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A Comparative Study of Product Development Process Using Computer Numerical Control and Rapid Prototyping Methods

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Authors' contributions

This work was carried out in collaboration between all authors. Author OMO designed the study. Authors OMO and FOO manufactured the products, wrote the protocol, performed the statistical analysis, wrote the first draft of the manuscript and managed literature searches. Author KJA managed the analyses of the study and literature searches. Author ARA supervised and interpreted the results. All authors read and approved the final manuscript.

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ABSTRACT

Manufacturing is the transformation of ideas, designs, materials and information into products for satisfaction of human needs. However, advanced manufacturing technology

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is the application of advances in production methodologies to increase productivity, improve existing products and produce quality new products that meet all global standards. This paper presents a comparative study of the Nigeria Coat of Arms, for use as a Seal, using computer numeric control (CNC) and rapid prototyping (RP) methods. The total production time of the components was considered in both cases of using the CNC machine and the RP machine. The same speed and feed rate were used in both machines but the machine physical differences: stress, temperature etc, were not considered. The production time using the CNC machine was 27.81 hours while on the RP machine, the production time was 8.43 hours. This goes to show that for product development, the RP machine would be more suitable than the CNC machine. In a developing economy like Nigeria, knowledge management of machine tool is a vital key to having vibrant manufacturing sector able to cope with the dynamic challenges of increasing globalised world.

Keywords: Rapid prototyping; Computer Numeric Control (CNC); CAD/CAM; machine tool; G-code.

1. INTRODUCTION

Manufacturing around the world is changing rapidly as a result of dynamics change in human needs, competitive challenges and emerging technologies. Recent advances in engineering and manufacturing techniques, information systems and business practices has made product development better, faster, cheaper and globally acceptable. Although, out of tolerance in manufacturing can produce a number of problems like surface finish and geometrical form [1,2]. Effort has been ongoing in recent time at intensifying knowledge in the identification, understanding and harnessing of most recent advances in manufacturing techniques to product development procedures. This is geared toward increasing productivity, improving existing products and producing quality new products that meet all global requirements. It has made manufacturing indispensable as the strength of any industrialized nation. Manufacturing refers to a range of human activity from handicraft to high tech, but its most commonly applied to industrial production, where raw materials are transformed into finished goods on a large scale. The earliest form of product development involves the use of hand-held tools for manufacturing products but recent developments in Advanced Manufacturing Technology (AMT) has seen the emergence of various Computer Numeric Control (CNC) machines.

Advanced manufacturing technology, defined as computer-controlled or micro-electronics-based equipment used in designing, manufacturing and handling of a product [3], finds application in Computer-Aided Design (CAD), Computer-Aided Engineering (CAE), robotics, automated guided vehicles and automated storage and retrieval systems. This technology enables rapid development of product. Conversely, Rapid Prototyping (RP), the creation of 3-dimension physical models of a product directly from Computer-Aided Design (CAD) with little human intervention [4], gives opportunity to potential investors to view model of such product before final commitments to its production. As a result of this, the fear and risk in term of time, cost and manufacturability among others, associated with production of products are eliminated.

The transition from the conceptual design to the manufactured product is such that the Computer-Aided Manufacturing (CAM) software application creates the detailed instruction of the CAD profile or geometry. This instruction or program drive the CNC machine tools to manufacture product. The instructions are conventionally represented in G-code and M-code. Recent developments in advanced manufacturing technology have seen programming of new generation machine tools in STEP-NC (STEP-AP238) program. The STEP-NC program is a data-rich language designed to overcome the current standard for defining the movement of machine tool axes. It allows more information about the machining process to be sent to the machine control and adds new information about the product being machined [5]. These include visual process showing geometric dimension and tolerance, on-machine simulation among others [6].

However, the knowledge of human needs bring major shifts to the world of manufacturing in the way companies develop their products. The first is economy frontage which makes companies continuously reduce their manufacturing cost, while concurrently improving the quality, reliability, modernity, aesthetic and durability of products in order to maintain their market positions.

