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Review Article

A Review on CNC Machine Tool Materials and Their Impact on Machining Performance

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Abstract

Modern production relies heavily on CNC (Computer Numerical Control) machine tools due to their precision and efficacy in a huge range of applications. A choice of materials in CNC machine tools significantly influences their performance, energy consumption, and machining capabilities. This paper reviews the impact of materials like steel alloys, aluminium alloys, polymer composites, glass ceramics, and tool steels on CNC machining processes. It also explores advancements in CNC technologies, including the adoption of the STEP-NC standard, which enhances flexibility, interoperability, and automation in CNC manufacturing. While these developments promise improvements in efficiency and adaptability, challenges such as standardisation and compatibility remain. The paper emphasises the need for further research and development to optimise material properties, improve energy consumption, and create more flexible CNC control systems. These advancements will contribute to the continued evolution of CNC machining, enabling manufacturers to produce high-quality, cost-effective products with greater precision and sustainability.

Keywords: *CNC machine tools, machining performance, materials, steel alloys, aluminium alloys, polymer composites, glass-ceramics, tool steels, STEP-NC, automation, energy efficiency, manufacturing, interoperability, precision machining*

Introduction

Despite their critical role in manufacturing, CNC machine tools have a high total energy consumption and low efficiency level. The whole amount of energy used and pollutants released over the lifetime of a machine tool are defined by its own energy consumption characteristics. So, to optimise machine tools for energy consumption, one must first conduct an in-depth study of energy consumption and its associated properties, then build a model based on reliability verification, optimise the machine's structural design according to the model, and finally use an evaluation system to measure the machine's total energy consumption. Beginning with an examination of energy consumption optimisation, this study delves into four areas of research on CNC machine tools based on energy consumption worldwide: the composition of machine tool energy consumption, design and optimisation techniques, modelling techniques, and evaluation techniques. The findings of the study suggest that the design of machine tools should take energy usage into consideration.

Modern manufacturing firms need to make sure they use the newest and most effective technology in order to stay competitive. One efficient method of creating goods with excellent accuracy and the right amount of surface roughness is via machining procedures[1]. Product geometries that are more complicated provide new, difficult production scenarios for cutting tool machining procedures [2][3]. The mechanical characteristics of product materials, particularly their hardness [4], are being improved and developed. Drilling, turning, and milling are all examples of classic or conventional machining techniques that rely on the cutting tool's hardness being greater than the material's [5].

Globalisation has enabled most nations to create products. This globalisation process has resulted in intense rivalry among manufacturing enterprises, resulting in variations in the quality of items produced. Therefore, most companies investigate other processes or techniques for making durable, high-quality goods at reduced costs. CNC machining procedures use the latest production technology[6].

A. *Structure of the paper*

Here is the outline of the paper: Section II covers the overview of computer numerical control (CNC). Section

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III Details CNC machine tools materials and their impact on machining performances. Section IV Examines the CNC production equipment interchange and flexibility. Section V presents a Literature review and identifies research gaps, and VI offers Recommendations for conclusions and future work.

Overview of Computer Numerical Control (CNC)

The CNC stands for "computer numerical control," which describes a kind of machine tool that allows the operator to direct the machine's operations by means of a predetermined set of instructions sent via a system of symbols, characters, and numbers [7].

When a CNC system is activated, the software receives the intended cuts and relays them to the relevant tools and equipment, which act autonomously, much like a robot. The code generator in the numerical system for CNC programming often makes the assumption that mechanisms are flawless despite the fact that errors are more likely to happen when a CNC machine is told to cut in many directions simultaneously [8].

A numerical control system's tool placement is defined by the component program, which is an input set. Programs for numerical control units are entered using punch cards. Conversely, computers receive programming commands for CNC machines using very small keyboards. It is possible to store CNC programs in a computer's RAM [9]. The programmers write and edit code. CNC systems thus provide a lot greater processing capability. Because more prompts may be added to older programs by changing the code, the nicest thing about CNC systems is that they are always changing.

