CHIP MORPHOLOGY AS A NON-INVASIVE INDICATOR OF CUTTING EDGE DEGRADATION IN HIGH-FEED MILLING OF TOOL STEEL

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This study examines the correlation between progressive flank wear and chip formation mechanics dur-ing high-feed milling (HFM) of DIN 1.2343 tool steel. The research compares length-based and weight-based methods for determining the chip compression ratio and shear plane angle ϕ, evaluating their sensitivity to tool degradation. Reaching the tool life limit is associated with a decreased angle ϕ, increased chip evacuation resistance, transformations in chip morphology and discoloration. Discrepancies between analytical methods are attributed to the side flow phenomenon and specific HFM tool geometries. The identified correlations enable non-invasive identification of the cutting edge condition via quantitative chip parameters, essential for eliminating micro-cracks in machined materials. In the context of manufacturing ballistic protection and structural military components, sub-sequent chip analysis allows for verifying process stability and preventing fatal component failure under extreme operating conditions in strategic applications.

KEYWORDS

High-feed milling (HFM), Tool wear, Chip morphology, Chip compression ratio, Shear plane angle, DIN 1.2343, Hardened tool steel.

1 INTRODUCTION

High-feed milling (HFM) represents a dominant technology for the roughing of hardened tool steels due to its capability to achieve high material removal rates while maintaining relatively low cutting forces. However, when machining materials such as DIN 1.2343 hardened and tempered to 55 HRC, the cutting process encounters the limits of the cutting edge's thermomechanical stability, leading to progressive degradation of the tool geometry. Traditional tool wear monitoring techniques, whether direct measurement methods (microscopic analysis) or indirect ones (analysis of wear related characteristics such as cutting forces or vibrations), require frequent interruptions of the machining process or necessitate the utilization of expensive measuring equipment. This study focuses on the chip as a primary waste product that simultaneously functions as a natural sensor, as it carries complex information regarding the cutting process in terms of mechanical and thermal loading. Through the analysis of chip morphology, the chip compression ratio, and the shear plane angle, it is possible to identify the critical moments of cutting process transformation, which directly predict the end of tool life. The objective is to verify whether optical analysis of changes in chip morphology and coloration can be used to evaluate cutting edge integrity without requiring external metrology equipment.

To understand morphological modifications and effectively diagnose tool condition via chip analysis, knowledge of the geometric parameters of chip formation is required. These parameters are highly specific in HFM technology compared to conventional orthogonal cutting. A recent study indicates that a faithful description of cutting mechanics in HFM necessitates considering the variable uncut chip thickness and the chip thinning effect typical of high-feed strategies. The specific geometry of HFM tools with low setting angles leads to a transformation of the chip cross-section. It is precisely this geometric complexity and the high sensitivity of the process to changes in cutting kinematics that underscore the importance of monitoring chip morphological alterations as an indicator of cutting edge degradation [Jacquet 2025].

The mechanics of HFM processes are characterized by a specific chip thickness to width ratio (b/h < 1), which fundamentally transforms the mechanisms of plastic deformation within the cutting zone. These kinematic specifics lead to a reduction of friction on the tool rake face and minimize chip exit resistance, manifesting as low values of the chip compression ratio and a correspondingly higher shear plane angle ϕ. Findings suggest that these parameters are directly linked to the thermomechanical balance of the process and the energetic intensity of generating a new surface. In the context of machining hardened steels, where intense thermal loading of the cutting edge occurs, any edge degradation should immediately manifest as a disruption of this stable state [Kuhlmann 2024].

Any abrupt change in cutting edge geometry directly modifies the stress balance within the surface layer. An increasing cutting edge radius leads to higher contact friction and thermal flux into the workpiece, generating dominant tensile residual stresses in the surface zone. This phenomenon is particularly critical in materials with low thermal conductivity, where high temperatures generated during the cutting process lead to microstructural transformation [Liu 2022]. Although HFM under optimal conditions can induce favorable compressive residual stresses into the surface layers, disruption of cutting process stability due to tool degradation eliminates this benefit [Tillmann 2016].

Another key factor influencing the stability of the HFM process is the force loading in the cutting zone, which is closely coupled with the cutting edge microgeometry. Numerical analysis using the Smoothed Particle Hydrodynamics (SPH) method confirmed that the configuration of cutting angles fundamentally affects the magnitude of process forces, with the transition toward negative geometries inducing a steep increase in force loading [Gyliene 2016].

