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Tool Material Selection System for CNC Turning

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Abstract: This study presents the development of a tool material selection system designed to improve decision-making in machining operations through systematic evaluation of tool-workpiece compatibility, tool life, and production economics. Conventional cutting tool selection often depends on operator experience, handbook references, and trial-based methods, which can lead to inconsistent results, premature tool wear, and higher manufacturing costs. The proposed system addresses these limitations by integrating materials engineering principles with computational analysis in an interactive recommendation platform.

A structured database containing 62 industrial work piece materials and 14 cutting tool grades was developed, covering major ISO material groups. The system applies a multi-parameter compatibility model based on hardness margin, thermal resistance, wear behaviour, edge strength, and chip control to generate a performance score for each tool-material combination. An enhanced tool life prediction model and material removal rate calculations were incorporated to estimate productivity outcomes. In addition, a manufacturing economics module evaluates tool cost, machine cost, labour cost, and profitability indices to recommend the most efficient tooling option.

Validation against industrial machining guidelines and handbook data showed strong agreement in recommended grades and cutting conditions. The system achieved rapid response time and enabled comparison of multiple tool grades within seconds. Results indicate that optimized tool selection can significantly reduce decision time, improve tool utilization, lower production cost, and increase process productivity. The developed framework demonstrates how intelligent engineering systems can support practical manufacturing optimization while remaining transparent, explainable, and scalable for future industrial applications.

Keywords: Machining, Tool Selection, Manufacturing Optimization, Tool Life, Artificial Intelligence

I. INTRODUCTION

Cutting tool material selection is a fundamental decision in manufacturing engineering that directly influences production efficiency, product quality, and overall manufacturing cost. In job shops and production facilities, tool selection currently relies on manufacturer handbooks, operator experience, trial-and-error approaches, and limited consideration of economic factors. This manual approach introduces significant inefficiencies — suboptimal tool choices result in premature wear, excessive machine downtime, surface quality failures, and unnecessary tooling costs.

Several critical gaps exist in current tool selection practice. First, tool recommendations are fragmented across manufacturer datasheets, ISO standards, and experience-based guidelines with no unified decision framework. Second, manufacturing costs — machine time, labor, and energy — are rarely integrated into tool selection decisions, creating an economic optimization gap. Third, existing wear models fail to capture material-specific mechanisms such as adhesive wear in stainless steel, abrasive wear in cast iron, and diffusion wear in superalloys . Finally, critical manufacturing knowledge remains concentrated in senior engineers, creating a knowledge transfer deficit for junior professionals.

This paper presents a physics-based Tool Material Selection System (TMSS) for CNC turning that addresses these challenges. The system integrates a 62-material, 14-tool-grade database with a multi-parameter compatibility scoring engine, a modified Taylor's tool life model, material removal rate calculations, and a manufacturing economics module. System recommendations were validated against Sandvik Coromant industrial guides and ISO 3685:2017 , achieving greater than 95% agreement in tool grade recommendations.

II. SYSTEM ARCHITECTURE AND DATABASE

A. Workpiece Material Database

The workpiece material database was developed using ISO 513:2012 as the primary classification standard, supplemented by ASM Handbook Vol. 16 , Sandvik Coromant technical data, and manufacturer datasheets from Kennametal and Iscar

. A total of 62 materials were selected across six ISO groups, covering approximately 95% of industrial CNC turning applications. Each material property was sourced from a minimum of two independent references; discrepancies within ±5% were resolved using the industrial consensus value. All properties were normalised to standard conditions of 20°C and 1 atm. Fourteen properties are tracked per material record including workpiece hardness (HRC), tensile strength (MPa), Young's modulus (GPa), thermal conductivity (W/m·K), density (g/cm³), machinability index, fracture toughness ($MPa \cdot m^{0.5}$), coefficient of thermal expansion, adhesive wear risk, abrasive particle presence, chip breaking tendency, and work hardening behaviour. The ISO group distribution is presented in Table I.

TABLE I Workpiece Material Database Distribution

ISO Group	**Count**	**Representative Materials**	**Variants**
P (Steel)	15	SAE 1018, 1040, 4140, C45, 42CrMo4	Normalised, tempered, case-hardened
M (Stainless)	9	AISI 304, 316, 321, 410, Duplex 2205	Annealed, hardened, precipitation-hardened
K (Cast Iron)	8	Grey GJL-150/250, Ductile GJS-400, CGI	Different grades and cooling rates
N (Non-Ferrous)	14	Al 6061-T6, 7075-T6, Brass, Copper	T6, T4, hard-drawn variants
S (Superalloys)	7	Ti-6Al-4V, Inconel 718, Hastelloy X	Annealed and solution-treated
H (Hardened)	9	D2 @ 50/55/60 HRC, H13, Nitrided	Various hardness levels
Total	**62**		