A. Different Types of CNC Machines

The 1940s saw the introduction of motors to regulate the motion of pre-existing tools, which led to the creation of the first numerical control machines. CNC machining emerged as a result of the mechanisms being improved by analogue computers and then digital computers as technology developed.

Most CNC weapons in use today are entirely electronic. Some of the most typical operations carried out by CNC machines include laser cutting, ultrasonic welding, and hole punching. CNC systems' most popular machines. Programs for CNC mills may be composed of both numerical and textual instructions, which are used to guide components over different distances. G-code or another proprietary language may be used for mill machine programming, depending on the requirements of the production team. The simplest mills only have three axes. However, the majority of contemporary mills can accommodate three more: Z, Y, and X [10].

- **Lathe:** Tools that can be indexed allow lathe machines to cut components in a circular motion. The use of CNC technology allows lathes to make fast, careful cuts. CNC lathes allow for the production of intricate patterns that would be impossible with traditional, hand-operated lathes. Typically, the control operations of CNC lathes and mills are rather similar. CNC mills and lathes both work using G-code and other proprietary codes [11].
- **Plasma cutter:** A plasma torch is used to cut materials in a plasma cutter. Metals are the most common materials utilised in this process, although it is not restricted to only those. Plasma is created by combining compressed-air gas with electrical arcs; this produces the heat and speed needed to cut metal.
- **Water Jet Cutters:** One tool used in computer numerical control machining is the water jet, which cuts through granite and metal with high-pressure water. Sand or another very abrasive substance is sometimes mixed with water. Factory machine components are often shaped by companies using this procedure. For materials that melt or otherwise become unusable when exposed to the high temperatures generated by traditional CNC machines, water jets provide a more comfortable alternative. Because water jets are cooler, they are utilised for a variety of tasks, including cutting and carving, in industries including mining and aerospace.

B. CNC Machine manufacture programming

Machines in CNC manufacturing are operated using numerical control, which involves programming a piece of software with particular instructions. The G-code language, which is used for CNC machining, is used to manage the speed, feed rate, coordination, and other machine behaviours [12].

Minimal human interaction is required during CNC machining cycles since machine tool tasks may be pre-programmed for location and speed. Machining with CNC systems starts with the development of 2D or 3D CAD files, which are then translated into computer code. After inputting the program's code, the operator conducts a test run to ensure the code is error-free.

These characteristics have contributed to CNC manufacturing's broad use in the industrial sector; the production processes for both metals and polymers rely heavily on the technology. Various machining methods are used, and CNC programming allows for full automation in CNC production; read on to find out more about these:

1) Open/Closed-Loop Machining Systems

Depending on the application, CNC machines use either an open-loop or a closed-loop approach to achieve position control. In the former, there is a unidirectional flow of data among the CNC controller and the motor. The controller's feedback capability allows for error correction in a closed-loop system. A closed-loop system can, therefore, compensate for errors in location and velocity.

The X and Y axes are often used to guide movement in CNC machining. The tool is then positioned and guided by stepper or servo motors that replicate the exact movements specified by the G-code. If the process is being operated with low force and speed, open-loop control may be used. For all other purposes, closed-loop control is necessary to provide the accuracy, velocity, and uniformity required by industrial uses such as metalworking.

2) CNC Machining Is Fully Automated

Computer-aided design (CAD) software establishes the dimensions for a particular item, and computer-aided manufacturing (CAM) software transforms those specifications into an actual final product. Drills, cutters, and other machine tools may be required for every particular workpiece. Many modern technologies combine many functionalities into one single cell to fulfil these needs. Instead, it might control a plethora of gadgets and even a pair of robotic hands to transfer parts between different programs inside an installation. It would be hard, if not impossible, to duplicate the uniformity in parts output that the CNC manufacturing process offers, regardless of the configuration.

CNC machine tools materials and their impact on machining performance

CNC (Computer Numerical Control) machine tools are essential in modern manufacturing, and the materials used in their construction significantly influence their machining performance. Each material offers unique properties that can enhance or limit the effectiveness of the machine in various applications.