In direct connection with force and geometric aspects, the correlation between wear progression and morphological chip transformation is crucial for the practical implementation of monitoring. Another research confirmed that the progression of cutting edge degradation, from initial abrasion to critical wear, is accompanied by clearly definable changes in chip segmentation. While a stable cutting process with an intact cutting edge generates chips composed of simple elements, an increase in wear triggers a transformation toward folded and subsequently segmented, serrated (saw-tooth) shapes [Halim 2019]. A study published by Çalışkan and Küçükköse [2015] states that the condition of the tool contact faces fundamentally affects the smoothness of chip evacuation. While low friction on the tool

rake face promotes the formation of short and geometrically uniform elements, any degradation of the cutting edge leads to an increase in adhesive forces. This shift in tribological equilibrium manifests as changes in chip length and shape stability, with the chips becoming longer and irregular as wear progresses.

Conversely, a detailed investigation of chip parameters published by Zhang et al. [2014] indicates that an increase in tool flank wear leads to a measurable reduction in chip length. This phenomenon is explained by the existence of the so-called critical chip thickness (CCT). If the theoretical uncut chip thickness becomes lower than this threshold due to cutting edge dulling, effective material separation does not occur, thereby deforming the resulting chip geometry.

A study by Langenhorst and Sölter [2024] emphasizes that the fraction of heat transferred into the workpiece is closely linked to the process kinematics and chip thickness through dimensionless thermal numbers. Under conditions of progressive wear, where edge dulling and rising cutting forces occur, the distribution of this heat changes fundamentally. Since heat from the cutting zone is primarily evacuated by the chip, any transformation of its morphology and coloration directly indicates a disruption of the thermomechanical equilibrium, which can lead to the induction of tensile residual stresses and the formation of micro-cracks.

An investigation of high-speed machining processes by Hortig and Svendsen [2007] shows that the dominant mechanism of chip formation is the initiation of adiabatic shear bands, which form when localized thermal softening overcomes the strain hardening of the workpiece. This material instability occurs when the rate of mechanical energy dissipation exceeds the material's capacity to conduct heat, leading to the localization of plastic flow into narrow bands. The stable generation of these bands is crucial for reducing cutting forces, yet their periodicity and character are highly sensitive to cutting edge microgeometry and tribological conditions.

Progressive cutting edge wear does not only alter the thermal balance, it directly affects the periodic nature of segmented chip formation. Research by Cotterell and Byrne [2008] demonstrated that saw-tooth chip formation is a two-stage process involving an initial upsetting phase accompanied by plastic deformation, followed by significant failure in the form of a drop in the shear plane angle ϕ. A study by Kovac and Sidjanin [1997] points out that this chip formation mechanism in steels is accompanied by the nucleation of voids and cracks in the primary shear zone, which dictate the character of the resulting chip. Under conditions of progressive edge wear, the stability of this mechanism is disrupted, manifesting as alterations in the geometric parameters of the chip and frequently resulting in the formation of unstable built-up edges.

Research conducted by Beșliu et al. [2018] during the machining of hardened tool steel showed that cutting forces in these processes act as a barometer for deformation and surface integrity, with the tool geometry exhibiting an exponential influence on the magnitude of the force field. In this context, progressive flank wear (VB) simulates an increase in the effective edge radius, leading to a transformation of the chip formation mechanism. A specific indicator of the extreme thermomechanical loading that accompanies tool degradation is the presence of the "white layer" and thermal cracks on the chip surface, signaling phase transformations and irreversible damage to the microstructure. A study by Vavruska et al. [2022] demonstrated that adjusting cutting-edge microgeometry via lapping or drag finishing significantly extends tool life when milling Inconel 718. This edge optimization alters the shear zone conditions, fundamentally improving chip formation mechanisms and stabilizing the tool load. Research conducted by Winnuwat et al. [2023] proved that trochoidal milling with a small step-over effectively suppresses build-up edge (BUE) formation on aluminum 6061-T6. The resulting cyclical force and temperature fluctuations optimize chip compression and segmentation, ensuring reliable chip evacuation.

A key role in diagnosing the HFM process is played by the chip compression ratio, which represents a fundamental energetic estimate of the thermomechanical interaction between the cutting edge and the machined material. Research by Storchak [2024] defines the chip compression ratio as the main similarity criterion of cutting processes, as it directly dictates the volume of work expended on plastic deformation and predicts the resulting force loading on the tool. The study of chip formation dynamics shows that chip compression values are the result of a dynamic equilibrium between adiabatic strain hardening and isothermal softening of the material, the latter dominating at higher cutting speeds. Progressive flank wear (VB), however, disrupts this stability.

