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STRATEGIC MATERIAL SELECTION: A KEYSTONE FOR ENHANCED PERFORMANCE IN CONVENTIONAL AND MODERN METAL MACHINING PROCESSES

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Abstract

This paper explores the pivotal role of strategic material selection in enhancing performance within conventional and modern metal machining processes. By comparing material properties, machinability indices, and compatibility with various machining techniques, the study highlights the implications of material choice on productivity, tool life, surface finish, and overall manufacturing efficiency. The paper offers a framework for selecting materials that optimize performance in evolving machining environments, including CNC, additive-subtractive hybrid systems, and advanced manufacturing technologies.

Keywords: Material selection, metal machining, tool wear, surface finish, modern machining, machinability

1. Introduction

The performance of metal machining processes, whether conventional or modern, is critically influenced by both the workpiece and the cutting tool materials. Strategic material selection determines machinability, surface integrity, energy efficiency, and tool life. In conventional machining operations such as turning, milling, and drilling, improper material choice can lead to excessive wear, thermal deformation, and economic losses. Likewise, in modern processes like Electric Discharge Machining (EDM), Laser Beam Machining (LBM), and Computer Numerical Control (CNC)-based manufacturing, material properties such as thermal conductivity, hardness, and chemical stability are central to process optimization. In recent years, Nigeria's growing emphasis on industrialization and sustainable manufacturing has drawn attention to the need for more practical, industry-relevant training through Technical and Vocational Education and Training (TVET).

Several studies underscore the importance of integrating advanced material knowledge into vocational training. Das *et al*. (2022) demonstrated how machine learning can predict optimal machining parameters based on material properties, highlighting a need for updated training tools in TVET. Ajie, Osoh, and Thomas (2022) emphasized the importance of up-skilling in metalwork technology for 21st-century relevance, calling for greater problem-solving capacity and digital literacy in vocational settings. Chukwu et al. (2024) highlighted mismatches in curriculum design, while Ogunleye and Shittu (2021) advocated for modernized facilities and curriculum reforms to reflect current industrial practices.

This study aims to explore the role of strategic material selection in improving the performance of conventional and modern metal machining techniques and to harmonize these insights with TVET programs. The study seeks to enhance curriculum relevance, promote industrial applicability, and support knowledge dissemination in vocational and technical education. The research focuses on material selection practices and machining process performance as taught and applied in Nigeria's TVET institutions. It evaluates current training modules, industrial collaborations, and the integration of research findings into practical skill development. The scope also includes evaluating recent advancements in material-focused machining research and how they can be embedded in technical training programs.

2. Overview of Machining Processes

Metal machining processes refer to a broad spectrum of manufacturing operations that involve the removal of material from a workpiece to achieve the desired shape, size, and surface finish. These processes are categorized primarily into conventional and modern (or non-traditional) machining techniques. Traditional machining processes, such as turning, milling, drilling, grinding, and shaping, rely on mechanical cutting tools to shear away unwanted material. These methods are widely used in Nigeria's manufacturing and technical vocational sectors due to their relative simplicity and adaptability to various work environments (Kalpakjian & Schmid, 2022). However, they often encounter limitations in machining hard-to-cut materials, achieving precision on complex geometries, and maintaining tool life. Modern machining processes, on the other hand, include techniques such as Electrical Discharge Machining (EDM), Laser Beam Machining (LBM), Ultrasonic Machining (USM), and Abrasive Water Jet Machining (AWJM). These processes are mainly designed to work with advanced materials like superalloys, ceramics, and composites, offering greater precision, less heat damage, and longer-lasting tools. (Rahman & Zitoune, 2022). Their relevance is rapidly growing in smart and sustainable manufacturing systems.

In Nigeria, combining traditional and modern machining methods is key to driving industrial growth, encouraging innovation, and building practical skills for the workforce. As Nigeria moves toward more advanced manufacturing, it is crucial to understand the basics and real-world uses of different machining methods. Strategic material selection plays a critical role in both traditional and advanced machining contexts, determining not only the efficiency of the cutting operation but also the overall product quality and cost-effectiveness. This underlines the need for a harmonized approach to machining education and practice, particularly through Technical and Vocational Education and Training (TVET) initiatives.