A. Steel alloys

Alloy steels were first employed in the pipeline, heavy machinery, automotive, and aerospace sectors in 1865. Alloy steels vary greatly in alloying. Low alloy steels have 1–2% Cr or Ni, whereas many stainless steels have 15–18% Cr. Hadfield, 316, and 4140 steels are examples of alloy steels. These steels may form martensite, bainite, or pearlite microstructures, which can provide a variety of properties. Their versatility has made them helpful in numerous industries. These are sometimes the only steel alloys with the right characteristics. Their application in automotive has led to safer and more fuel-efficient vehicles. Without the employment of high-quality alloy steels for the secure pipeline transportation of oil, modern life would not be possible. Development is thus necessary to expand markets, enhance goods, and advance mankind. This importance prompted Metals to publish the alloy steel special issue you are reading. The following 23 publications from a variety of authors and nations illustrate the current state of alloy steel research [13].

B. Aluminum alloys

The crust's most plentiful metal is aluminium. The metal has low weight, high specific strength, strong thermal and electrical conductivity, corrosion resistance, and formability. The intrinsic face-centred cubic (FCC) crystal structure with low dislocation slip resistance makes pure aluminium practical despite its 2.7 g/cm3 density (one-third of steel). A dense, self-restoring oxide coating forms instantly, providing high corrosion resistance in oxidising situations. By adding alloying elements, aluminium can be customised for strength, weldability, and formability. Aluminium solutes include copper, manganese, silicon, magnesium, and zinc. Wrought and cast aluminium alloys exist. The latter type is extensively alloyed for cast ability and strength and is rarely used as arc deposition wire consumables. Starting now, wrought alloys are covered. Eight series of aluminium wrought alloys are based on their major alloying components. Below is a brief overview of the series and its WAAM qualities [14].

C. Polymer composites

Polymer composites are corrosion-resistant, which is a major selling point for using them instead of the traditionally utilised metallic shields. This is why tracking the polymers' deterioration is crucial. Morphological characterisation techniques, such as scanning electron microscopy (SEM) and transmission electron microscopy (TEM), should be used to ascertain the distribution of the fillers employed to enhance the shielding. A variety of techniques, including X-ray diffraction (XRD), tensile testing, and FTIR spectroscopy, may be used to assess the mechanical properties and chemical makeup of the composites [15].

D. Glass-ceramics

Glass ceramics are commonly employed in many activities due to their unique qualities that meet certain needs. The ease with which glass ceramics may achieve zero porosity allows them to display exceptional translucency or even transparency in the optical field. Because of this, optical applications benefit greatly from glass ceramics. Telescope and laser gyroscope mirror blanks have been manufactured with LAS or clear low-thermal expansion glass ceramics. Military applications for glass ceramics include missile nosecones and high-performance aircraft. The materials utilised for these purposes need to be able to withstand the extreme atmospheric conditions of flying at high speeds: Low thermal expansion, great mechanical strength, resistance to abrasion, and transparency to navigational radar waves are all characteristics of this material. Bioglass has been effectively utilised in medical applications.

E. Tool steels

Hardness is the most common attribute considered when considering a heat treatment for tool steels. Resistance to plastic deformation and resistance to abrasive wear are correlated with high hardness. In addition to hardness, various material qualities that depend on surface engineering methods and applications are also crucial, and they grow more significant as more complicated tools are used. Factors such as creep and wear resistance, machinability, compressive and bending strengths, fracture toughness, and so on are included. Various standards and testing procedures are used to specify and determine the qualities of materials.

CNC production equipment interchange and flexibility

These efforts and attempts to tackle the issues of CNC manufacturing equipment exchange and flexibility are summarised in this paper.

