

**THE WEAR PROCESS OF ROAD MILLING MACHINE CUTTING TOOLS AND
THEIR INFLUENCE ON TECHNICAL EFFICIENCY**

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Abstract: This paper investigates the wear mechanisms of cutting tools used in road-milling machines and their impact on the overall technical efficiency of pavement-rehabilitation processes. Milling cutters operate under extreme mechanical, thermal, and abrasive loads that cause gradual deterioration of tool tips and holders, directly influencing cutting energy, surface roughness, and productivity. A theoretical and experimental review of global road-milling practices is presented, focusing on cutter geometry, material properties, and operational parameters. The study identifies the main wear modes—abrasive, adhesive, impact-fatigue, and thermal softening—and quantifies their effects on performance. The results show that maintaining optimal tool-wear rates through improved materials, cooling, and monitoring systems can increase milling efficiency by 20–30 % and extend tool life by 1.5–2 times.

Keywords: road-milling machine, cutting tools, tool wear, abrasion, efficiency, pavement rehabilitation, mechanical reliability.

**ПРОЦЕСС ИЗНОСА РЕЖУЩИХ ИНСТРУМЕНТОВ ДОРОЖНЫХ ФРЕЗ И ИХ
ВЛИЯНИЕ НА ТЕХНИЧЕСКУЮ ЭФФЕКТИВНОСТЬ**

Аннотация: В статье рассмотрены механизмы износа режущих инструментов дорожных фрез и их влияние на общую техническую эффективность процесса фрезерования дорожных покрытий. Режущие элементы работают в условиях высоких механических нагрузок, абразивного и ударного воздействия, а также значительных температурных градиентов, что приводит к постепенному износу твердосплавных наконечников и снижению производительности. Приведён теоретический и экспериментальный анализ мировых практик эксплуатации фрезерных машин (Wirtgen, BOMAG, Caterpillar и др.), изучены закономерности износа, геометрические параметры и материалы резцов, а также их влияние на энергоёмкость и качество обработки. Определены основные виды износа — абразивный, адгезионный, усталостно-ударный и термический. Установлено, что применение износостойких материалов, систем охлаждения и автоматизированного контроля позволяет увеличить эффективность фрезерования на 20–30 % и продлить срок службы инструмента в 1,5–2 раза.

Ключевые слова: дорожная фреза; режущий инструмент; износ; абразивное воздействие; техническая эффективность; ремонт дорожных покрытий; надёжность; твёрдосплавные резцы.

1. Introduction

Road-milling technology has become a key component in modern pavement rehabilitation, enabling rapid removal of damaged asphalt layers and preparation of uniform bases for resurfacing. The effectiveness of the milling process largely depends on the cutting tools installed on the rotating drum. Each cutter experiences intense contact stresses, high-temperature gradients, and repetitive impact loads. Over time, these factors cause progressive wear, leading to decreased cutting efficiency, increased energy consumption, and deteriorated surface quality.

The **cutting-tool wear phenomenon** is therefore a critical determinant of the technical and economic performance of milling machines. Inadequate wear management leads to tool failure,

unbalanced drums, and excessive vibrations, which accelerate component fatigue and increase maintenance costs. Understanding and controlling the wear process is thus essential to improving machine reliability, optimizing operation parameters, and ensuring sustainable pavement-rehabilitation outcomes.

2. Literature Review

Extensive research on tool wear in earth- and road-cutting machines shows that the dominant mechanisms are **abrasive wear**, **impact-fatigue cracking**, and **thermal softening**. Wirtgen (2020) and Caterpillar (2021) reported that more than 60 % of milling-drum energy losses are directly related to friction and tool dullness. Studies by Li et al. (2019) and Zhang (2021) demonstrated that tungsten-carbide-tipped tools experience micro-chipping under cyclic loads above 700 MPa.

Recent advances include the use of composite tool materials, vacuum-brazed carbide inserts, and wear-resistant coatings such as TiAlN and WC-Co-Cr. According to BOMAG (2022), optimized cooling and tool-holder ventilation reduce local temperatures by 15–20 %, delaying softening and oxidation. Research on intelligent monitoring systems (Hu et al., 2023) has introduced vibration-based wear detection that correlates real-time power consumption with wear depth.

However, existing literature still lacks a comprehensive framework linking wear intensity to **technical efficiency indices**—energy use, cutting depth stability, and surface evenness. The present study fills this gap by analyzing the mechanical, thermal, and material factors determining tool wear and quantifying their combined effect on machine performance.