Another major shift, among others, is the increasing entrepreneurial spirit (business model) driven by the emergence of small and medium scale companies, service providers/bureaus and individual entrepreneurs that utilise low-cost, modern machines such as CNC machines, to quickly prototype and manufacture their products. By this, customer can get a low volume and customized products within a short time and at a reduced price.

A range of advanced manufacturing technology-based machines, using Computer Aided Design and Manufacturing (CAD/CAM), have emerged as being suitable to meeting these changing needs in the manufacturing industries. Among these machines are the CNC milling and the Rapid Prototyping machine. The output of the CAD/CAM which represents the software and programming part of the manufacturing procedure (protocol) is sent to CNC machines to physically produce the parts by removing unwanted material from solid blocks to form physical model of the part.

The objective of this work is to describe the production protocols for producing the Nigeria Coat of Arms, for use as a seal, using Roland Modella Pro II Rapid Prototyping machine and compare the result to that obtained using a VMC PDC-650H Milling machine.

2. PRODUCT DEVELOPMENT

Development of product involves having a good idea of human need, transformation of the ideas, designs, materials and information (data) into products aimed at satisfying the need. In contrast, the intensified knowledge in the area of advanced manufacturing are gathered, filtered, refined and disseminated to improve product development. This knowledge can be categorize into knowledge of products/ services (products required to meet a certain need), processes/procedures (knowledge of the procedure essential for the production), production technology (the type of technology that will be suitable for the production), customers and markets (knowledge of the target customers or markets), competitors (which product or industry could be a contender), the people, etc. The management of advances in recent manufacturing technologies such as advances in programming of machine tool are the cardinal point emphasized by this work.

CNC machines are generally controlled by G and M-codes which represent number values and co-ordinate points where each number is assign to a particular operation. They are either entered manually to CAD by the production personnel or automatically generated by computer software as realised in robust and advanced CNC machines. They are able to accurately and repeatedly control motion in various directions, easily programmed, easy to store and change programs, safer to operate and generate closer tolerances than manual machines.

Rapid Prototyping machines operate either subtractive or additive processes each offering benefits in the modern manufacturing age. It is used to produce concept models, function models, marketing and presenting models, investment casting and pattern making, medical and engineering analysis models. But massive productions cannot be manufactured by this method. The choice of investing in one or the other technology depends on flexibility in material selection, tooling required and performance of the machine throughout the workflow process.

- Materials are added on or built up in the creating process of additive rapid prototyping and;
- For subtractive rapid prototyping, material is removed from a block of material using more traditional standard machine processes such as milling, turning or drilling with CNC machines. Both Roland Modella Pro II MDX-540 (Fig. 1) and the CNC VMC PDC-650H milling machine (Fig. 2) used for this study operates on this method.