A. Impediments of Current CNC Technologies

Traditional CNC machines included capabilities like multi-process manufacturing, error correction, and multiple axes of control. However, these characteristics increased software complexity and reduced machine part versatility. Opposition to integrated design management is one attempt to solve this problem; it employs OSACA and a linear combination structure regulator to enable third-party apps to be used in the gamepad alongside the regular Microsoft version. Popular in the business world are computer controls, which eliminate the need for physical equipment by storing PLC logic in a computer. A standard language for CAD, CAPP, CAM, and CNC is necessary for suppliers and customers to avoid data loss while aggregating and interpreting each frame's information, regardless of advancements in CNC programming and infrastructure [16]. Although several CAM technologies enable NC manufacturing, their flexibility and interoperability remain significant barriers to their broad adoption[17].

B. Product Data Compatibility and Interoperability

CAD, CAPP, and CAM are examples of downstream components that CNC machines connect with during product development and manufacturing. It is possible for CAD and CAM systems to exchange information using neutral data communication protocols like VDA, SET, and the basic graphical transmission standard. The provision of geographic coordinates is a limitation of these standards, which do not address all CAD/CAPP/CAM business requirements [18]. Information exchange issues between CAD/CAM and CNC machines persist. CAD Numerical approaches leverage desktop technology [19] to propose and regulate production facilities using CAD data and materials. CAM structures use desktop structures to plan and control production using minimal CAD geometric knowledge. Some comments include inaccurate, low-level data that is difficult to alter, validate, or simulate.

C. Inflexible CNC Control Regime

In place of grinding components, the ISO 6983 stainless steel range controls the cutting centre point path along plant axes. ISO 6983 defines programming language grammar but generally leaves meaning unclear and restricts software implementation. Programs become computers after completing a software application using computer cleaning equipment. CNC controller suppliers have developed tailored leadership frameworks to enhance CNC controls and boost ISO 6983 capabilities. The inflexible CNC regulatory regime makes CAM system outputs unadaptable, hindering interoperable numerical control equipment. Both consciousness and mechanical optimisation are possible.

D. The STEP-NC Standard

A database foundation for advanced CNCs is developed by global manufacturers, consumers, and educational institutions on ISO 14649 (STEP-NC). NC development often uses the database architecture to standardise CNC controllers and NCcode output [20]. Two STEP-NC implementations are underway by ISO. The Standard Framework and Interpreted Prototype are ISO 14649 application frameworks. Additionally, people can learn to use and differentiate them. CNC machine tool movements are not provided by ISO 14649, which is a component computing approach, according to NC programming criteria. STEP-NC can precisely describe industrial equipment trajectories, but this edition lets cognitive processor STEPNC microcontrollers decide. A single STEP-NC component software may be utilised by several production tool controllers if it satisfies performance criteria.

E. STEP-NC International Community

The partnership, managed by Siemens, has 15 partners and serves customers like Volvo, Daimler Chrysler, and research institutions. The Swiss, along with Agie, Starrag, and CADCA Mation, are leading the charge to standardise wire-cut and die-sink EDM. Research has been carried out at Korea's Pohang University of Science and Seoul National Academy on processor machining and rotating designs that comply with ISO 14649 standards. There are additional academic communities engaged with this issue in New Zealand and the UK. At Sheffield Hallam Polytechnic in the UK, the Wolfson School of Industrial Research in Computer

Science & Technology (IJIRCST) management has developed a STEP-compliant, Agent-Based CAM system [21][22]. Using STEP-NC AIM, the Mechatronics Laboratory at New Zealand's University of Auckland is developing a cooperative manufacturing system. STEP Tools Inc.'s Glamour model STEP-NC project has automated the US CAD-to-CNC manufacturing process using STEP or AP-238 and was funded by the National Institute of Standards and Technology.

F. New STEP-NC Enabled Control

Through partnerships with industry-leading CNC devices and Open Module Architectural Drivers, a number of world-renowned scientists have achieved the remarkable ability to translate STEP-NC-specific input into CNC commands. A STEP-NC Interpretation, which can accurately carry out the grinding processes outlined in ISO 14649, is developed and integrated into these computers to achieve this goal. There was a connection between Gibbs CAM and an OMAC machining process during stage 3 of the Runway prototypeMission. The AP238 data file, which included the whole production order, allowed Gibbs CAM to generate tool-path data[23][24]. This indicates a higher level of CAM/CNC convergence than is typically accomplished using ISO 6983 since the tool-path information was transferred to a downstream production centre using "ischemic multi-communications" rather than standard G codes.

