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CNC Programming, Simulation, and Machining of Standard Engineering Component

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Abstract: *As a result of its extremely high accuracy, automation capacity, repeat ability, and efficiency, computer numerical control (CNC) machining has become one of the most important manufacturing methods in modern times. The present study aims at using modern CNC manufacturing processes in CNC programming, simulation, and CNC machining of an engineering part. For manufacturing a conventional engineering part with very high accuracy and surface finish, the study involves CNC program development, tool path creation, selection of machining parameters, simulation, and actual CNC machining. To understand CNC machining processes, conditions of machining, tool motion, and optimization of manufacturing process, the study analyzed CNC turning and milling operations. The standard G codes and M codes, taking into consideration the shape of components, order of machining, and tools specification were utilized to design the CNC program. The use of Computer-Aided Manufacturing (CAM) software was applied for simulating the process of machining, where tool paths would be verified for errors and to avoid tool collision and maximize machining time before the production phase. In machining process analysis, various machining parameters such as spindle speed, feed rate, depth of cut, machining speed, and tool material were considered. The results revealed that, through the reduction of errors in programming, prevention of wear of tools, and improvement in cutting conditions, CNC simulation significantly enhances machining efficiency. The surface finish, accuracy, and efficiency in machining were enhanced as a result of proper selection of machining parameters. The results also revealed that CNC machining is more productive, flexible, and repeatable than conventional machining processes. Moreover, it is associated with reduced manufacturing costs compared to conventional machining*

Keywords: CNC Programming, CNC Machining, Simulation, G-Code, Engineering Component

I. INTRODUCTION

Because of its high accuracy, automation potential, repeatability, and production efficiency, computer numerical control (CNC) machining has become one of the most sophisticated and extensively utilized manufacturing technologies in contemporary industries. Automatic machining procedures with little human interaction are made possible by CNC systems, which use numerical data and programmed instructions to control machine tools. The use of CNC technology in manufacturing industries like automotive, aerospace, defense, marine, biomedical, and precision engineering has greatly expanded due to the quick development of industrial automation and the need for intricate engineering components with exceptional dimensional accuracy [1]. Because CNC machining can create complex geometries, maintain consistent quality, and cut production time and manufacturing costs, it has supplanted many traditional machining techniques. CNC machining includes computer programming, machine tools, and automated control system for performing functions such as turning, milling, drilling, boring, threading, and contouring. In CNC machines, g-code and m-code that direct the machine operations concerning the speed of spindles, feeds, tool paths, coolant action, and other machining processes are utilized. The machine control unit reads the generated part program and directs precise tool motion on various axes to form the required part shape [2]. CNC machines are best suited for batch manufacture, customization and high precision engineering processes due to its flexibility allowing rapid change of the machining programs. Since the effectiveness of the code influences the accuracy of the machining operation, it is imperative to have an efficient process of CNC programming to ensure the production process is successful. The methods of CNC programming include both manual programming and computer-aided manufacturing (CAM) software. Although CAM software uses optimum paths for machining through automatic tool path generation based on the geometry of the parts designed through CAD software, manual programming offers machining instructions using standard G-code and M-code. With its benefits of reducing complexities, minimising errors, and enhancing the conditions for cutting, CAM software has greatly enhanced machining effectiveness [3]. CNC programming also allows effective control of machining parameters such as spindle speed, feed rate, depth of cut, and tool motion, thereby improving the accuracy of dimensions and surfaces. As it facilitates the verification of processes through simulation before engaging in actual machining, CNC simulation has become more and more important in CNC machining. Typical applications of CNC simulation software include program validation, path checking, collision detection, machining time calculation, and machining process improvement. By making use of simulations, manufacturers can save on materials, machine idle time, and damaged tools due to faulty programming and inefficient processes. Process planning and optimization have been made feasible through simulation of real machining operations via modern CNC simulators [4]. The integration of CAD/CAM technology and CNC simulation in automated environments has greatly enhanced manufacturing efficiency and process reliability. In CNC manufacturing, machining performance, tool life, metal removal rate, surface quality, and machining accuracy depend greatly on the values of machining parameters. The processes of chip breaking, cutting forces, heat generation, vibrations, and machining accuracy depend on parameters such as cutting speed, feed, spindle speed, depth of cut, and tool geometries. Dimensional errors, accelerated tool wear, inadequate surface finish, and increased machining costs can be expected due to wrong machining parameter settings. Machining parameter optimization becomes an important part of obtaining productive and efficient machining process results [5]. Due to different physical properties, chip breaking capabilities, and machinability, diverse technical materials such as mild steel, aluminum alloy, stainless steel, brass, titanium alloy, and composite materials possess different machinability levels. CNC Turning and CNC Milling are among the most common machining processes for manufacturing highly complex geometrical shapes of technical parts, which must be machined within tight dimensional tolerances. While CNC Milling is mainly employed for flat surface machining, slotting, curving, and other highly complex three-dimensional features, CNC Turning is primarily performed for cylindrical or rotary parts. Complex-shaped parts can now be more accurately machined with faster setups due to the availability of multi-axis CNC machines [6]. The quality of machined surfaces and machining productivity have been significantly improved due to the widespread application of advanced cutting tools, coated inserts, carbide tools, and fast machining operations. The adoption of computer numerical control machining has risen in recent times as a result of several benefits that it offers compared to the conventional machining process. In production, CNC machinery increases productivity, enhances consistency, reduces labor dependency, minimizes human errors, increases flexibility, and enhances safety. Moreover, CNC machining facilitates mass production with consistency in quality and reduced inspection processes through automated machining. CNC machining also facilitates incorporation of robotics, artificial intelligence, industry 4.0, and smart manufacturing for advanced automation of industrial processes [7]. Consequently, there is the growing demand for CNC programmers and CNC machine operators as a result of these developments. This study centers around the application of CNC turning and milling techniques to program, simulate, and machine an ordinary engineering component using CNC. Preparation of CNC part programs with G-codes and M-codes, simulation of machining processes via CAD/CAM software, selection of appropriate machining parameters, and evaluation of machining performance constitute the main thrust of this research study. Analysis of dimensional precision, surface finish, machining time, and process optimization in CNC machining operations is another aspect of the present research effort. The findings of the research study are expected to provide valuable insights into CNC machining technology and aid its further development.