A study by Antic et al. [2012] focused on chip parameter analysis and machining process dynamics confirmed that chip segmentation is closely bound to cutting tool flank wear. As edge degradation progresses, the character of segmentation changes (transitioning from continuous to discontinuous chip formation). Visual evidence of these changes is further provided by the transformation of the chip contact side, which, due to increasing wear, becomes significantly uneven and wavy compared to the smooth surface generated by a new cutting edge.

The identification of the aforementioned correlations between the tool degradation and the morphology of the formed chip represents valid pillars for the development of diagnostic systems for tool condition monitoring, which utilize the waste product as a complex information source regarding cutting process stability.

2 EXPERIMENTAL SETUP AND METHODOLOGY

This section outlines the experimental framework, material specifications, and analytical methodologies employed to investigate the correlation between tool wear progression and chip deformation characteristics. The following subsections detail the properties of the machined hardened steel, the configuration of the cutting tools and CNC system, the selection of operational parameters, and the exact procedures utilized for quantitative chip morphology evaluation.

2.1 Materials and Tools

Experimental measurements were conducted on a Haas VF-2SSYT CNC vertical machining center. The workpiece material selected for the investigation was DIN 1.2343 (X37CrMoV5-1) tool steel, which was heat-treated to a final tempered hardness of 55 HRC. This grade of steel is characterized by its high toughness and high resistance to thermal softening, making it an industry standard for the manufacturing of precise die-casting molds. The chemical composition of this steel is listed in Tab. 1. The experimental setup utilized for the testing is illustrated in Fig. 1.

Table 1. Chemical composition of X37CrMoV5-1 steel [wt. %]. [LUCEFIN GROUP 2018]

C	Si	Mn	P	S	Cr	Mo	V
0.33-0.41	0.80-1.20	0.25-0.50	Max 0.03	max 0.02	4.80-5.50	1.10-1.50	0.30-0.50

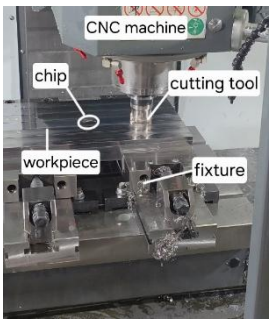


Figure 1. Experimental testing configuration (machine-tool-workpiece-fixture setup).

For the high-feed milling (HFM) process, indexable inserts from different manufacturers were selected, designated as samples B, C, and F. Although these tools are designed for the same technological operation, they differ in their cutting edge geometry. Details of the cutting tools used are listed in Tab. 3. Further technical specifications cannot be disclosed, as these represented experimental tools in the development stage. The cutting conditions employed (see Tab. 2) were kept constant across all utilized tools to ensure that the progressively developing tool wear remained the sole variable in the process.

Table 2. Cutting conditions utilized for the experimental testing.

v_c [m.min^{-1}]	n [min^{-1}]	a_p [mm]	a_e [mm]	f_z [mm]	v_f [mm.min^{-1}]
270	2305	0.5	37	0.56	1290.8

Table 3. Supplementary information regarding the geometry of the cutting tools.

Sample	Manufacturer	Milling Cutter Body	Indexable Insert	Parameter	Value	Unit
B	Pramet	50A05R-SMOZD09-C	V1	Setting angle	10	°
C	Pramet	50A05R-SMOZD09-C	V2	Rake angle	10	°
				Substrate material	M8310	—
				Coating	PVD	
F	Tungaloy	TXSW09M050B 22.0R07	SWMT 0904ZER-MM	Setting angle	12	°
				Rake angle	3.5	°
				Substrate material	AH8015	—
				Coating	PVD	—



a) b)

Figure 2. Detailed view of the tool configurations: (a) samples B and C, (b) sample F.

2.2 Chip Parameters and Analytical Methodologies

During the experimental testing, chip collection was performed at predetermined intervals throughout the machining process. Upon completion of each machining cycle, a microscopic analysis of the cutting tool was carried out to measure the flank wear value VB. This value was subsequently compared against the predefined tool wear criterion, and the integrity of the main cutting edge was assessed. The maximum net machining time for monitoring the tools was set to 70 minutes.

A total of 5 representative chips were randomly sampled and evaluated for each measurement time step. For the chip analysis and the calculation of the primary deformation parameters, two distinct methodologies were employed: the length-based method and the weight-based method. To quantify the deformation processes, fundamental computational relationships were utilized to determine the chip compression ratio (see Eq. 1), the shear plane angle, and the chip exit velocity from the cutting zone.