G. Challenges and Opportunities

There are still many challenges that need to be resolved before the NC community, particularly CNC engineers and operations, embraces STEP-NC, despite the fact that early research has shown that it could be a valuable tool for making CNC machine products that are more accessible, interoperable, and sophisticated. These issues would tremendously benefit opposing organisations, such as manufacturers of NC machines and CNC controllers, as well as professional CAD/CAPP/CAM vendors.

Literature Review

This section provides the background research on the CNC Machine Tool Materials and Their Impact on Machining Performance. Some of previous studies are as follows:

In, Li (2022), there is a strong correlation between the number of uses and the service life of CNC machine tools. The optimal blade service life and design goals must be determined in order to calculate the cutting amount. Typically, there are two kinds of tools: those with the highest efficiency and those with the lowest cost. The quickest working hours per task are the foundation of the first approach, while the lowest processing cost is the foundation of the second. The following considerations should be considered while choosing an NC cutter: the cutter's complexity, processing technology, and grinding cost. For more durability than a single blade, go for precision and precision blades. When swapping out rotary blades, it's possible to enhance processing efficiency by making greater use of the tool's processing characteristics via a shorter tool life. Tool loading, tool changing, and tool adjustment require more time on automated cutting machines, modular machine tools, and multi-tool machine tools, particularly when the stability of the tool is a concern[25].

In, Ding, (2010) The vibration issue has emerged as a significant barrier to the production of precision goods due to the higher operating rates of CNC machine tools. Good structural rigidity and good damping are two crucial functional criteria for a CNC machine tool bed. Metals often used for bed construction are quite rigid but not very dampening. Although epoxy concrete materials are costly, they may meet the aforementioned standards when utilised for bed construction. The use of composite concrete beds for CNC machine tools is shown in this paper. These beds are made of steel fibre cement concrete core and epoxy concrete structure faces. In addition to meeting the CNC machine tool bed's specifications, the beds are less expensive[26].

According to Xiao-bao, Wen-he and Lin (2011), A CNC machine tool with two spindles is developed for dental restorations. The machine tool's mechanical structure and critical components have been meticulously studied and chosen based on the specific characteristics of its intended uses. After defining the required function of the machine tool, the functional analysis approach was used to analyse the denture processing characteristics. The processing system's mechanical structure was then established, and performance parameters for important system components were supplied. This machine tool is capable of reaching speeds of up to 60,000 rpm because of its high-speed electro-spindle and controlled velocity. The driven unit, which allows for improved motion precision control, is supplied with stepping motors. The whole machine tool's finite element model was created on Ansys Workbench, and an examination of its dynamic properties was conducted. This technique was used to identify the structure's weak point, which will enable the optimisation design of the structure technologically[27].

In, Mun and Jeong, (2020) cutting tools and the manufacturing process are two elements that are directly tied to the effectiveness of production and the calibre of the final goods. Reduced product production results from the inability to effectively adjust the cutting parameters to prolong the cutting tool's life. Alternatively, forecasting the cutting tool's remaining wear duration is crucial. For optimal product production, it is crucial to accurately anticipate the remaining wear duration of the cutting tool, since it wears down rapidly under these circumstances and the associated line stops when damage cannot be sustained. The interdependence of the tool's components makes it challenging to predict its RUL under cutting conditions. In this research, they use CNN, BILSTM, and other algorithms to predict a CNC machine tool's RUL. The RUL prediction system takes into consideration factors that affect complex RUL using the BiLSTM-based CABLST Malgorithm and improves Taylor's tool life equations[28].