II. MATERIAL & METHOD

Using widely used engineering materials and machining accessories appropriate for CNC manufacturing operations, the current study on CNC programming, simulation, and machining of a typical engineering component was conducted. Because of its excellent machinability, moderate strength, affordability, and extensive industrial applicability in manufacturing industries, mild steel was chosen as the main workpiece material. The material has the necessary mechanical qualities for turning and milling operations, including sufficient hardness, ductility, and dimensional stability. Because mild steel offers good surface quality and satisfactory machining performance during CNC machining processes, it is widely utilized in the fabrication of automotive, structural, and machine components. A CNC Turning machine along with a CNC Vertical Milling Machine having an automatic control system was used for machining. As HSS and carbide cutting tools exhibit better wear properties, hardness, thermal resistance, and cutting performance, therefore, they have been selected for the purpose of machining. Finishing operations where better surface finish and higher dimensional accuracy were needed were performed using HSS cutting tools, while the carbide cutting tools were used mainly for roughing and faster cutting. Tool holders, collets, chuck assemblies, and coolant systems were employed in machining processes for proper workpiece holding, vibration damping, and cooling. Water-based coolant was applied during the machining process to decrease temperature, increase surface finish, and reduce tool wear. In order to test the turning and milling operation, the geometry that would be studied includes those with stepped diameter, slots, drilled holes, chamfer, and flat faces. The component dimensions are drawn using the CAD software according to the standard procedure. G-code and M-codes have been utilized in CNC programming to control spindle rotation, feed, position of the cutting tool and sequence of machining. Prior to machining, tool paths, collision checks, machining process verification, and optimization of the machining parameters are done by simulating the machining process using CAM software. Machining parameters include spindle speed, feed rate, cutting speed, and depth of cut which are selected based on the nature of workpiece and cutting tool used in machining [10].

Table 1: **Materials and Equipment Used in the Investigation**

Item	Specification / Type	Purpose
Workpiece Material	Mild Steel	Machining of engineering component
CNC Turning Machine	2-Axis CNC Lathe	Turning operations
CNC Milling Machine	Vertical CNC Milling Machine	Milling operations
Cutting Tool	HSS and Carbide Tools	Material removal
CAD Software	AutoCAD / SolidWorks	Component design
CAM Software	MasterCAM / Fusion 360	Tool path generation and simulation
Coolant	Water-Soluble Cutting Fluid	Cooling and lubrication
Measuring Instruments	Vernier Caliper, Micrometer	Dimensional inspection