The chip compression ratio is defined by the following relationship:

$$\Lambda = \frac{h_{DC}}{h_D} \; [-] \tag{1}$$

where: h_{DC} – real thickness of the removed chip [mm],
h_D – theoretical (uncut) chip thickness [mm].

A key element of this study is the comparison of two distinct methods for determining the chip compression ratio:

- Length-based method (k_L): This method is based on the direct measurement of the developed length of the actual chip (L_2) using a digital microscope (see Fig. 2) and its subsequent comparison with the theoretical length of the cutting edge path in engagement (L_1). This methodology directly reflects the longitudinal plastic deformation.

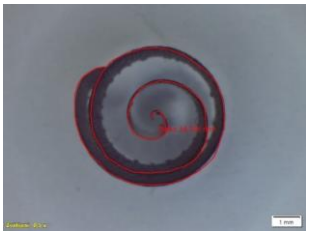


Figure 3. Detailed view of the chip length measurement under a digital microscope.

- Weight-based method (k_W): This approach is derived from the law of conservation of volume. The calculation requires weighing the mass of the chip samples (see Fig. 3), measuring the chip width, knowing the material density, and calculating the theoretical chip thickness. For the specific application to HFM machining, this method utilizes the mean chip thickness h_m (see Eq. 2).



Figure 4. Chip samples weighing process.

The mean chip thickness is defined by the following relationship:

$$\boldsymbol{h_m = sin(K_r) \cdot f_z \cdot \frac{360 \cdot a_e}{\pi \cdot Def \cdot \psi}} \; [\boldsymbol{mm}], \tag{2}$$

where: a_e – radial depth of cut [mm],
D_{ef} – effective cutter diameter [mm],
f_z – feed per tooth [mm·tooth^{-1}],
K_r – setting angle of the main cutting edge [°],
ψ – cutter engagement angle [°].

Closely related to the chip compression ratio is the shear plane angle ϕ (see Eq. 3), which defines the orientation of material separation within the primary deformation zone; it can also be stated that it determines the orientation of the primary shear zone relative to the cutting velocity vector. This angle can be analytically derived from the chip compression ratio and the tool rake face angle, where a higher positive value of the rake angle generally increases the angle ϕ and improves the machining conditions.The shear plane angle is defined by the following relationship:

$$\Phi = tan^{-1} . \left(\frac{\cos(\gamma_0)}{k_h - \sin(\gamma_0)} \right) [m.min^{-1}], \quad (3)$$

where: γ_n – rake angle [°].

The mechanics of plastic deformation are directly related to the chip exit velocity from the cutting zone, v_{ch} (see Eq. 4). This variable can be analytically determined based on the law of conservation of volume from the relationship between the cutting velocity v_c and the chip compression ratio Λ (or the shear plane angle ϕ, respectively). A decrease in the velocity v_{ch} is then a direct consequence of more intensive material upsetting associated with cutting edge degradation.

The chip exit velocity from the cutting zone is defined by the following relationship:

$$v_{ch} = v_c . \frac{\sin(\Phi)}{\cos(\Phi - \gamma_0)} [m.min^{-1}] \quad (4)$$

3 RESULTS

3.1 Experimental Results for Variant B Tools

Comparing the results of the variant B tool samples is highly critical, as it provides key methodological evidence of a direct causal relationship between cutting edge wear and chip morphology. Throughout the entire test, sample B1 exhibited high stability of the cutting geometry without significant flank wear (see the photographic documentation of tool wear and chip morphology in Fig. 5). Tool wear evaluation and chip collection were carried out approximately every 5 minutes of machining. The test for tool B1 was stopped after 70 minutes of net cutting time. This condition of the tool serves as an ideal baseline for the subsequent tools—since cutting edge B1 did not experience accelerated wear, the mechanics of chip formation remained constant over the entire duration. The shear plane angle ϕ remained within the optimal range of 40° to 44° at all times, the chip compression ratio showed no sudden spikes, and no significant change was observed in the chip exit velocity from the cutting zone v_{ch} (see the summary graphical relationships in the middle of Fig. 5).