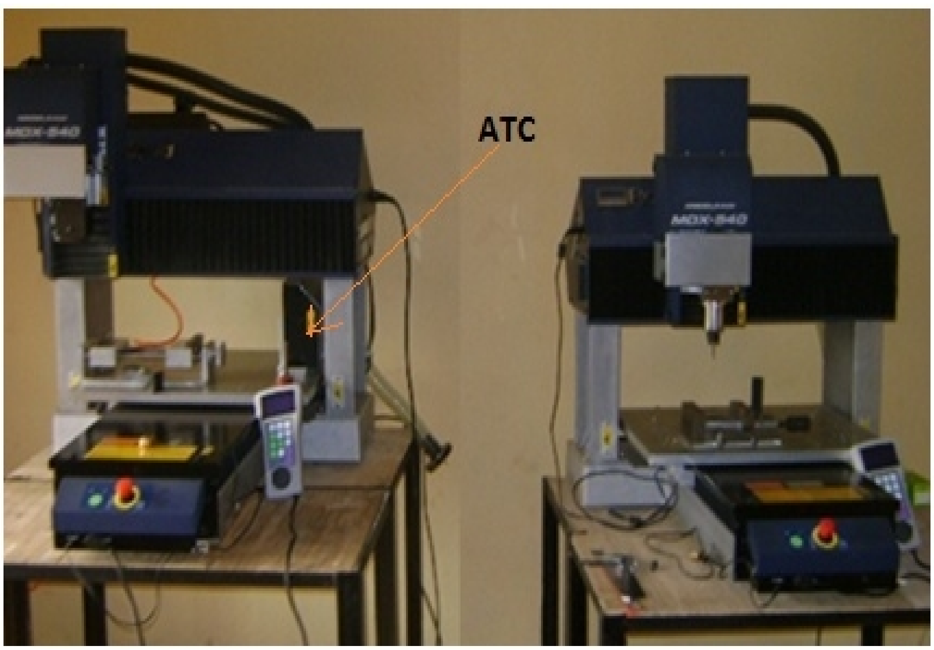

Fig. 1. View of the RP milling machine

2.1 General Concept of CNC Protocol/Process Flow

CNC machine consist basically two components: the machine tool and controller (machine control unit, MCU). This, as a result, makes every CNC machine a collection of systems coordinated by the controller. Each controller unit (MCU) is manufactured with a standard set of build-in codes and other codes are added by the machine tool builders which vary from machine to machine. The CAD/CAM create a link between the product design and manufacturing where the CAD system is used to develop a geometric model of the part or product which is afterwards used by the CAM system to generate part programs for CNC machine tools. The CAD/CAM function can be performed by the same system or separate systems located in different places. Therefore, integrating the CAD/CAM logically within a company yields the concept of computer-integrated enterprise (CIE) where all aspect of the enterprise is computer aided, from management and sales to product design and manufacturing. The flow of Computer-Aided CNC protocols is:

- Develop the 3D geometric model of the part or product using CAD.
- Decide the required machining operations and cutter-path directions.
- The tooling required is chosen.
- Manually write or run CAM software to generate the CNC part program.
- Verify and edit program.
- Manually input or download the part program to the appropriate machine.
- Verify the program on the actual machine and edit if necessary.
- Run the program and produce the part.

The conventional CNC milling machine shows the cutting-path or part program manually written with code representation. The codes are inputted into the machine to perform the product development.

Fig. 2. View of the VMC PDC-650H milling machine

2.2 Materials Requirement and Equipment

Products can be developed with a variety of non-ferrous materials, on the Roland Modella Pro II MDX-540 machine, such as wood, Acrylonitrile Butadiene Styrene (ABS) plastic, brass, aluminium, copper, etc. The factors influencing the choice of materials used are the function of the part, complexity of model, cost of material, availability, estimated machining time, and manufacturability to name few. Copper plate material was used for this work because of its availability and the function of the product.

The RP machine used is capable of modelling and shaping high precision prototypes and industrial models in a fast and most accurate way [7]. It's designed with a work area of 500 (X) x 400 (Y) x 155 mm (Z) with optional fourth axis and automatic tool changer. A depth sensing feature of the machine determines the tool offset distance from the Z-axis. Its SRP Player CAM software makes programming and generation of cutting-path (both simple and complex) easy. Once the 3D geometric model is developed, the CAM software of the machine automatically generates the cutting path for the machine. The rigid worktable makes clamping of the workpiece easy, firm and uniformly levelled. The levelling was achieved using spirit level tool. The magazine features a 4-position automatic tool changing options.

The conventional CNC Vertical Machining Center (VMC) PDC-650H used is also computer controlled to cut different materials. It's designed with table size of 700mm X 400mm and X/Y/Z travel length of 650mm/500mm/520mm. The machine is equipped with 24 automatic tool changer capability to realise several processing procedures which are based on CNC programming. It's able to translate G code programs consisting of specific numbers and letters to move the spindle head to any of its three (3) different axes (X/Y/Z).

2.3 Machine Parameter Setting

After the material and tool for the job are specified, the essential parameters set on the RP machine software includes: the tool size, material of prototype or product, speed of machine, feed rate, depth of cut, etc.

2.3.1 Tool size

Tool size determines the quality, time of completion, accuracy of the finished work and resemblance of the prototype to the original product. This is selected based on the material to be machined, model size, smallest possible profile to be machined etc.

2.3.2 Tool offset

Tool offset is done to determine the height of the tool with respect to the work table. This information will be applied by the machine to determine the optimal depth of cut into the material of prototype.