Method

Designing components, CNC programming, simulation, machining, and evaluation of machined components were some of the methodologies followed in the current study. The engineering component was designed using CAD software according to standard specifications of dimension and machining. For further machining processes, tool paths generation and simulation analysis, the designed model was imported into the CAM software. In order to control machine tool movements, rotation of the spindle, feed rates, coolant control, and machining sequences, CNC programs were developed using standardized G codes and M codes. Both manual programming and CAM programming processes were considered to understand the concepts of CNC machining and process optimization [11]. To determine tool path confirmation, collision avoidance, reduce programming errors, and determine machining time, simulation of the machining process was conducted before the actual machining took place. Visualization of the machining process including the tool path, removal of material, cutting order, and cutting strategy became feasible with the help of simulation. In order to improve the machining process efficiency and avoid unnecessary movements of the tool, tool selection and machining parameters were optimized using the simulation process. Furthermore, wastage of material

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and machine downtime was prevented by avoiding over cutting, under cutting, and interference of tools [12]. Using the CNC part program, machining processes have been completed using the CNC lathe and CNC milling machines. Chamfering, drilling, straight turning, step turning, and facing operations are the methods used for creating the cylindrical shape on the component, based on the created CNC part program. Milling processes have been conducted to obtain the smooth surface, slots, pockets, and contour shapes based on the design specifications. Spindle speed, feed rate, depth of cut, and cutting speed have been selected based on the cutting tool and workpiece properties. The coolant has been continuously supplied in order to minimize the temperature and increase the longevity of the tool [13]. By using conventional measuring instruments such as vernier calipers and micrometers, the fabricated part was analyzed for dimensional tolerance, surface quality, and machining capability after the machining process was completed. Machining accuracy and capability were evaluated by comparing the obtained dimensions with the design requirements. Surface quality and machining capability were determined using parameters such as dimensional tolerance, tool wear pattern, machining cycle time, and machining capability index. The effectiveness of CNC programming and simulation on increasing productivity, machining accuracy, and fabrication quality in modern CNC machining technology was evaluated by comparing the results of machining and simulation analyses [14].

Table 2: **Machining Parameters Used for CNC Operations**

Parameter	**Turning Operation**	**Milling Operation**
Spindle Speed	800–1200 rpm	1000–1500 rpm
Feed Rate	0.15–0.30 mm/rev	100–250 mm/min
Depth of Cut	0.5–2 mm	0.5–1.5 mm
Tool Material	Carbide / HSS	Carbide End Mill
Coolant Condition	Wet Machining	Wet Machining
Machining Type	Facing and Turning	Slotting and Milling

III. EXPERIMENTAL WORK

In this respect, the aim of the experimental study conducted for the purpose of the current research is to analyze the aspects of CNC programming, simulation, and machine operation during the process of manufacture of an average engineering part. Mild steel was selected as a material of choice because it is widely used in various manufacturing enterprises, is hard but machinable enough. First, the material had to be prepared according to the required dimensions. Several types of machining activities have been conducted using CNC lathing and milling machines, namely facing, turning, drilling, slotting, contour milling, and chamfering. Machining accuracy, tool movements, machining parameters, surface finishing, and machining effectiveness during CNC operations constituted the main subject of this research [15]. Firstly, the engineering part was designed through CAD using the normal standards for engineering drawings. Geometrical characteristics such as stepped diameters, drilling, smooth surfaces, notches, chamfering, among others were incorporated into the CAD model in order to study different milling processes. The path of tools, machining procedure, and material removal techniques among other could be observed through the simulation technique before actual production. In CNC part programming, standard G and M codes were used in order to control the process parameters such as coolant supply, spindle revolutions, feed motion, tool motion, and cutting procedures. Any errors in the programming, tool collision, and other aspects were detected prior to machining through simulation of the CNC program [16]. In terms of controlled cutting process, CNC turning and milling machines have been employed for the machining process. In order to produce stepped profiles and cylindrical surface in relation to the specified dimensions, initially, the facing and turning operations have been executed. After that, drilling operations have been conducted through the use of appropriate drill gear to create holes at specified positions. For attaining proper geometry of the parts, carbide end mill was used for conducting various milling operations like slotting, contour milling, and flat surface machining. Cutting parameters, which include spindle speed, feed rate, cutting speed, and depth of cut, have been determined for machining operation in reference to the type of cutting tool and work material [17]. The machined part was subsequently analyzed to evaluate the quality of machining and dimensional accuracy of the part through measuring techniques like surface finish tester, micrometer, and vernier caliper. Dimensional variations and machining accuracy were determined based on the comparison between the dimension of the part and those of the original part parameters. Surface finish quality and machining performance were also evaluated according to dimensional accuracy, tool wear behavior, and machining time. Experimental results of the machining process were then compared to the simulations to analyze the effect of CNC programming and simulation in machining productivity and accuracy improvement. It was proven that in making engineering parts, CNC simulation significantly decreases machining errors and increases machining accuracy while minimizing wastage [18].