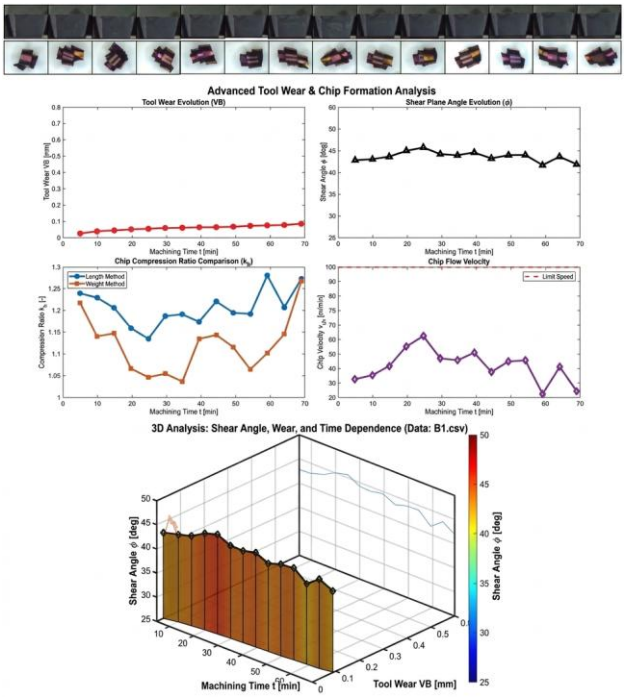


Figure 5. Evolution of chip morphology and its characteristics during machining with tool B1.

Selected variables are also visualized in a comprehensive 3D plot in the bottom of Fig. 5, which graphically illustrates the drop in the shear plane angle under increased wear. The results of sample B1 confirm that without elevated cutting edge degradation, the plastic deformation process remains almost entirely stable.

However, a completely different trend was exhibited by sample B2, where a tipping point occurred after 50 minutes of net machining time, initiating accelerated wear. To illustrate the precise kinematic and wear evolution, Table 4 presents a representative dataset from B2 sample, which reflects the characteristic behaviour observed across all other evaluated carbide tools (except sample B1).

Table 4. Representative dataset of measured and calculated parameters for sample B2.

Time t [min]	Chip Length L [mm]	Chip Mass m [g]	k_h - (Length method) [-]	Uncut Chip Thickness h_{DC} [mm]	Mean Chip Thickness h_m [mm]	k_h (Weight method) [-]	Shear Angle ϕ [°] (Weight method)	ϕ [°] (Length method)	Flank Wear VB [mm]
4,9	37,585	0,042	1,185	0,052	0,050	1,049	48,363	44,237	0,038
9,8	43,467	0,043	1,025	0,047	0,050	0,941	52,060	49,168	0,057
14,7	38,463	0,041	1,158	0,050	0,050	1,010	49,648	45,014	0,064
19,6	37,005	0,040	1,204	0,054	0,050	1,074	47,567	43,716	0,065
24,5	40,354	0,042	1,104	0,049	0,050	0,985	50,514	46,637	0,067
29,4	37,842	0,040	1,177	0,056	0,050	1,115	46,290	44,465	0,071
34,3	42,024	0,043	1,060	0,051	0,050	1,014	49,519	48,016	0,073
39,2	40,856	0,041	1,090	0,051	0,050	1,024	49,178	47,057	0,074
44,1	38,134	0,039	1,168	0,052	0,050	1,040	48,677	44,725	0,075
49,0	39,856	0,039	1,118	0,060	0,050	1,204	43,705	46,216	0,076
53,9	30,895	0,033	1,442	0,067	0,050	1,347	40,014	37,835	0,365

Immediately after exceeding the critical tool wear limit, a distinct change in the morphology and color of the formed chip was observed (see Fig. 6). The shear plane angle ϕ dropped abruptly to the threshold of 35°, which was accompanied by a steep increase in the chip compression ratio and a significant reduction in the chip exit velocity vch by more than 35% (see the middle graph of Fig. 6 and the 3D plot in the bottom of Fig. 6). The photographic documentation of the chips verified that while the chips from machining with tool B1 remained uniform with consistent coloration, tool B2 caused an immediate transformation in shape and color after the 50th minute. This indicates a temperature rise in the primary zone above 300°C due to increased wear and chipping of a portion of the tool's main cutting edge.