2.3.3 Spindle speed

Spindle speed is worth noting to prevent damage of tool, damage to the electric motor, damage of the material for prototype as well as to produce a good prototype. It is set based on the type of material, the quality of work, capacity of the machine and the tool composition.

2.3.4 Feed rate

Feed rate is the rate at which the tool feeds on the material per cycle of cut. It is important to quality of finish, for increase in the life span of tool and prevention of machine vibration. This is a function of the tool, material, quality etc.

2.3.5 Material and size

The material to be used must conform to the type specified for use on the machine (non-ferrous material). It must not be more than the size of the machine table and must be enough to cut out the prototype or product size from it.

The machine interface showing these features are shown in Figs. 3 and 4.

In the case for the CNC VMC PDC-650H, among the important parameters to be noted are:

2.3.6 Spindle speed

Spindle speed is set corresponding with x1/ x10/ x100 band switch on the portable handwheel box for low, medium and high speed respectively.

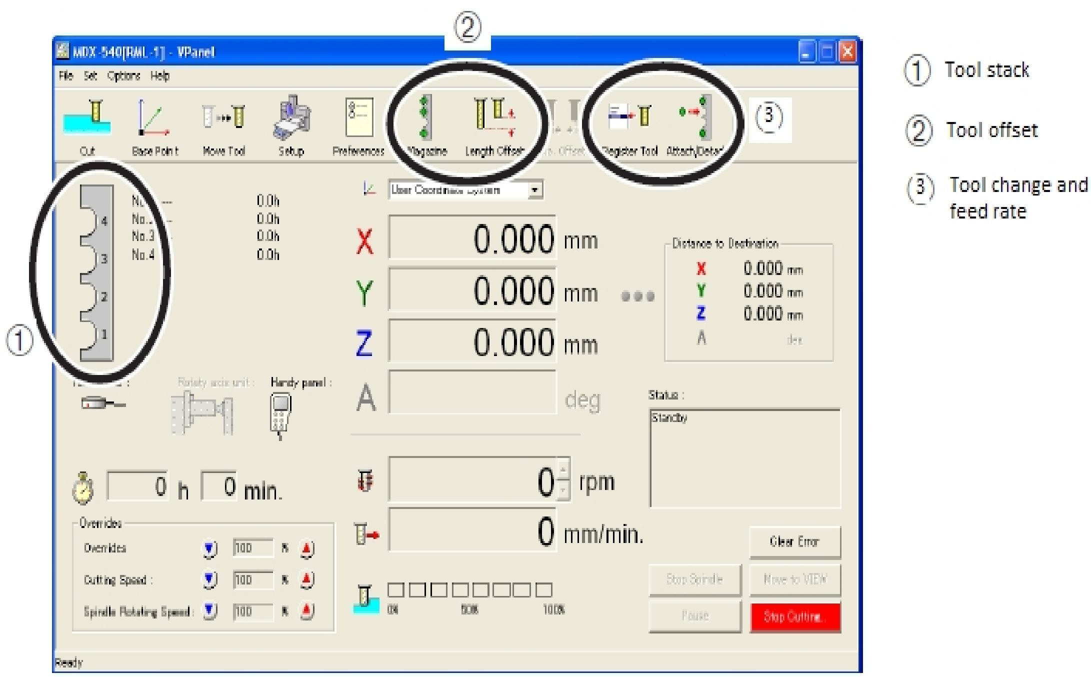

Fig. 3. V Panel software interface

2.3.7 Breakpoint return federate

Breakpoint return federate is where the operation is to continue after a paused program.

2.3.8 Dry run federate

This is used during automatic mode when the “dry run” is active. It’s valid for only G01 (Linear interpolation), G02 (circular interpolation in CW direction) and G03 (circular interpolation in CCW) block.

Others are maximum feed rate, maximum acceleration, X/Y/Z parameters and tool offset.