2.1 Conventional Metal Machining Processes

Conventional metal machining processes, such as turning, milling, shaping, drilling, grinding, and slotting, are basic methods of removing metal to form desired shapes. These methods rely on mechanical force to remove material from a solid workpiece using sharp cutting tools. Each process has its unique characteristics. For instance, turning produces cylindrical shapes using a rotating workpiece, milling removes material with a rotating multi-point cutter to achieve flat or complex surfaces, shaping creates straight-line cuts with a reciprocating tool, drilling produces round holes with a rotating drill bit, grinding uses abrasive wheels to achieve fine surface finishes and dimensional accuracy, while slotting is used to cut internal slots and keyways with reciprocating motion.

Even though these processes are widely used, they come with some clear drawbacks. One major issue is tool wear, which is especially common when working with hard or abrasive materials. This often leads to frequent tool changes and higher running costs. They also generate significant heat, which can lead to thermal distortion of workpieces and dimensional inaccuracies. Additionally, conventional methods do not possess the precision required for complex geometries and micro-scale components found in modern industries.

In Nigeria, where many manufacturing operations still rely heavily on these traditional techniques, the limitations are amplified by inadequate material selection strategies and insufficient access to advanced cutting tools. When materials are not properly matched with the right machining methods, it can shorten tool life, result in rough surface finishes, and increase the amount of wasted material. That is why it is so important to choose materials wisely, taking into account factors like hardness, how easy they are to machine, and how they handle heat, to get the best results from the machining process.

2.2 Modern Metal Machining Processes

Modern metal machining processes have emerged as transformative tools in the evolution of global manufacturing, enabling the production of highly precise, complex, and durable components. These technologies, which include CNC machining and additive subtractive hybrids, are transforming the industrial world by making production more efficient, cutting down on material waste, and giving engineers and machinists more flexibility in their designs. Computer Numerical Control (CNC) machining automates traditional operations like milling, drilling, and turning using computer programming, offering high precision, repeatability, and speed. It enables manufacturers to produce intricate parts from a wide range of materials while maintaining dimensional accuracy and surface finish. 3D Printing or additive manufacturing, particularly using metal powders, constructs parts layer by layer. This process is invaluable for rapid prototyping, custom tooling, and complex geometries that are otherwise unachievable through conventional means.

Electric Discharge Machining (EDM) and Laser Beam Machining (LBM) are non-traditional processes that remove material without direct contact. EDM uses electrical sparks to cut through conductive materials, making it ideal for hard metals and fine features. LBM uses focused laser beams for high-precision cuts, commonly applied in electronics and aerospace sectors. Similarly, Electron Beam Machining (EBM) leverages high-energy electrons in a vacuum, allowing for micro-scale fabrication with exceptional accuracy.

Ultrasonic Machining (USM) and Plasma Arc Machining (PAM) are used for brittle or thick materials, utilizing high-frequency vibrations and ionized gas streams, respectively. Electrochemical Machining (ECM) relies on anodic dissolution, offering stress-free machining of complex shapes in hard metals.

Furthermore, Hybrid and Additive-Subtractive processes integrate the strengths of both CNC and additive manufacturing, allowing real-time adjustments, minimal material waste, and high customization. These systems are pivotal in toolmaking and aerospace applications.

The value of these modern techniques lies in their technological advancement and in their capacity to support sustainable manufacturing and mass customization. However, their success is fundamentally dependent on strategic material selection. Understanding thermal properties, electrical conductivity, and material behaviour under different energies is crucial to optimize tool life, minimize waste, and ensure product integrity. When used effectively alongside smart material selection, these technologies can greatly improve industrial performance, especially in developing countries like Nigeria that are working to build a stronger manufacturing sector.

3. Importance of Material Selection in Metal Machining

Material selection plays a foundational role in determining the efficiency, quality, and cost-effectiveness of metal machining operations. A critical concept in this regard is *machinability,* which refers to the ease with which a material can be cut or shaped using machining tools. Machinability is influenced by the material's hardness, toughness, thermal conductivity, and microstructure (Kalpakjian & Schmid, 2022). Materials with good machinability tend to generate lower cutting forces, produce smoother surfaces, and cause less wear on tools—thereby improving operational efficiency and reducing maintenance downtime.

