



DYNAMIC CUTTING FORCE ANALYSIS IN FACE MILLING OF EN31 STEEL USING COATED CARBIDE INSERTS

A Study on Dynamic Signal Analysis Using Time-Domain and Frequency-Domain Methods

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Abstract: This paper presents a dynamic cutting force analysis in face milling of EN31 steel using coated carbide (SPMW 120408-TN 7535) inserts. Cutting force signals were acquired using a Kistler 9257B piezoelectric dynamometer at 10,000 Hz sampling rate, and surface roughness was measured using a Taylor Hobson Surtronic S-Series profilometer. A 2^3 full factorial design of experiments (DOE) was employed for the first experimental set ($2^3 = 8$ runs + 2 centre points = 10 total), and a full factorial design for the second set. Signal analysis was performed in both time-domain and frequency-domain using MATLAB. Results from the first set indicate that depth of cut is the most significant parameter influencing cutting force, while feed rate governs surface roughness. Frequency-domain analysis revealed that machining at low speed (58.9 m/min), low feed (20 mm/min), and high depth of cut (0.75 mm) produces unstable, non-repeatable machining conditions. In the second set, with depth of cut constant at 0.25 mm, feed rate emerged as the sole significant factor for both cutting force and surface roughness. Optimal parameters identified are: cutting speed 235.62 m/min, feed 0.25 mm/tooth (second set), and depth of cut 0.25 mm, yielding minimum cutting force, lowest vibration amplitude, and best surface finish.

Index Terms – Face milling, EN31 steel, coated carbide inserts, cutting force, surface roughness, dynamic signal analysis, frequency-domain analysis, factorial design of experiments.

I. INTRODUCTION

Milling is one of the most extensively used material removal processes in modern manufacturing, particularly for producing flat and complex surfaces. Face milling, where the cutting action occurs primarily at the face of a rotating multi-tooth cutter, is indispensable in automotive, aerospace, die-mould, and precision engineering industries. EN31 steel (equivalent to AISI 52100, a high-carbon chromium alloy steel) is widely used for bearings, gauges, collets, and precision components due to its high hardness and excellent wear resistance. However, its machinability presents significant challenges, demanding careful selection of cutting tools and process parameters.

Cutting force measurement is the most direct and effective method for monitoring machining operations. Conventionally, average cutting force is used for process evaluation; however, this approach fails to capture the dynamic nature of the process, including vibration, chatter, and tool engagement transients. Dynamic force signal analysis, employing time-domain and frequency-domain methods, provides far richer information about machining stability, tool condition, and surface quality.

Coated carbide inserts are the preferred tool material for milling hardened steels due to their superior wear resistance, thermal stability, and maintained cutting edge integrity at elevated temperatures. The selection of process parameters—cutting speed, feed rate, and depth of cut—critically determines cutting force magnitude, surface roughness, machining stability, and tool life.

This paper presents a comprehensive experimental investigation on face milling of EN31 steel using SPMW 120408-TN 7535 coated carbide inserts. The objectives are: (i) to analyze the effects of process parameters on cutting force and surface roughness using factorial design of experiments; (ii) to perform time-domain and frequency-domain analysis of the dynamic cutting force signal; and (iii) to identify optimal process parameters for stable, efficient, and high-quality machining.

II. LITERATURE REVIEW

Degarmo et al. [1] and Schmid [2] laid the foundational framework for understanding material removal processes and machining mechanics. Davim [3] provided a thorough treatment of machining fundamentals and recent advances in difficult-to-cut materials. Ezugwu [4] identified critical improvements in machining difficult aerospace superalloys, emphasizing the role of cutting parameters on tool life and surface integrity.

Teti et al. [6] presented a landmark review of advanced machining monitoring approaches, covering force, vibration, acoustic emission (AE), and temperature-based sensing. They highlighted the superiority of dynamic signal analysis over static averages for process health monitoring. Jemielniak [7] demonstrated effective tool failure detection through AE signal analysis. Masmiaati et al. [8] optimized cutting conditions for minimum residual stress, cutting force, and Ra in end milling of S50C steel using response surface methodology, establishing feed as the dominant surface roughness factor.