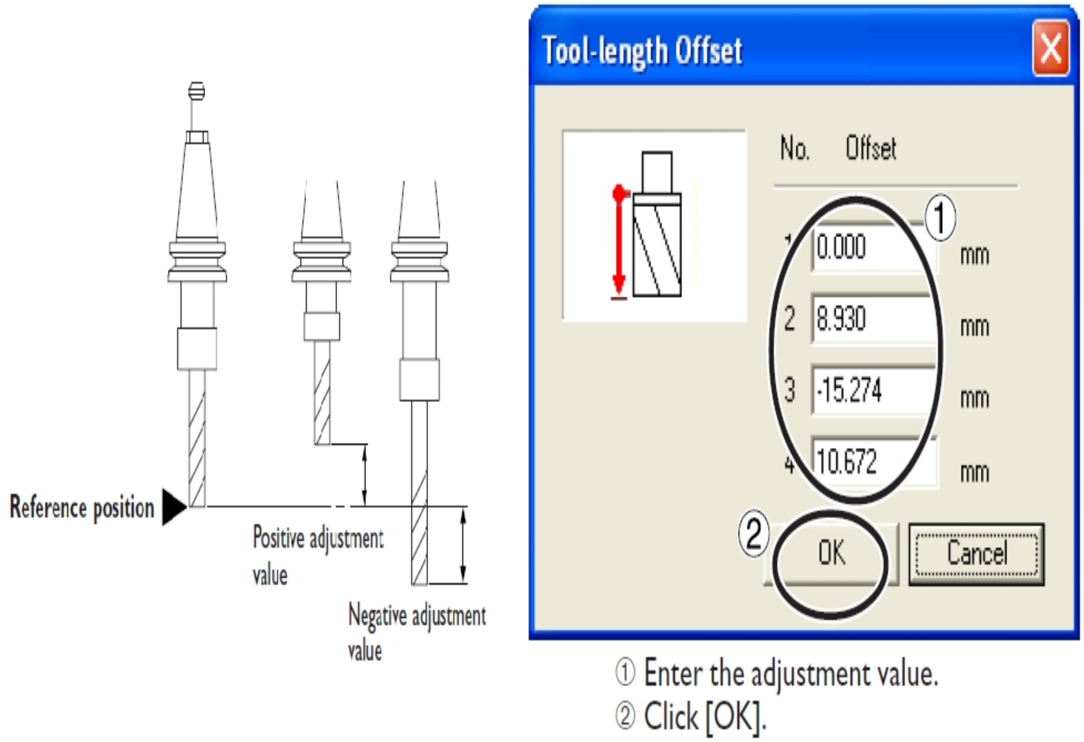

Fig. 4. Tool Offset Position Sub-menu

2.4 Procedures Using RP Machine

The procedures for production of the "Nigeria Coat of Arms" on a copper plate using the Roland Modella Pro II are elaborated thus:

2.4.1 Software

The 3D-engrave and SRP player CAM software tools were used in the process development of the Nigeria coat of Arms model.

A BITMAP (.BMP) picture of the Nigerian Coat of Arms was acquired and imported into the 3D software environment (Fig. 5) where the following parameters were set.

- The model size with respect to the material size to be used, (100 mm x 100 mm).
- The relief size and pattern for the model, (1.0mm and embossed).
- The resolution which determines the pitch of the tool path (0.2mm). The smaller the resolution, the better the finishing and the longer the time of completion irrespective of the type of material used.
- The model could then be visualized in 3D.
- The resulting 3D image of this model was then saved with a file name and exported as a .STL file format.

Subsequently, the .STL image file was imported into SRP Player CAM environment (Fig. 6) where the material and tool to be used were selected. This solely depends on the good judgement of the production personnel because it is not suggested by the machine.

The following settings were specified on the SRP player CAM interface.

(a) Model size and orientation for correct outlay of x, y, z axes; (100 mm x 100 mm x 1 mm).
(b) A good finished milling operation with spindle maximum speed of 12, 000 rpm (the default).
(c) 3 mm and 2 mm HSS ball-end mill were selected for the “Roughing” and “Finishing” operation respectively. The software automatically generates the cutting profile for the selected tool size and then display the estimated cutting time.

The total operation time of machine is given as:

$$T_0 = t_s + t_m \tag{1}$$

Where: T_0 = operation time,
t_s = set-up time and
t_m= machine time.