In, Li et al., (2016) examines the properties of CNC machining's energy consumption and, using a theoretical analysis as a foundation, proposes a set of operational solutions to increase CNC machining's energy efficiency. In order to prove that the suggested operational tactics work, a series of experiments are conducted[29].

In, Zhao, Ma and Wang, (2022) Several typical methodologies are summarised in this research based on all fault diagnostic solutions. Since the advent of CNC machine tools, many cutting-edge defect detection methods have emerged, such as vibration diagnostics, nondestructive testing, expert systems, fault trees, and DL. A long way has been covered in these approaches, from the simple "look, hear, and touch" to complex neural networks and intelligent detecting algorithms. DL is only one approach; the best one to use will depend on the specifics of the issue at hand[30].

In this paper, Kit, Wong and Siang, (2022) The data mining strategy employed is classification, and two algorithms, linear regression and MLP, are used to generate the prediction model. There was a separation of the acquired data into two sets: training and testing. In order to construct the prediction models, 40% of the data is used as training data, while 60% is utilised as testing data. The anticipated tool life is then checked using Taylor's Extended Tool Life calculation in accordance with ISO standards 3685 and 8688-2. When compared to the tool life predicted by Taylor's technique, the findings demonstrate that our suggested method is competitive[31].

Table 1 provides a comprehensive overview of each study, highlighting the objectives, methods, challenges, and advantages suitable for inclusion in CNC machine tools and materials.

Table 1: Summary of background study on comparative analysis for CNC Machine Tool Materials

Reference	Objectives	Features	Challenges	Advantages
Li (2022)	Explore the relationship between service life and cutting efficiency	Analysis of maximum efficiency tools vs. minimum cost tools	Balancing tool life with processing efficiency; complexity of tool selection	Optimizes tool selection for better performance and longevity
Ding (2010)	Assess materials for CNC machine tool beds to reduce vibration issues	Composite concrete (epoxy concrete with steel fibre cement core)	Low damping of conventional materials affects precision	Higher stiffness and damping at a reduced cost
Xiao-bao et al. (2011)	Design a CNC machine tool for dental restorations	High-speed electro-spindle, FEA using Ansys Workbench	Need for precision and dynamic analysis of machine components	Enhanced precision control and structural optimisation
Mun & Jeong (2020)	Predict the Remaining Useful Life (RUL) of cutting tools	BiLSTM-based CABLSTM algorithm, CNN, Taylor's tool life equations	Difficulty in predicting RUL due to varying cutting conditions	Improved accuracy in predicting tool wear and optimising usage
Li et al. (2016)	Analyse energy consumption in CNC machining and improve efficiency	Theoretical analysis, experimental validation	High energy consumption during CNC processes	Operational strategies leading to enhanced energy efficiency
Zhao et al. (2022)	Summarise methods for fault diagnosis in CNC machine tools	Novel fault detection methods: vibration diagnosis, nondestructive testing, deep learning	Transition from traditional to intelligent fault detection methods	Selection of the most appropriate detection method for situations
Kit et al. (2022)	Build predictive models for tool life using data mining techniques	Linear regression and multilayer perceptron algorithms	Ensuring model accuracy in tool life predictions	Results validated against ISO standards, showing model reliability

Conclusion and Future Scope

The operational performance and efficiency of CNC machine tools are enormously dependent on a material utilised in a making of a machine tools. Carbon steels, alloy steels, aluminium alloys, polymer laminates, glass ceramics and tool steels offer different properties, including hardness for strength, and chemical resistance, amongst other attributes that can be overlaid to a given machining task. Therefore, as manufacturing progresses further, material developments will always be a key focus in the development of CNC technology, enhancing precision and less energy despite the concerns of flexibility and interchangeability. But still, there remains challenges like Multiple axis control, Error control, Data sharing etc. which limits the effectiveness of CNC systems.

The future prospects should therefore consider improving material characteristics and dealing with technological constraints that affect the optimisation of CNC machining. This will not only enhance the quality of produced products but also minimize the effect of the environment on production, thus making CNC machining more friendly to the environment for many companies across the spectrum.

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