Marinescu and Axinte [9] critically evaluated AE signals for detecting milling malfunctions, while Lee et al. [12] demonstrated precision process monitoring using AE in manufacturing contexts. Huang et al. [15] conducted vibration analysis in milling of titanium alloy based on cutting force signal processing in the frequency domain, identifying chatter frequencies and instability thresholds. Smith [18] provided the mathematical foundations for digital signal processing—including FFT—applicable to cutting force signal analysis. Collectively, the literature establishes a strong case for dynamic force signal analysis as the preferred approach for comprehensive machining process evaluation.

III. EXPERIMENTAL SETUP AND INSTRUMENTATION

A. Work Material

EN31 steel (AISI 52100) was selected as the workpiece material. It contains 0.95–1.10% carbon and 1.2–1.6% chromium, providing hardness up to 62 HRC (heat treated) and excellent wear resistance. It is widely employed in bearing races, collets, gauges, and precision tooling—components that demand high surface quality and dimensional accuracy. Its elevated hardness and work-hardening tendency make it challenging to machine, necessitating optimized process parameters.

B. Cutting Tool and Insert

A 40 mm diameter face milling cutter body was used as the tool holder. The insert selected was SPMW 120408-TN 7535, a PVD-coated carbide insert with a multi-layer coating for enhanced wear resistance and thermal stability. The double-positive rake geometry reduces cutting forces and promotes thinner chip formation. Insert selection followed the Sandvik Coromant systematic methodology [5], considering workpiece material, operation type, required surface quality, and recommended cutting data ranges.

C. Machine Tool

Milling experiments were performed on a vertical CNC milling machine with adequate spindle power and rigidity. The machine was carefully calibrated before each experimental session to eliminate setup-induced errors.

D. Kistler 9257B Dynamometer

Cutting force signals were acquired using the Kistler 9257B three-component piezoelectric dynamometer. The feed force component (F_y) was selected as the primary response variable for face milling. Signals were sampled at 10,000 Hz using DynoWare software with a measurement duration of 160 seconds per experiment. Raw data in CFG format was converted to CSV in MATLAB for analysis.

E. Surface Roughness Measurement

Surface roughness was measured using the Taylor Hobson Surtronic S-Series contact profilometer. Arithmetic mean roughness (R_a) in micrometers was recorded as the surface quality metric. Three measurements were taken at different locations on each machined surface, and the average value was reported.

IV. METHODOLOGY

A. Design of Experiments

Factorial design of experiments (DOE) was adopted for systematic study of process parameters and their interactions. For the first experimental set, three factors were investigated: cutting speed (A), feed rate (B), and depth of cut (C). A 2^3 full factorial design with two centre points was generated using Minitab 17, ensuring randomization of run order. Total runs: 10 ($2^3 = 8$ factorial runs + 2 centre points). Table 1 shows the process parameters and their levels.

TABLE 1: PROCESS PARAMETERS AND LEVELS — FIRST EXPERIMENTAL SET

Parameter	Symbol	Level -1 (Low)	Level 0 (Centre)	Level +1 (High)
Cutting Speed (m/min)	A	58.9	84.2	117.8
Feed Rate (mm/min)	B	20	40	63
Depth of Cut (mm)	C	0.25	0.50	0.75

For the second set, depth of cut was fixed at 0.25 mm, and a full factorial design with speed (A) and feed (B) as two factors at three levels each was employed (Table 2), yielding 10 runs (9 factorial + 1 center point repeat).

TABLE 2: PROCESS PARAMETERS AND LEVELS — SECOND EXPERIMENTAL SET (DOC = 0.25 MM)

Parameter	Symbol	Level -1	Level 0	Level +1
Cutting Speed (m/min)	A	84.82	117.8	235.62
Feed Rate (mm/tooth)	B	0.30	0.35	0.40

B. Signal Analysis Methods

Time-Domain Analysis: Since milling is an intermittent cutting process, the force signal exhibits periodic peaks (during tool-workpiece engagement) and rapid drops (during disengagement). Statistical parameters—maximum (maxima), mean, and standard deviation—were extracted from three representative zones: entry, steady-state, and exit. Zone averages were used for Pareto analysis.

Frequency-Domain Analysis: The Fast Fourier Transform (FFT) was applied to convert the time-domain force signal into the frequency domain. Dominant excitation frequencies correspond to the spindle RPM and its harmonics. The DC component (zero-frequency peak) was excluded. Large unexpected spectral peaks indicate chatter or instability.