The estimated machine time was considered for both “roughing” and “Finishing” operations. The time taken to prepare the clamping and cleaning was also considered in the set-up time.

2.4.2 Machine operation

Once the clamping had been well achieved, the tools for the job were fixed in their harbours and stacked in the automatic tool changer (ATC) of the machine (Fig. 1). A limiting switch electrically wired to the monitor/control device of the machine detects the presence of tools in the stack and communicate same to the V-Panel software of the computer system as well as the handy panel on the machine.

The tools were calibrated to determine its offset distance from the work table and the machine coordinates were set (referenced) for the new job to be produced.

Once the start button on the SRP Player is clicked ‘ON’, the machine operation starts.

2.5 Procedures Using VMC PDC-650H Machine

A series of G-codes representing the cutting-paths of the part programs were written and inputted in the VMC programming interface of the machine. 2mm HSS end mill was used with a spindle maximum speed of 3000 rpm. A part program of the G-codes for this work is shown in the appendix. The description of the codes is as stated below:

S code - Spindle Speed Function
F code - Feedrate Function
D code - Tool Radius Offset
H code - Tool Length Offset
G code - Preparatory Function
M code - Miscellaneous Function

3. RESULTS AND DISCUSSION

The results obtained, of the complete production of the Nigeria Coat of Arms from 3D engrave software to SRP player and then the final product, using the RP machine as carried out by a personnel are as shown in Figs. 5, 6 and 7. The machine time to complete the physical model was 8 hours and 6 minutes and the preparation and set up time was 37 minutes which brings the total operation time to 8 hours and 43 minutes. The model obviously resembled the original picture; it revealed the essential features and conformed to the designed dimensions. The tool sizes used for the operations enhanced the good product output. Though the material used for the work (copper) is susceptible to corrosion but it further enhanced the good finishing of the model. There are limitations arising from the use of the RP machine. Among these are the limitation to prototype and small products only; the machine is not very rugged; the tools wear out easily since it is air-cooled; and the machine stops after a long hour of use due to increase in temperature.

Conversely, the time taken by one personnel to write the codes, prepare the work and machine time added up to 27.81 hours with the CNC VMC PDC-650H milling machine.

It was produced at a much faster rate and more accurately with the RP machine than what was obtainable with the conventional CNC mills.