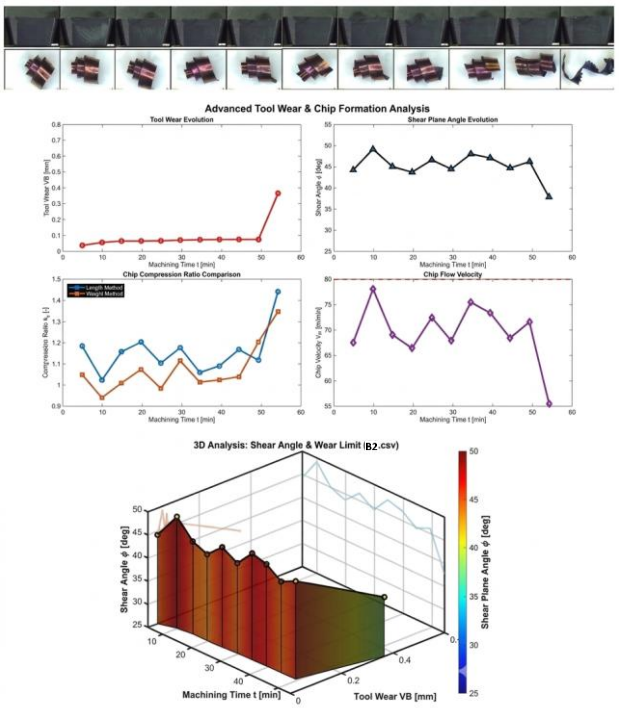


Figure 6. Evolution of chip morphology and its characteristics during machining with tool B2.

3.2 Experimental Results for Variant C Tools

The trend observed in the variant B tool samples, specifically the direct correlation between the chip deformation parameters and the onset of accelerated wear, was fully corroborated by the variant C tools. These tools, featuring a very similar cutting edge geometry, exhibited a significantly shorter period of stable machining; however, the deformation response after exceeding critical wear remained identical (see Fig. 7 and Fig. 8). After 20 minutes of machining with these tools, accelerated tool degradation occurred, causing a visually striking change in chip morphology (see the top of Fig. 7). This modification manifested as shorter and thicker formed chips, which led to an increase in the chip compression ratio and a sharp drop in the shear plane angle from an initial range of 40–45° down to approximately 30° (see the bottom of Fig. 7 and Fig. 8). The results from the C samples confirmed an elevation in temperature within the cutting zone under increased cutting tool wear and higher friction, which is consistent with the recorded chip exit velocity values. Continued machining with such a degraded cutting edge would pose an immediate risk of inducing undesirable tensile residual stresses into the surface layer of the DIN 1.2343 steel.

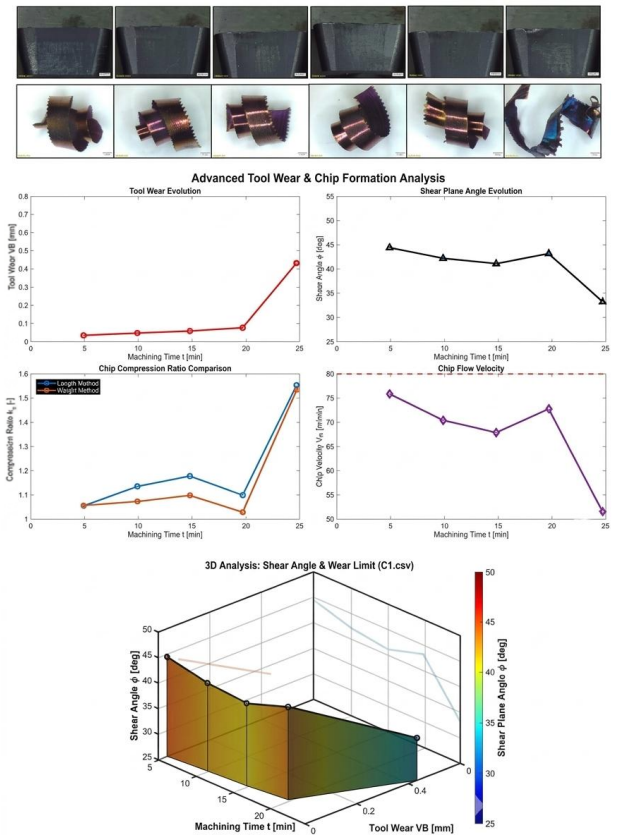


Figure 7. Evolution of chip morphology and its characteristics during machining with tool C1.