V. RESULTS AND DISCUSSION

A. First Experimental Set: Cutting Force and Surface Roughness

Table 3 presents the measured cutting force (F_y) and surface roughness (R_a) for the first 10 experimental runs.

TABLE 3: EXPERIMENTAL RESULTS — FIRST SET

Exp.	Speed (coded)	Feed (coded)	DOC (coded)	Avg. F_y (N)	R_a (μm)
1	-1	-1	+1	448.14	1.60
2	0	0	0	451.54	1.73
3	+1	+1	+1	741.39	2.51
4	0	0	0	405.60	2.09
5	+1	-1	-1	204.49	1.04
6	-1	+1	-1	248.19	2.59
7	-1	-1	+1	525.17	1.60
8	+1	+1	+1	771.53	3.33
9	-1	+1	-1	221.05	2.66
10	+1	-1	-1	180.07	1.23

B. Time-Domain Analysis — First Set

The time-domain analysis revealed that depth of cut is the most dominant factor influencing cutting force. Table 4 presents the average maxima, mean, and standard deviation computed across entry, steady-state, and exit zones for each experiment.

TABLE 4: AVERAGE TIME-DOMAIN STATISTICAL PARAMETERS — FIRST SET

Exp.	Avg. Max (N)	Avg. Mean (N)	Avg. Std. Dev. (N)
1	448.14	375.30	41.97
2	451.54	392.78	30.38
3	741.39	637.62	69.83
4	405.60	347.29	34.85
5	204.49	179.36	15.48
6	248.19	222.99	16.00
7	525.17	444.54	54.66
8	771.53	660.83	75.82
9	221.05	193.06	15.48
10	180.07	155.08	16.26

Experiments 3 and 8 (both at high depth of cut, DOC = 0.75 mm) recorded the highest forces (741 N and 772 N respectively)—nearly triple those at low DOC. Standard deviation also increased proportionally, indicating greater force fluctuation. Experiments 1 and 7 (low speed, low feed, high DOC) showed the second-highest mean forces despite low speed and feed, confirming the dominance of DOC. The force signal exhibited characteristic pulse-wave behavior, with distinct peaks during insert engagement and rapid drops during disengagement, necessitating peak-based statistical analysis.

C. Statistical Analysis — Cutting Force (First Set)

Pareto charts and main effects plots generated in Minitab 17 confirmed that depth of cut (C) has the highest standardized effect on cutting force, followed by speed (A) and feed (B), all crossing the significance threshold at $\alpha = 0.05$. The main effects analysis shows: (i) Cutting speed: moderate positive effect, as higher speed increases impact force at engagement; (ii) Feed rate: positive effect via increased uncut chip thickness; (iii) Depth of cut: strongest effect—cutting force increases by approximately 3× when DOC rises from 0.25 mm to 0.75 mm due to the larger material volume removed per pass.

D. Statistical Analysis — Surface Roughness (First Set)

Pareto analysis for surface roughness identified feed rate (B) as the only statistically significant parameter at $\alpha = 0.05$. Cutting speed and DOC had negligible influence on Ra. This is consistent with classical milling theory where $Ra \propto f^2/R$ (f = feed per tooth, R = tool nose radius). As feed increased, lay patterns deepened on the machined surface, degrading finish. Surface roughness at the high feed level was approximately three times that at the low feed level.

E. Frequency-Domain Analysis — First Set

Table 5 presents the FFT amplitude values for each experiment. The fundamental frequency peak corresponds to the spindle RPM, with subsequent peaks being harmonics. The DC component was excluded.

TABLE 5: FREQUENCY AMPLITUDE VALUES — FIRST SET

Exp.	Speed (coded)	Feed (coded)	DOC (coded)	Amplitude (N)
1	-1	-1	+1	67.46
2	0	0	0	36.59
3	+1	+1	+1	38.52
4	0	0	0	33.90
5	+1	-1	-1	16.90
6	-1	+1	-1	27.20
7	-1	-1	+1	83.67
8	+1	+1	+1	40.98
9	-1	+1	-1	23.32
10	+1	-1	-1	15.09

Experiments 1 and 7 (low speed, low feed, high DOC = 0.75 mm) produced the highest vibration amplitudes (67.46 N and 83.67 N) and non-repeatable signals, indicating machining instability. High DOC at low spindle speed creates unfavourable dynamic conditions. Experiment 5 (high speed, low feed, low DOC) produced the minimum amplitude (15.09 N), confirming the optimal stability of this combination. The cutting force signal was confirmed to be a clean pulse wave, free from extraneous noise or chatter frequencies, under all other conditions.

