Lee (2007) "Compound rapid prototyping based on CNC machining and layered manufacturing", *Journal of Liaoning Technical University (Natural Science Edition)*, Vol.26, No. 4, pp.599-601.