Tool wear is one of the most pressing concerns in metal machining. Poor material selection can lead to rapid tool degradation, frequent replacement, and increased operational costs. For example, materials with high abrasiveness or low thermal conductivity transfer heat to the tool rather than dissipating it, accelerating tool failure. Conversely, selecting materials with favourable machining characteristics extends tool life and reduces the need for frequent intervention (Kumar, Banga, & Singh, 2023).

Cutting force, a critical parameter in machining, is also significantly influenced by material properties. Materials that are overly hard or sticky require more force, increasing energy demand and causing potential damage to equipment.

Surface quality is another performance indicator impacted by material selection. Inconsistent or unsuitable materials may lead to poor surface finishes, affecting product functionality and aesthetics, especially in precision industries like aerospace or medical device manufacturing. Additionally, material selection directly affects energy consumption. Hard-to-machine materials require higher spindle speeds and longer machining times, thereby increasing energy usage and reducing overall productivity.

Economically, the implications are profound. Inefficient machining due to poor material choice results in higher production costs, lower throughput, and increased scrap rates. On the other hand, choosing the right material can boost productivity, make better use of resources, and help maintain consistent product quality, which will in turn leads to higher profits and a stronger competitive edge. This makes material selection not just a technical choice, but a key strategic decision in both traditional and modern machining practices.

4. Key Material Properties for Metal Machining

In metal machining, choosing the right material is not just a basic step but a key factor that affects how efficient the process is, how well tools perform, and the quality of the finished product. Important material properties like hardness, toughness, and thermal conductivity play major roles in how a material handles mechanical stress and heat. These factors also influence the microstructure, chemical makeup, chip formation, and wear behaviour that are critical to both traditional and modern machining processes.

Hardness, which measures how resistant a material is to deformation, directly impacts tool wear and the amount of force needed for cutting. Harder materials like high carbon steel or superalloys require more cutting force, leading to more heat and faster tool wear. The extra heat can also change the surface structure of the part, which may reduce dimensional accuracy and long-term performance (Singh *et al*., 2023). The hardness of a material depends on its chemical composition. Elements like carbon and molybdenum improve strength but can reduce how easily the material can be machined. Toughness, or the ability of a material to absorb energy without breaking, is also critical. Materials like stainless steel are tough and resist cracking under stress, which is good for durability. However, they tend to harden as they are machined. This makes cutting more difficult, increases stress on tools, and can cause unpredictable results. Tough materials also produce stringy chips that can clog the cutting area and reduce surface quality (Zhou *et al*., 2022). Thermal conductivity affects how well heat is removed from the cutting area. Materials like aluminum and copper transfer heat efficiently, helping to keep tools cooler. On the other hand, materials like titanium trap heat, raising the temperature and increasing tool wear. This can lead to poor surface quality and shorter tool life.

Chip formation is also linked to material properties. Brittle materials tend to form short, breakable chips, which are easier to manage but rough on tool edges. Ductile materials usually create long, continuous chips that are harder to control and may wrap around tools or the workpiece. The shape and size of chips provide clues about how well the material is responding to the machining process.

Conversely, understanding how hardness, toughness, and thermal conductivity interact helps machinists and engineers choose the best materials for specific tasks. Poor material selection can lead to tool failure, high energy use, and low product quality. On the other hand, smart choices can greatly improve efficiency, reduce costs, and lead to a more reliable manufacturing process for Nigeria as a growing industrial sectors.

5. Strategic Material Selection Framework

The development of a material selection framework is central to optimizing performance in both conventional and modern metal machining processes. This framework involves a structured approach that evaluates material properties, machining requirements, tooling compatibility, environmental considerations, and economic implications before finalizing a material for any machining operation. In metal machining, choosing the right materials depends not only on important mechanical qualities like strength, hardness, toughness, and how well the material conducts heat, but also on how easy it is to machine. This includes factors like how quickly tools wear down, the way chips form during cutting, the quality of the finished surface, and how much cutting force is needed. A comprehensive framework begins with identifying the machining objective to determine whether it is dimensional precision, surface integrity, or production speed. Next, the material properties are carefully compared to the product goals by looking at things like strength, heat resistance, and chemical makeup. Nowadays, advanced tools like computer simulations, machine learning, and environmental impact assessments are used to predict how well the material will perform during machining, how long the tools will last, and what the overall environmental effects might be. After that, the chosen materials are checked to see how well they work with the machining methods available, whether it is traditional techniques like milling and turning or newer technologies like CNC, EDM, and laser machining. Considerations also include tooling materials, coolant requirements, and machining environment, ensuring that the combination enhances tool life, reduces energy consumption, and improves product quality.

