A Literature Review and Finite Element Analysis of Chip Formation in Metal Cutting Using Different Tools and Workpiece Materials

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Abstract - This paper presents a comprehensive literature review and finite element analysis (FEA) of chip formation in metal cutting using Abaqus, comparing soft high-speed steel (HSS) tools and hard tungsten-carbide (WC) tools across various workpiece materials. Soft HSS tools are analyzed for difficult-to-machine alloys, including cast iron, titanium alloys, high-carbon steel, and hardened steel, while hard WC tools are analyzed for soft non-ferrous metals, such as aluminium, copper, zinc, and lead. Key machining parameters—cutting speed, feed, cutting temperature, chip morphology, and lubrication type—are summarized. The study highlights the effects of tool hardness and workpiece material on chip formation, cutting-zone temperature, and tool life, providing guidance for literature-based FEA modeling and future experimental validation.

Key Words - Chip formation, Finite Element Analysis (FEA), Abaqus, HSS Tool, Tungsten-Carbide (WC) Tool, Aluminium, Copper, Zinc, Lead, Cast Iron, Titanium Alloy, Steel, Machining Parameters.

1.INTRODUCTION

Metal cutting is a critical manufacturing process widely used in industry for shaping metallic components. The quality of machining, tool life, and productivity depends strongly on the interaction between the cutting tool and the workpiece material, as well as process parameters such as cutting speed, feed rate, and lubrication. Understanding chip formation mechanisms is essential because it directly influences cutting forces, surface finish, thermal effects, and tool wear.

Difficult-to-machine materials, such as cast iron, titanium alloys, high-carbon steel, and hardened steels, present challenges due to high hardness, low thermal conductivity, or chemical affinity with tool materials. In contrast, soft non-ferrous metals, including aluminium, copper, zinc, and lead, are highly ductile and prone to adhesion on cutting tools, often producing continuous chips and surface defects if not properly controlled.

Recent studies emphasize the use of finite element analysis (FEA) as a powerful tool to investigate chip formation and predict cutting-zone temperatures, stress distribution, and tool–workpiece interactions without extensive experimental trials. Abaqus FEA software allows coupled thermo-mechanical analysis to capture realistic chip morphology and thermal effects for a wide range of materials.

This paper presents a literature-based FEA study of chip formation using soft HSS tools for difficult-to-machine alloys and hard WC tools for soft non-ferrous metals. Key machining parameters, including cutting speed, feed, cutting temperature, chip morphology, and lubrication strategies, are summarized. The study aims to provide guidelines for optimizing machining conditions and preparing literature-informed FEA models for future research in metal cutting.

2.Literature Review and Discussion

The body of the paper consists of numbered sections that present the main findings. These sections should be organized to best present the material.

2.1 Overview of Metal Cutting and Chip Formation

Metal cutting is a fundamental manufacturing process used to shape metallic components by removing material in the form of chips. The process involves complex thermo-mechanical interactions between the cutting tool and the workpiece, affecting cutting forces, surface finish, tool wear, and heat generation. Chip formation is a key phenomenon that influences machining efficiency and tool life.

Difficult-to-machine materials, such as cast iron, titanium alloys, high-carbon steel, and hardened steels, present challenges due to high hardness, low thermal conductivity, and chemical affinity with the cutting tool. Soft non-ferrous metals, such as aluminium, copper, zinc, and lead, are highly ductile and can adhere to cutting tools, forming continuous chips or built-up edge (BUE). Understanding these behaviors is essential for optimizing cutting parameters.

Finite Element Analysis (FEA) using Abaqus provides a method to study these interactions virtually, predicting chip morphology, cutting-zone temperature, and tool stress without extensive experiments.

2.2 Tool and Workpiece Materials

2.2.1 Soft High-Speed Steel (HSS) Tools

Soft HSS tools are widely used for machining metals with moderate hardness. Fig. 1 summarizes reported machining parameters and chip formation behavior for difficult-to-machine alloys.

Abbreviations Defined:
- HSS: High-Speed Steel
- BUE: Built-Up Edge

Observations:
- Cast Iron (Gray CI): Short, broken chips; minimal BUE; often

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dry machining.
- Titanium Alloys (Ti-6Al-4V): Continuous, adhesive chips; high tool wear; flood, cryogenic, or MQL recommended.
- High-Carbon Steel: Continuous or BUE chips; wet/MQL preferred; dry possible with reduced tool life.
- Hardened Steel (≥ 45–60 HRC): HSS not suitable; extreme wear; CBN or PCD tools recommended.

2.2.2 Hard Tungsten-Carbide (WC) Tools

Hard WC tools are effective for machining ductile, soft metals. Fig. 2 summarizes typical machining parameters for aluminum, copper, zinc, and lead.

Abbreviations Defined:
- WC: Tungsten-Carbide
- MQL: Minimum Quantity Lubrication

Observations:
- Aluminum (Al): Continuous ductile chips; BUE risk at low speed; wet/MQL preferred.
- Copper (Cu): Sticky, continuous chips; wet/MQL strongly recommended.
- Zinc (Zn): Continuous to slightly segmented chips; dry machining possible.
- Lead (Pb): Very soft, short chips; dry machining sufficient.

2.3 Literature-Based Finite Element Analysis (FEA) Observations

Reported FEA studies using Abaqus indicate:
- For HSS tools, high cutting temperatures and tool wear occur in titanium alloys and hardened steels, while cast iron and high-carbon steels show moderate temperature and manageable chip formation.
- For WC tools, soft non-ferrous metals exhibit continuous chips, lower temperature rise, and lower tool stress, confirming literature observations.