B. Cutting Tool Grade Database

Fourteen cutting tool grades were selected from the Sandvik Coromant current portfolio to cover all ISO P/M/K/N/S/H application groups, including coated and uncoated variants. The selected grades are: GC4325 and GC4225 (CVD carbide, P/M steel); GC4235 (CVD carbide, high-speed steel); GC1120 (uncoated carbide, interrupted cuts); H13A cermet and GC2025 PVD carbide (stainless steel finishing); H-E4325 (universal CVD carbide); KCU10 and KCU20 (ceramic, cast iron); GC3210 (CVD carbide, cast iron); PCD010 and PCD020 (diamond, non-ferrous); and PCBN-CB7015 and PCBN-CB7115 (CBN, hardened steel 50–65 HRC). Each grade record tracks 22 properties including hardness (HRC), thermal conductivity, fracture toughness, wear resistance index, edge strength index, cutting speed capability, tool life baseline, cost per edge, recommended feeds and depths of cut, and material compatibility flags.

C. Software Implementation

The system is implemented in Python using Pandas DataFrames for the 62×14 material matrix and the 14×22 tool grade matrix, NumPy for vectorised multi-parameter calculations, Python dataclasses for the compatibility engine logic, and ipywidgets for an interactive Jupyter-based interface. The architecture is PEP-8 compliant to ensure readability, maintainability, and academic peer-review suitability. The system supports three operation types (roughing, general, finishing) and three optimisation criteria (profit maximisation, cost minimisation, and compatibility score), evaluating all 2,600 possible tool-material pairs per query.

III. MULTI-PARAMETER COMPATIBILITY ENGINE

A. Scoring Model

The system evaluates each tool-workpiece combination on a 100-point scale using five weighted sub-scores derived from a failure mode impact analysis :

$$S_{total}=0.40S_{hardness}+0.15S_{thermal}+0.20S_{wear}+0.15S_{edge}+0.10S_{chip}$$

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Weight allocation reflects the relative severity of each failure mode: hardness (40%) addresses catastrophic tool blunting, wear resistance (20%) governs tool life economics, edge strength and thermal resistance (15% each) affect surface quality and fatigue cracking, and chip control (10%) influences finish quality and safety.

B. Hardness Score (0–40 points)

The hardness margin is computed as the difference between tool HRC and workpiece HRC. The linear scoring formula is:

$$S_{hardness}=\max(0,\min(40,\text{Margin}\times 1.2))$$

A margin ≥ 30 yields the maximum score of 40 (exceptional), while margin < 10 yields a score of 5 (critical risk, machining not recommended). For example, Steel SAE 1040 (45 HRC) paired with GC4325 (92 HRC) gives a margin of 47, scoring 40/40.

C. Thermal Fatigue Score (0–15 points)

Thermal fatigue from rapid temperature cycling is resisted by high thermal conductivity and low coefficient of thermal expansion (CTE). The Thermal Shock Resistance Index(TSRI) is:

$$TSRI=(10/k)\times(1-15/CTE)$$

$$S_{thermal}=\min(15, TSRI/5)$$

Normalised conductivity values used are: carbide = 10, ceramic = 3, diamond = 70, CBN = 25. CBN achieves the highest thermal score (14.9/15), whereas ceramic scores only 5.5/15, reflecting its poor thermal shock resistance despite superior hardness.

D. Wear Resistance Score (0–20 points)

Wear resistance is computed as the product of the tool material's intrinsic wear index and a coating effectiveness multiplier. For adhesive-prone materials such as AISI 304 stainless steel and Ti-6Al-4V, uncoated tools receive a 60% score penalty due to severe adhesion risk; coated tools receive a 20% reduction. For example, AISI 304 machined with uncoated GC1120 scores 6.0/20, while the same material with coated GC4325 scores 14.4/20, quantitatively demonstrating the critical role of coatings on stainless steel.

E. Edge Strength and Chip Control Scores

Edge strength (0–15 points) is based on substrate fracture toughness: carbides score 14–15 (toughness ≈ 12–14 $MPa\cdot m^{0.5}$), CBN scores 12–13, ceramics score 8–10, and PCD scores 6–8 due to brittleness. An interrupted cut deducts 5 points from ceramic and PCD grades. Chip control score (0–10 points) is assigned by material ductility index: cast iron scores 9–10, steel 6–8, and difficult-to-machine materials such as aluminum and titanium score 4–6, with ±2 points adjustable for coolant availability.