The framework incorporates cost analysis and sustainability metrics, ensuring that the selected materials are economically viable and environmentally responsible. In regions like Nigeria, this structured selection approach is critical for industrial growth, resource optimization, and technical skill development. Integrating such a framework into Technical and Vocational Education and Training (TVET) systems would help bridge the gap between theory and practice, empowering a generation of machinists and engineers equipped for precision and innovation.

5.1 Criteria for Material Selection

In both conventional and modern metal machining processes, the selection of appropriate materials is pivotal to achieving optimal performance, cost efficiency, and product quality. A strategic material selection process relies on multiple criteria that ensure materials align with the machining objectives, tooling capabilities, and end-use performance expectations.

One of the foremost criteria is the Machinability Index, which quantifies how easily a material can be machined. This index takes into account factors such as cutting speed, tool life, surface finish, and chip formation. Materials with a high machinability index typically result in lower cutting forces, minimal tool wear, and superior surface quality, making them ideal for high-throughput machining operations.

Another vital criterion is Application Performance Requirements. The selected material must meet the functional demands of the final product, such as mechanical strength, wear resistance, thermal stability, and corrosion resistance. For example, aerospace components demand materials that can withstand extreme stress and temperature, while automotive parts may require a balance of strength and lightness.

Compatibility with machine tools is also essential. Not all machine tools can efficiently process all metals. For instance, harder or abrasive materials may require advanced tooling systems or specific machining parameters. Ensuring that the material is suitable for available machinery helps avoid unnecessary wear or damage to tools and machines, thereby reducing downtime and maintenance costs.

Environmental and sustainability factors are becoming more important. The material chosen has a big impact on the environmental footprint of machining, including how much energy is used, how recyclable the material is, and the amount of waste produced. Sustainable materials that can be recycled, are safe for the environment, and do not require a lot of energy to manipulate with modern manufacturing practices.

5.2 Decision-Making Tools

Choosing the right material in metal machining is essential for boosting efficiency, reducing costs, and improving the quality of the final product. However, this is not a straightforward task. It involves carefully balancing many factors like mechanical properties, environmental impact, machinability, cost, and how the product will ultimately be used. To help engineers and experts navigate these complexities, various tools and methods have been developed to simplify and organize the material selection process (Das *et al*., 2023; Ogunleye & Shittu, 2022).

One widely used tool is the material selection chart, often called the Ashby diagram.

This chart visually represents important properties such as strength, stiffness, density, and thermal conductivity in simple two-dimensional graphs.

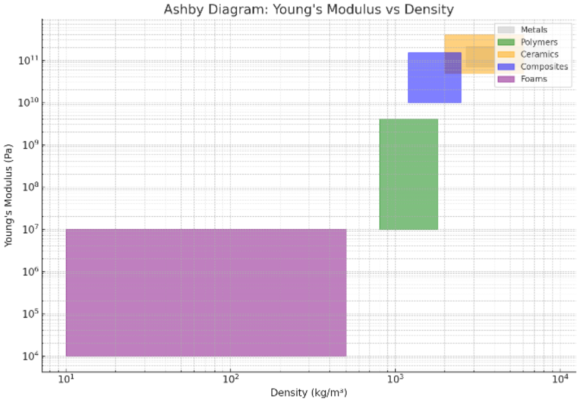

Figure 1: Ashby Diagram showing the relationship between Young's Modulus and Density

for various materials

These charts make it easier for users to quickly compare different materials and find the best fit for their needs. For example, if an engineer needs a material that is both lightweight and strong, they can use the chart to identify options that meet both criteria (Ajie *et al*., 2024).