FEA Modeling Parameters Reported in Literature:
- Material Model: Johnson–Cook plasticity and damage.
- Friction Coefficient (μ): 0.1–0.6, depending on lubrication.
- Boundary Conditions: Tool considered rigid; workpiece fixed at base.
- Thermo-Mechanical Coupling: To capture heat generation in the cutting zone.
- Mesh Density: Fine mesh in shear zones for accurate chip prediction.

2.4 Machining Parameters and Effects on Chip Formation

1. Cutting Speed (Vc):
- Higher speeds increase cutting-zone temperature and risk of BUE in soft metals.
- HSS tools require lower speeds compared to WC tools.

2. Feed Rate (f):
- Low feed reduces chip thickness and adhesion; high feed can increase tool stress and temperature.

3. Lubrication:
- Wet, MQL, or cryogenic methods reduce adhesion and tool wear, especially for titanium alloys and copper.

4. Chip Morphology:
- Short, broken chips are advantageous for cast iron.
- Continuous chips dominate in aluminum and copper.

Fig. 1. Typical Machining Parameters and Chip Formation Behaviour for Soft HSS Tools

Workpiece	Cutting Speed (Vc)	Feed (f)	Cutting-Zone Temp (°C)	Chip Formation	Lubrication Recommendation
Cast Iron (Gray CI)	50 – 200 m/min	0.05 – 0.30 mm/rev	200 – 500	Short/broken chips; minimal BUE	Dry; coolant optional
Titanium Alloys (Ti-6Al-4V)	5 – 30 m/min	0.03 – 0.15 mm/rev	400 – 900	Continuous/segmented chips; strong adhesion; severe wear	Flood / high-pressure / cryogenic / MQL; dry not recommended
High-Carbon Steel (unhardened)	30 – 120 m/min	0.05 – 0.30 mm/rev	300 – 700	Continuous or BUE chips; smoother at high speed	Wet / MQL preferred; dry possible but tool life reduced
Hardened Steel (≥ 45 – 60 HRC)	HSS not recomme-nded	Very low feed	Very high	Segmented/shear-localized; burnishing common	CBN / PCD tools; dry or minimal coolant

Fig. 2. Typical Machining Parameters and Chip Formation Behaviour (Hard Tungsten-Carbide Tool – Soft Non-Ferrous Workpieces)

Workpiece	Cutting Speed (Vc)	Feed (f)	Cutting-Zone Temp (°C)	Chip Formation	Lubrication Recommendation
Aluminium (Al alloys 6000/7000)	150 – 600 m/min	0.05 – 0.40 mm/rev	150 – 350	Continuous, ductile chips; BUE risk at low speed	Wet / MQL preferred; dry possible for roughing
Copper (Cu & Cu-alloys)	100 – 400 m/min	0.05 – 0.30 mm/rev	200 – 450	Continuous, ductile, sticky; BUE risk	Wet / MQL strongly recommended
Zinc (Zn / brass alloys)	120 – 300 m/min	0.05 – 0.25 mm/rev	150 – 300	Continuous to slightly segmented chips	Dry common; coolant optional
Lead (Pb & Pb-alloys)	80 – 200 m/min	0.05 – 0.20 mm/rev	100 – 250	Short, thin chips; very soft	Dry sufficient

3. Future Work and Research Gaps

Based on the literature review and FEA analysis of chip formation, the following areas are suggested for future research:

1. Experimental Validation: Conduct real machining tests to validate FEA predictions for different tool–workpiece combinations.
2. Advanced Tool Materials: Investigate new tool coatings, ceramics, and hybrid composites to improve tool life and chip control.
3. Optimization of Machining Parameters: Explore multi-objective optimization of cutting speed, feed, and lubrication using simulation and experiments.
4. Sustainable Machining: Study MQL, cryogenic cooling, and dry machining for energy-efficient and environmentally friendly processes.
5. FEA Model Improvements: Develop more accurate thermo-mechanical models and material behavior representations to enhance predictive accuracy.

Addressing these areas can help bridge the gap between simulations and practical machining, guiding optimized, efficient, and sustainable metal cutting.

4. CONCLUSIONS

This paper presents a comprehensive literature review and finite element analysis (FEA)-based study of chip formation in metal cutting using different tool and workpiece materials. Key conclusions are:

1. Soft HSS tools are suitable for moderate-speed cutting of cast iron and some steels but not recommended for hardened steels and titanium alloys without active cooling. Hard WC tools perform efficiently on soft non-ferrous metals, enabling higher cutting speeds with minimal adhesion and stable chip formation.
2. Difficult-to-machine alloys, such as titanium and hardened steels, generate high cutting-zone temperatures and adhesive or segmented chips, while soft non-ferrous metals produce continuous, ductile chips, with some risk of built-up edge.
3. Cutting speed, feed, and lubrication strongly influence chip morphology, temperature, and tool wear. Flood cooling, cryogenic methods, or minimum quantity lubrication (MQL) are recommended for high-temperature or adhesive materials, whereas dry machining is acceptable for cast iron and some soft metals.
4. Literature-based FEA using Abaqus provides reliable predictions of chip formation, cutting-zone temperatures, and tool stresses, supporting optimization of machining parameters without costly experimental trials.
5. The findings offer a framework for simulation-based optimization and experimental validation in industrial applications.

Overall, proper tool selection, workpiece material understanding, and optimized cutting parameters, supported by FEA, can improve machining efficiency, tool life, and product quality.

The integration of FEA with experimental validation represents a promising direction for future research in sustainable and precision machining

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