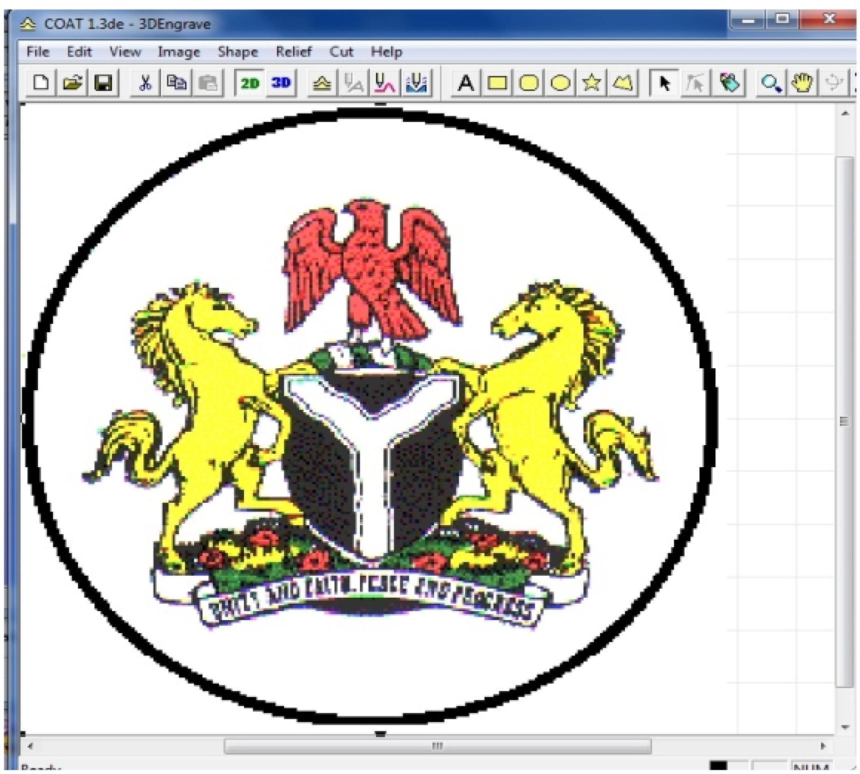

Fig. 5. View of the Nigeria coat of arms on 3D-engrave software

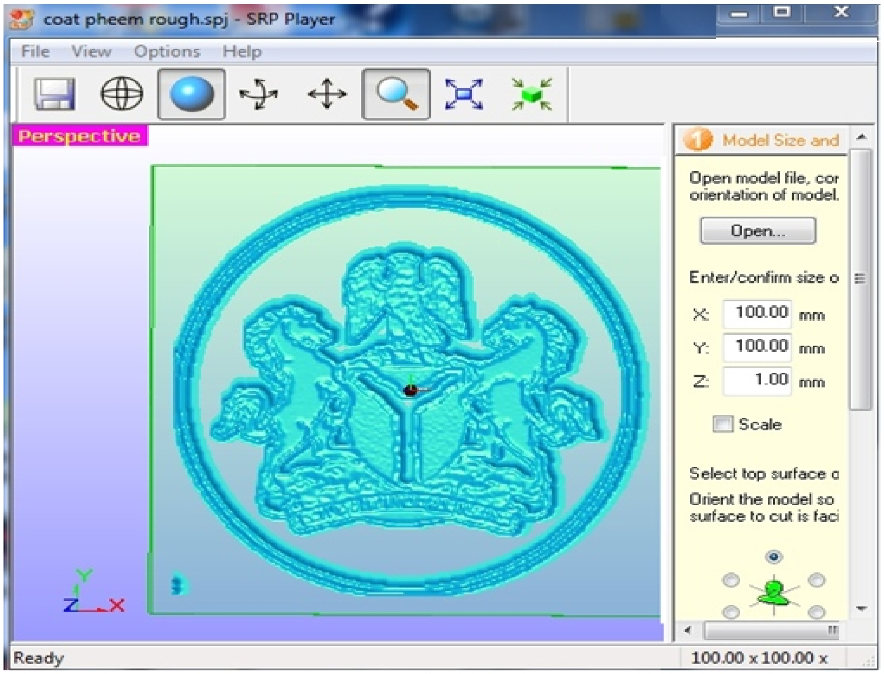

Fig. 6. View of the Nigeria coat of arms on SRP player CAM software

Fig. 7. Physical model of the Nigeria coat of arms

4. CONCLUSION

The benefits of intensified knowledge in the identification of human need, understanding and harnessing of the advanced manufacturing technology in Rapid Prototype machine have been utilized to develop a product model at a much faster rate, more accurately and with less human effort compared to that obtained with the conventional CNC machine. These results indicate that in a developing economy like Nigeria, knowledge management is a key to having vibrant manufacturing sector able to cope with the dynamic challenges of increasing globalised world.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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APPENDIX

G-code of part program for the Nigeria Coat of Arms production

G-code representation for milling the outer circular profile using 2mm HSS end mills

```
G00 X0 Y0 Z10
M03 S1500
G01 Z-2 F15
G02 X102 Y0 R51
G02 X0 Y0 R51
G00 Z10
X2 Y0
G01 Z-2 F15
G02 X100 Y0 R49
G02 X2 Y0 R49
G00 Z10
M05
M30
```

Where,
G00 X0 Y0 Z10 - G00 means rapid positioning and X0 Y0 Z10 is the starting coordinate of the work.
M03 S3000 – M03, Spindle rotates clockwisely at speed of 3000rpm.
G01 Z-2 F600 - G01, Linear interpolation at 2mm depth and federate of 600mm/min.
G02 X102 Y0 R51 – G02, circular interpolation at radius 51mm upto (102, 0) coordinate point.
G02 X0 Y0 R51 - Circular interpolation at radius 51mm upto (0, 0) coordinate point.
.
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.
M05 - Spindle stop.
M30 - Program end.

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