Another valuable approach is the Analytical Hierarchy Process, or AHP. This method involves comparing materials in pairs and ranking them based on different weighted factors. It allows decision-makers to blend objective data with expert opinions to evaluate trade-offs between factors like machinability, cost, corrosion resistance, and sustainability (Chukwu *et al*., 2024).

When the available data is uncertain or vague, fuzzy logic can be a powerful tool. It works by mimicking human reasoning and can interpret descriptive terms such as “high wear resistance” or “moderate thermal conductivity.” This makes it easier to evaluate complex material behaviours in real-world situations where precise numbers might not always be available (Das *et al.,* 2023).

Today, advanced software like Granta EduPack brings all these tools together in one platform. With large material databases, visual tools, and optimization algorithms, this software helps users, from students to professionals, filter materials based on specific needs, run simulations, and understand the trade-offs involved. This makes the material selection process more accessible and effective, whether in educational settings or industry (Ogunleye & Shittu, 2022).

6. Comparative Analysis of Material Performance

Analysing material performance is essential for understanding how different engineering materials respond under specific machining conditions. For example, Steel, Aluminium, and Titanium alloys are three widely used metals in manufacturing. Table I explores their behaviour across conventional and advanced machining processes. This table highlights variations in machinability, tool wear, surface finish, and overall production efficiency. It also offers insights into material-specific challenges and advantages, guiding strategic decisions in material selection for optimized industrial performance and cost-effectiveness.

Table I: Material Performance Comparative Analysis

S/N	Criteria	Steel	Aluminium	Titanium Alloy
1	Machinability (Conventional Setup)	Moderate to Good (depends on carbon content)	Excellent (high-speed, low power needed)	Poor (high cutting forces and tool wear)
2	Machinability (Advanced Setup)	Improved with CNC, coated tools and coolant systems	Excellent; responsive to high-speed CNC & EDM	Fair to Moderate with advanced cooling, coating, EDM, and hybrid machining

3	Thermal Conductivity	Moderate (around 50 W/m·K)	High (~205 W/m·K) – dissipates heat well	Low (~21 W/m·K) – heat builds up during machining
4	Tool Wear Rate (Conventional)	Moderate; needs careful cutting conditions	Low; minimal tool wear	High; aggressive on uncoated tools
5	Tool Wear Rate (Advanced)	Reduced with coated carbide tools	Minimal wear using optimized CNC settings	Requires advanced tooling (e.g., PCD, coated carbide)
6	Surface Finish Potential	Good with sharp tools and lubrication	Excellent with high-speed finishing	Fair – requires multiple passes and fine finishing strategies
7	Work Hardening Tendency	Low to moderate (depends on alloy type)	Very low; easy chip removal	High – work-hardened layer increases difficulty of machining
8	Chip Formation Behaviour	Continuous or segmented (manageable)	Continuous; manageable in CNC	Long and stringy – challenging chip removal
9	Tool-Material Interaction (Conventional)	Average; abrasive interaction with harder grades	Smooth; minimal chemical affinity	Strong chemical affinity; risk of diffusion wear and galling
10	Tool-Material Interaction (Advanced)	Improved with coatings/lubrication	Excellent compatibility	Requires high-tech solutions (coatings, coolant, low feed speeds)
11	Application Suitability	Heavy-duty components (shafts, gears, dies)	Lightweight applications (aerospace, automotive frames)	Critical components (aerospace turbines, implants)
12	Cost of Material (per kg)	Low to moderate (₦799 – ₦3,197)	Moderate (₦3,197 – ₦5,595)	High (₦31,973 – ₦79,934)
13	Overall Machining Cost	Moderate – wide tool availability	Low – less power, time, and tool cost	Very High – costly tools, slower feeds, frequent changes
14	Cost-Performance Balance	Economical for mass production; good for general machining	High value in light-weight, high-volume production	Justifiable only in high-performance, critical industries
15	Sustainability & Recyclability	High recyclability; energy-intensive production	Very recyclable; energy-efficient machining	Recyclable but high energy cost and environmental impact during processing

7. Challenges in Material Selection for Machining

In both conventional and modern machining systems, selecting the right material requires balancing several often-conflicting properties. Chukwu *et al.* (2024) explain that a major challenge is the trade-off between machinability and mechanical performance. Materials with high strength, hardness, and corrosion resistance, such as titanium alloys and hardened steels, often have poor machinability. These materials demand higher cutting forces and have low thermal conductivity, which causes rapid tool wear and increased energy consumption during machining.