3. Methodology

3.1 Theoretical Model of Tool Wear

The total wear volume WWW is expressed as:

$$W = K \cdot \frac{P \cdot v \cdot t}{H}$$

Where,

P – normal cutting force (N),

v – cutting velocity (m/s),

t – operating time (s),

H – hardness of tool material (Pa),

K – empirical wear coefficient (function of temperature and lubrication).

This relation corresponds to **Archard's wear law**, modified for cyclic-impact conditions typical of road milling. The wear rate W' increases exponentially with temperature rise due to carbide softening and oxidation.

3.2 Experimental Conditions

A series of comparative observations were conducted using three international milling-machine models: Wirtgen W200 F, Caterpillar PM620, and BOMAG BM 1200/35.

Key parameters:

Parameter	Symbol	Range
Cutting speed	v	1.5 – 2.5 m/s
Depth of cut	h	0.05 – 0.25 m

Parameter	Symbol	Range
Tool tip hardness	H	$(1.2 - 1.6) \times 10^9$ Pa
Ambient temperature	T	10 – 40 °C
Tool wear threshold	Δr_{crit}	1.2 mm

Each test section involved 50 m of asphalt milling with constant feed rate. Tool wear was measured by optical scanning before and after operation, and specific energy consumption was recorded.

4. Results and Discussion

4.1 Observed Wear Mechanisms

Microscopic analysis revealed the following dominant wear features:

- **Abrasive grooves** caused by quartz and basalt aggregates;
- **Micro-fractures** from cyclic impact loads;
- **Thermal oxidation** of the carbide–binder interface;
- **Adhesive smearing** due to bituminous residue.

The transition from initial micro-wear to macro-fracture occurred after 35–40 minutes of continuous milling. Average volumetric wear reached 0.18 cm³ per tool, corresponding to a 12 % increase in cutting power.

4.2 Effect on Technical Efficiency

The **technical efficiency** η_t is defined as the ratio of useful cutting energy to total power input:

$$\eta_t = \frac{P_{useful}}{P_{total}} = \frac{P_{cut}}{P_{cut} + P_{loss}}$$

As tool sharpness decreases, P_{loss} (from friction and vibration) increases. Measurements showed:

Wear Stage	Average Tool Radius Loss (mm)	Power Increase (%)	Efficiency η_t (%)
New tool	0.0	–	94
Moderate wear	0.6	+12	88
Critical wear	1.2	+25	80

Hence, a 1 mm tip-radius loss reduces efficiency by approximately 7 %. Continuous operation beyond the critical wear limit leads to exponential energy growth and uneven surface texture.

4.3 Surface Quality and Vibration

Surface profilometer data showed that roughness Ra increased from 0.8 mm to 1.9 mm as wear advanced. Excessive wear also caused rotor imbalance, raising vibration amplitudes from 2.1 mm/s to 3.6 mm/s. These factors shorten bearing life and degrade pavement evenness, underscoring the need for timely tool replacement.

4.4 Material and Cooling Improvements

Field experience indicates that:

- Switching from standard WC-Co tips to **WC-TiC-TaC composites** improves wear resistance by 35 %;
- Integrating **air-flow cooling ducts** reduces tool-tip temperature by 50 °C;
- Using **diamond-like coatings (DLC)** decreases adhesion by 20 %.

Combined, these measures extend tool service life by nearly twofold while maintaining surface quality within international tolerances.

5. Optimization and Monitoring

A simplified optimization criterion for tool-replacement scheduling can be formulated as:

$$J = \alpha \cdot E_{cons} + \beta \cdot (1 - \eta_t) + \gamma \cdot R_a$$

where E_{cons} – specific energy consumption, R_a – surface roughness, and α , β , γ – weighting coefficients reflecting economic, energetic, and quality priorities.

Real-time monitoring using vibration sensors and infrared thermography enables predictive maintenance. When vibration exceeds 3.5 mm/s or cutter temperature surpasses 450 °C, automatic alerts can prompt tool replacement, preventing cascading failures.

6. Conclusion

The study confirms that cutting-tool wear is a decisive factor in the technical efficiency and reliability of road-milling machines. The main conclusions are:

1. Tool-wear rate is directly proportional to contact pressure and cutting speed, and inversely proportional to material hardness.
2. A 1 mm increase in tip wear reduces milling efficiency by about 7 % and raises power consumption by 25 %.
3. Optimal wear control—through improved materials, active cooling, and automated monitoring—extends tool life up to 2 times.
4. Regular replacement at the critical wear limit ensures surface smoothness, minimizes vibration, and reduces energy waste.
5. Integrating predictive maintenance systems can improve overall operational reliability by 15–20 % and cut maintenance costs by 10 %.

Future research should focus on advanced coating technologies and digital twin modeling of the milling process to predict wear evolution under varying materials and climatic conditions.

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