Table 3: **Experimental Conditions for CNC Machining**

Parameter	**Turning Operation**	**Milling Operation**
Workpiece Material	Mild Steel	Mild Steel
Cutting Tool	Carbide Tool	Carbide End Mill
Spindle Speed	800–1200 rpm	1000–1500 rpm
Feed Rate	0.15–0.30 mm/rev	100–250 mm/min
Depth of Cut	0.5–2 mm	0.5–1.5 mm
Coolant Type	Water-Soluble Coolant	Water-Soluble Coolant
Machining Operations	Facing, Turning, Drilling	Slotting, Contour Milling
Inspection Tool	Vernier Caliper, Micrometer	Vernier Caliper, Surface Tester

IV. RESULT & DISCUSSION

In comparison with the conventional techniques used in machining, CNC machining provides better surface finish, great dimensional accuracy, and efficient cutting of materials based on the experiments conducted on CNC programming, simulation, and CNC machining of an engineering part. In the process of turning and milling, the designed CNC program, which included the application of G codes and M codes, was able to control the spindle and feed movements as well as the machining process itself. CNC simulation allowed successful verification of tool path, detection of any possible errors in programming, and prevention of interference between tools and material during the process of machining. All three aspects - facing, straight turning, and step turning - were effectively carried out using the CNC turning process according to the specifications required for the components. The selected parameters of the cut provided a good surface finish quality, smooth chip formation, and stable machining operation. It was observed that a higher spindle speed along with an appropriate feed rate contributed to good surface finish in continuous machining, but the use of such a combination also led to tool wear. During the turning operation, it was seen that low feed rate caused good dimensional accuracy and reduced vibrations. Carbide cutting tools performed better than the high-speed steel cutting tools due to their hardness and heat stability. Carbide end mills were also used effectively in carrying out the milling operations like slotting, contouring, and flat surface cutting. During the whole milling process, CNC milling provides dimensional and geometrical accuracy continuously. Effective optimization of the tool path reduces machining time and improves machining efficiency, as observed through simulations. Smoother finished surfaces can be achieved, and chatter vibration is minimized through proper selection of spindle speed, feed rate, and depth of cut. In spite of this, because of tool deflection and machine vibrations, large depth of cut results in cutting forces, which leads to slight dimensional variation. It is thus clear from the above study that optimization of machining parameters in CNC milling significantly improves machining quality. The high level of accuracy and consistency associated with CNC machines was evidenced through dimensional inspection of the fabricated part, where the dimensions found were very close to those required. Variations in dimensions were caused by wear of tools, vibrations, and temperature effects while machining for long periods of time. Compared to conventional machining processes, CNC machining produced parts whose surfaces were consistently smoother with low surface roughness values. Through simulations performed before the machining process, CNC machines avoided many mistakes in programming due to proper tool movements and cuts. Overall, it was established that CNC programming and simulation play an