Ogunleye and Shittu (2022) point out that another significant limitation is the lack of standardized machinability databases. Engineers and machinists often rely on fragmented or outdated data, which makes informed decision-making difficult. This gap is especially evident in Technical and Vocational Education and Training (TVET) institutions and small-scale industries, where access to modern characterization tools is limited. According to Ogunleye and Shittu, the absence of centralized, validated data slows down the material selection process and increases dependence on trial and error.

Ajie *et al.* (2024) discuss tool-material incompatibilities as another major barrier to efficient machining. Some materials, including nickel-based superalloys and composites, tend to form strong bonds with cutting tools or cause rapid diffusion wear, which leads to premature tool failure. These problems are worsened in setups without advanced coatings or adaptive cooling systems that could help reduce tool wear. Das *et al.* (2023) highlight that many traditional materials do not perform well with newer machining technologies such as laser cutting, hybrid systems, or additive-subtractive processes. These advanced techniques require materials with specific properties, and materials designed for conventional machining may not meet the demands of modern equipment. This necessitates new approaches in material design and processing to keep up with evolving manufacturing technologies.

8. Future Trends and Innovations

As the global manufacturing industry advances rapidly, future trends in strategic material selection are being shaped by technological innovation, sustainability goals, and the increasing demand for performance optimization. One of the most promising developments is the emergence of smart materials developed to respond dynamically to machining conditions. These materials can alter properties such as stiffness, shape memory, or thermal conductivity during machining, which helps in reducing tool wear, improving dimensional accuracy, and enhancing process stability, especially in high-speed and precision applications.

Artificial Intelligence (AI) is also playing a transformative role in material selection. Predictive material selection systems powered by AI can analyse extensive datasets from past machining operations and material behaviours to identify optimal materials for specific applications. This reduces the trial-and-error traditionally associated with material selection and supports better decision-making in real-time.

Also, using virtual models of machining environments, known as digital twins, is transforming how manufacturing processes are planned. These systems allow manufacturers to simulate and evaluate how different materials perform under various machining parameters before committing to physical trials. This not only improves productivity but also lowers operational risks and material waste.

Equally important is the growing emphasis on sustainability and circular economy principles. Material selection now increasingly factors in recyclability, energy consumption during machining, and environmental impact. Choosing materials that support sustainable practices contributes to regulatory compliance and enhances corporate social responsibility.

9. Conclusion

This study has demonstrated that strategic material selection is not just a technical necessity but a key performance multiplier in both conventional and modern metal machining processes. Key findings indicate that the selection of appropriate materials directly influences critical machining parameters such as tool life, cutting forces, energy consumption, surface quality, and overall productivity. In Nigeria's manufacturing sector, where traditional machining is still common and advanced technologies are hard to access, choosing the wrong materials often leads to higher costs, frequent machine failures, and lower product quality. The integration of smart and sustainable manufacturing technologies further intensifies the need for materials that are not only highly machinable but also environmentally responsible and compatible with digital innovations such as AI, IoT, and CNC automation. Strategic material selection thus serves as a bridge between efficiency and innovation, sustainability and precision.

Bridging the disconnect between material science and machining practice, especially through Technical and Vocational Education and Training (TVET), is essential for building a skilled and future-ready workforce. Emphasizing material behaviour, machinability indices, and application performance in technical curricula will position Nigeria's machinists and engineers to respond effectively to evolving industrial demands.

To address these challenges and unlock the full potential of strategic material selection, it is recommended that industry stakeholders and policymakers prioritize curriculum reform, invest in training infrastructure, and support academia-industry partnerships. Future research should focus on creating indigenous machinability databases, exploring the performance of local materials under different machining regimes, and applying AI-driven decision-making tools. A coordinated national policy that integrates material science into machining education and practice will significantly advance Nigeria's manufacturing resilience, sustainability, and global competitiveness

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