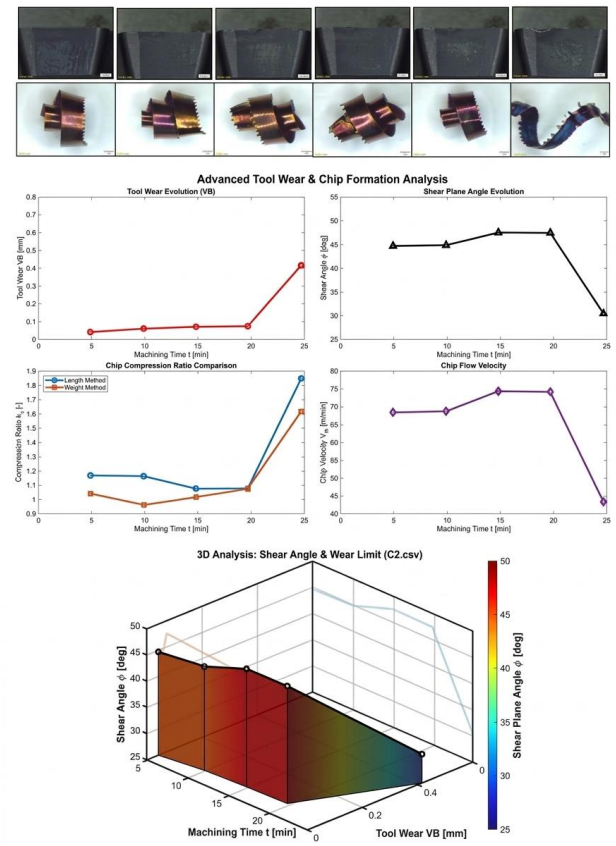


Figure 8. Evolution of chip morphology and its characteristics during machining with tool C2.

3.3 Experimental Results for Variant F Tools

To enhance the complexity of the results and to validate the established methodology, variant F tools were employed, featuring a completely different geometry and carbide grade. However, the microscopic analysis yielded results identical to those of tools B2, C1, and C2. Furthermore, the F samples exhibited the shortest machining time before experiencing accelerated wear, which resulted in a visually observable change in the evacuated chips (see Fig. 9 and Fig. 10).

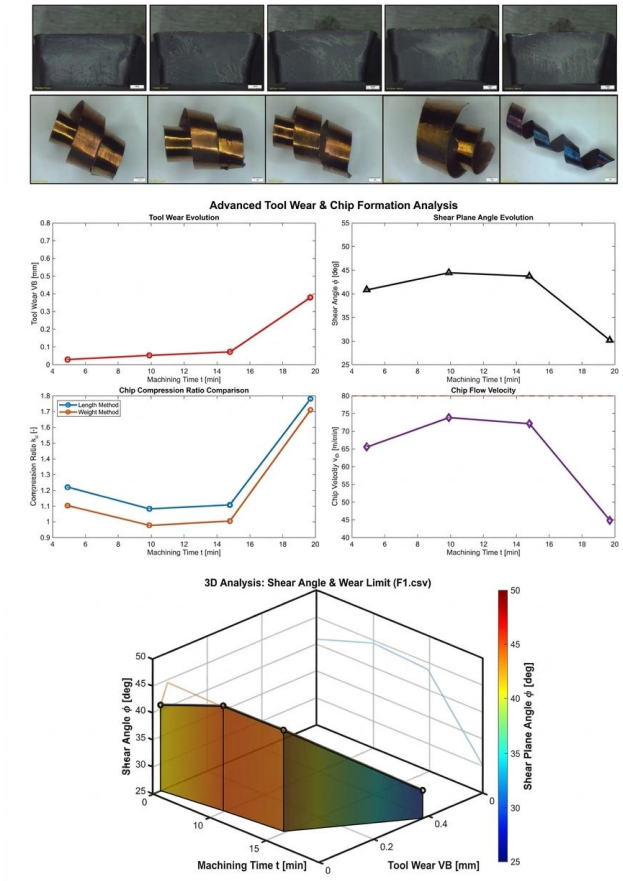


Figure 9. Evolution of chip morphology and its characteristics during machining with tool F1.

Despite the low tool life, it is appropriate to emphasize the sensitivity of the methods used to determine the chip compression ratio (see the middle graphs in Fig. 9 and Fig. 10). The length-based and weight-based analytical methods used are virtually interchangeable for calculating the chip compression ratio and other chip parameters. The measured experimental data are again complemented by graphical representations illustrating the evolution of tool wear and the shear plane angle over time.

Consequently, the results for the tool variants F definitively confirmed that even with lower tool life and edge durability. The change in chip morphology and coloration remains a universal and reliable indicator of the end of tool life.