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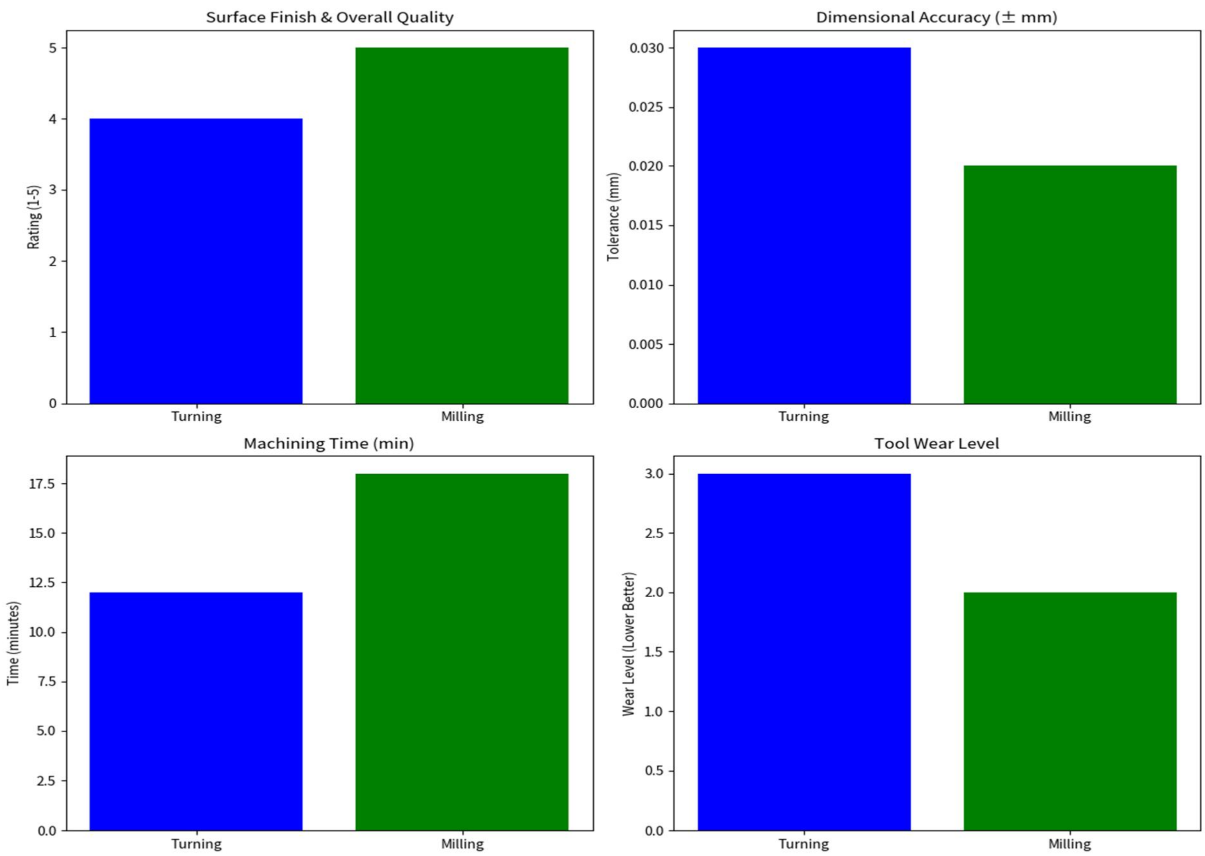
important role in improving production quality, dimension accuracy, and machining efficiency. While engineering component fabrication took place, CNC simulation helped avoid setup errors, reduce machining errors, and enhance machining reliability. Furthermore, it was found out that machining efficiency, tools life, and surface finish are heavily influenced by appropriate selection of machining parameters and tool materials. In creating complex engineering parts with high precision and repeatability and reduced machining time, CNC machining can be regarded as a very suitable technique. Integration of CAD/CAM programs with CNC machining helps improve manufacturing efficiency in modern industry.

Table 4: **Experimental Results of CNC Machining**

Parameter	**Turning Operation**	**Milling Operation**
Surface Finish	Good	Very Good
Dimensional Accuracy	±0.03 mm	±0.02 mm
Tool Wear	Moderate	Low
Machining Time	12 min	18 min
Material Removal Rate	Medium	High
Vibration Level	Low	Moderate
Coolant Performance	Effective	Effective
Overall Machining Quality	Satisfactory	Excellent



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V. CONCLUSION

With CNC turning and milling processes, the current study has been quite successful in exploring the aspects of CNC programming, simulation, and machining of an engineering part. The study revealed that CNC machining provides better dimensional accuracy, better polishing capability, excellent repeatability, and better material removal as compared to conventional methods of machining. For machining the parts, the CNC codes have been programmed through the use of G-codes and M-codes so as to ensure precise motion of tools while machining. Verification of the path of tools, avoidance of any error in programming, and collision prevention in machining was achieved by CNC simulation. The research further revealed that surface finish, dimension tolerance, tool wear, and machine efficiency are all highly influenced by machining variables like spindle speed, feed rate, depth of cut, and the material of the cutting tool used. Thermal distortion while machining was minimized and efficiency in machining maximized through the appropriate application of carbide tools and optimal machining environment. Thanks to better control of the tool path and machining, CNC machining achieved better dimensional tolerance and surface finishing than turning. In general, through the research conducted, it was realized that CNC programming and simulation are vital in enhancing machining efficiency, reducing manufacturing mistakes, minimizing material wastage, and ensuring the quality of products produced. With the integration of CAD/CAM technology in the CNC machining system, it becomes possible to produce complex engineering parts through automation and high accuracy and within a relatively reduced time frame.

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