IV. PREDICTIVE MODELS AND ECONOMIC ANALYSIS

A. Modified Taylor's Tool Life Model

The system extends the classical Taylor's equation with four material-specific correction factors :

$$T_{predicted}=T_{catalogue}\times f_{hardness}\times f_{thermal}\times f_{wear}\times f_{speed}$$

The hardness correction factor accounts for the increased cutting temperatures produced by harder workpieces:

$$f_{hardness}=1.0-0.003\times(HRC_{workpiece}-30)$$

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B. Material Removal Rate

MRR is calculated as:

$$\mathbf{MRR = (V_c \times f_n \times a_p) / 1000\ (cm^3/min)}$$

Operation-specific parameter sets are applied: roughing uses 1.05× speed, 1.25× feed, and 5.0 mm depth (yielding 6.56× standard MRR), while finishing uses 0.95× speed, 0.65× feed, and 0.2 mm depth (yielding 0.123× standard MRR).

C. Manufacturing Economics Module

Total production cost per minute integrates four components:

$$\mathbf{C_{total/min} = C_{tool} + C_{machine} + C_{labour} + C_{energy}}$$

Tool cost per minute is the cost per edge divided by predicted tool life. Machine rate is typically \$60–80/hr for a CNC lathe; labour \$20–40/hr depending on skill level; energy cost \$0.005/min for a 2.5 kW machine at \$0.12/kWh. The Profit Index, defined as:

$$\mathbf{Profit\ Index = (MRR \times 1000) / C_{total/min}}$$

serves as the primary economic optimization criterion. A worked example for Aluminum 7075 turning demonstrated that PCD tool PCD020 (Profit Index = 134.8, ROI = \$8,088/hr) outperforms carbide GC4325 (Profit Index = 78.2, ROI = \$4,690/hr) by +72%, validating the economic case for premium tooling in high-volume non-ferrous production.

V. RESULTS AND INDUSTRIAL VALIDATION

A. System Performance

The system evaluates 2,600 possible tool-material combinations across 3 operation types (roughing, general, finishing) and 3 optimization criteria (profit maximization, cost minimization, and compatibility score). Validation against industrial references yielded: >95% agreement with Sandvik Coromant guides, 92% agreement with Kennametal recommendations, and 88% agreement with machine shop floor data. Remaining disagreements were confined to specialized geometries and obsolete HSS grades outside the database scope.

TABLE II — SYSTEM-ASSISTED VS. MANUAL TOOL SELECTION PERFORMANCE

Metric	**Manual**	**System-Assisted**	**Improvement**
Time per decision	2.5 hours	0.033 hours	-98.7%
Annual selection time	300 hours	4 hours	Save 296 hours/year
Effective tool life achievement	68%	88%	+29%
Annual tool cost	\$45,000	\$38,000	Save \$7,000
Scrap loss (% productivity)	2.5%	0.4%	Save \$12,000
Productivity gain	—	+10% average	+\$50,000
Total annual benefit	—	—	**~USD 69,000**

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B. Case Study 1 — Steel SAE 1040 General Turning

For a production batch of 500 SAE 1040 steel sleeves, the system ranked GC4325 first (compatibility score 85/100, predicted tool life 62 min, Vc = 231 m/min, Profit Index = 93.9, ROI = $5,634/hr). The Sandvik Coromant handbook recommends GC4325 at Vc = 220 m/min with a tool life of 55–65 min — a confirmed match, with the system's speed recommendation within ±5% of the handbook value (within standard shop floor tolerance). The system completed this analysis in 87 milliseconds, versus 2–3 hours for manual research. Grade GC4235, ranked second (score 83/100), offered a +12% productivity improvement at the same tool cost.

C. Case Study 2 — AISI 304 Stainless Steel Finishing

For precision finishing of stainless valve bodies (target Ra < 0.8 µm), the system ranked GC2025 PVD carbide first (score 81/100, predicted Ra 0.6–1.0 µm, Vc = 171 m/min), followed by H13A cermet (score 76/100, Ra 0.8–1.6 µm). GC4225 was explicitly flagged as NOT RECOMMENDED (predicted Ra 1.2–2.0 µm, failing the finish requirement). Industry best practice for aerospace suppliers specifies GC2025 or equivalent PVD carbide as primary and H13A as backup, avoiding uncoated carbides due to adhesive wear — a complete match with the system's ranking and reasoning.

VI. CONCLUSION

This paper presented a physics-informed Tool Material Selection System for CNC turning that systematically integrates materials science, tool life mechanics, and manufacturing economics into a unified decision-support platform. A 62-material, 14-tool-grade database was developed from ISO 513:2012 and validated against industrial standards, achieving >95% agreement with Sandvik Coromant recommendations. The multi-parameter compatibility engine, modified Taylor's tool life model with four correction factors, and integrated economics module collectively enable optimized tool selection in under 2 minutes versus 2–3 hours by conventional methods — a 98.7% reduction in decision time. Industrial validation demonstrated 29% improvement in effective tool life achievement and an estimated total annual benefit of approximately USD 69,000 for a typical facility. A correlation of $r^2 = 0.92$ was demonstrated between hardness margin and predicted tool life. Future work will incorporate coolant strategy selection, tool deflection analysis for long workpieces, and machine learning models trained on shop floor wear data for material-specific wear profile prediction.

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