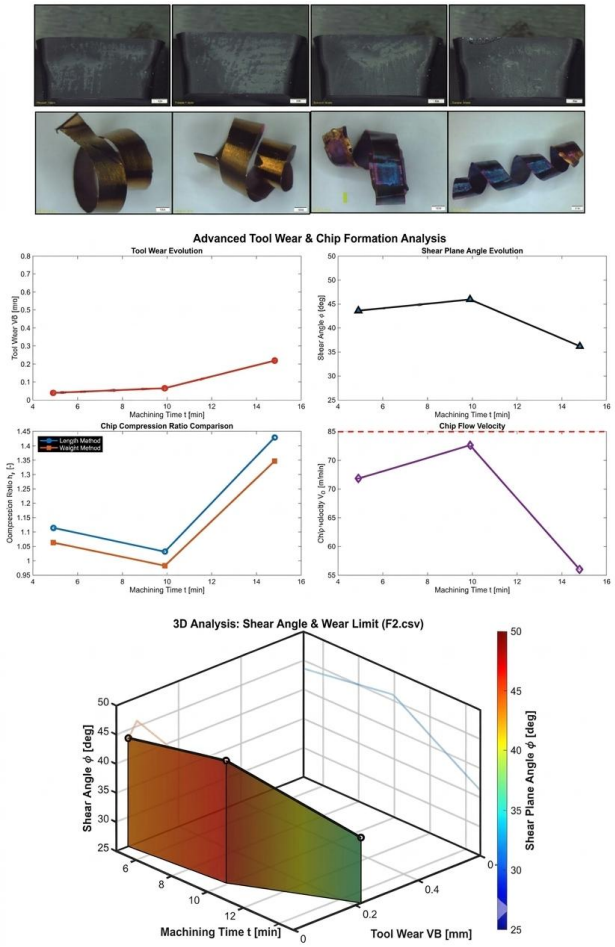


Figure 10. Evolution of chip morphology and its characteristics during machining with tool F2.

4 DISCUSSION

This study demonstrated a consistent relationship between progressive tool flank wear and the mechanics of chip formation during the high-feed milling (HFM) of DIN 1.2343 steel (55 HRC). Six independent carbide tools validated the methodology of utilizing the chip as a promising indicator for monitoring process dynamics. Although standard tool life criteria (e.g., ISO 3685) typically define critical flank wear at VB = 0.3 mm, the present experimental data revealed that deformation instability is triggered earlier, at a threshold of VB = 0.2 mm. Beyond this critical limit, the analytically derived shear plane angle ϕ decreases non-linearly by approximately 30% toward 30°, while the calculated chip exit velocity vch drops by more than 35%. These precise variations indicate a sharp increase in plastic deformation and the energetic intensity of the cutting process.

A comparison of the methodological approaches revealed the limitations of the weight-based method, which underestimates the actual deformation due to intense material side flow along the chip edges (causing the chip compression ratio to drop below 1). Conversely, the length-based method tracks pure longitudinal shortening, thereby representing a significantly more reliable diagnostic tool for HFM strategies. Exceeding the VB = 0.2 mm limit triggers a thermomechanical instability characterized by changes in chip morphology and coloration, which are easily observable by eye. The reduction of the shear plane angle ϕ toward 30° indicates increased deformation energy and friction within the cutting zone. While subsurface integrity was not directly evaluated in this study, such

thermomechanical shifts represent a potential risk factor for inducing tensile residual stresses or micro-structural alteration, which warrants further investigation.

5 CONCLUSIONS

This study evaluated the mechanics of chip formation as an indicator of cutting-edge degradation during the high-feed milling of DIN 1.2343 steel (55 HRC). The primary conclusions are:

- Deformation Instability Threshold: Exceeding VB = 0.2 mm induces a distinct deformation instability, where the derived shear plane angle ϕ decreases toward 30° and calculated chip exit velocity v_{ch} drops by over 35%.
- Methodological Reliability: The length-based chip compression ratio method is significantly more reliable for HFM strategies than the weight-based method, which might be distorted by lateral material side flow at higher wear levels.
- Diagnostic Capability: The analysis of chips as visual process indicators represents an effective, non-invasive tool for early-stage warning against surface degradation in high-value components.

Potential directions for future research include:

- Surface Integrity Degradation: Directly measuring thermal distribution and residual stress profiles.
- Ballistic Resistance Correlation: Analyzing the correlation between chip morphology and the ballistic resistance of the machined components.
- Defense Engineering Applications: Verifying and applying the methodology to specific areas of defense engineering when machining different structural materials.
- Automated Visual Inspection: Implementing the established relationships into automated visual chip inspection systems.

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