F. Tool Wear Observations

Post-experiment microscopic inspection of the inserts after the first set revealed minimal flank wear and no crater wear, indicating that cutting conditions were well within the TN 7535 insert's operating envelope. Inspection after the second set (higher speeds and feeds) showed slightly increased but still acceptable wear, confirming the suitability of the coated carbide grade for EN31 steel machining under the tested parameters.

G. Second Experimental Set — Constant Depth of Cut

Based on the first set findings, DOC was fixed at 0.25 mm (lowest level, which minimizes cutting force and vibration) and the study was extended to higher cutting speeds and feed rates. Table 6 presents the experimental results.

TABLE 6: EXPERIMENTAL RESULTS — SECOND SET (DOC = 0.25 MM, CONSTANT)

Exp.	Speed (coded)	Feed (coded)	F _y (N)	R _a (µm)
1	+1	-1	238.97	4.24
2	+1	-1	247.73	4.42
3	-1	-1	255.25	3.90
4	0	0	405.90	7.97
5	-1	+1	473.07	6.60
6	+1	+1	307.85	6.33
7	-1	+1	353.55	7.62
8	+1	+1	341.41	6.68
9	0	0	314.40	5.87
10	-1	-1	220.56	3.60

Pareto analysis for the second set confirmed that feed rate (B) is the sole statistically significant parameter for both cutting force and surface roughness. At the elevated speeds used (84.82–235.62 m/min), speed variation had negligible differential impact on force. Surface roughness at maximum feed was nearly twice that at minimum feed, consistent with the theoretical f^2 relationship.

H. Frequency-Domain Analysis — Second Set

TABLE 7: FREQUENCY AMPLITUDE VALUES — SECOND SET

Exp.	Speed (coded)	Feed (coded)	Amplitude (N)
1	+1	-1	12.52
2	+1	-1	6.63
3	-1	-1	20.99
4	0	0	12.45
5	-1	+1	45.51
6	+1	+1	12.51
7	-1	+1	35.37
8	+1	+1	13.96
9	0	0	20.00
10	-1	-1	34.17

Vibration amplitudes were highest at low speed with high feed (Experiments 5 and 7: 45.51 N and 35.37 N). High cutting speed consistently produced low amplitudes regardless of feed (6.63–13.96 N), demonstrating the stabilising effect of high-speed machining. No extraneous spectral content was detected under any condition, confirming the pulse-wave nature of the face milling cutting force signal. This finding validates the measurement system integrity and process cleanliness.

VI. CONCLUSIONS

This study presented a systematic experimental investigation of dynamic cutting force analysis in face milling of EN31 steel using SPMW 120408-TN 7535 coated carbide inserts. The following conclusions are drawn:

1. Depth of cut is the most significant parameter influencing cutting force. An increase in DOC from 0.25 mm to 0.75 mm raises cutting force by approximately 3×, with proportional increase in standard deviation, indicating greater dynamic instability.
2. Feed rate is the primary factor governing surface roughness (Ra). Its influence follows the classical f^2 relationship. Cutting speed and DOC have negligible effect on Ra within the tested ranges.
3. Frequency-domain analysis confirms that machining at low cutting speed combined with high depth of cut produces high vibration amplitudes and non-repeatable, unstable conditions. This parameter combination must be avoided in practice.
4. With DOC held constant at 0.25 mm and elevated speeds, feed rate remains the sole significant factor for both force and surface roughness. High-speed machining effectively suppresses vibration amplitude.
5. The dynamic cutting force signal in face milling exhibits a pure pulse-wave form in the time domain, with a corresponding clean harmonic spectrum in the frequency domain, confirming the absence of chatter or noise under optimal conditions.
6. Optimal process parameters for face milling EN31 steel with the tested insert are: Cutting Speed = 235.62 m/min, Feed Rate = 0.25 mm/tooth (medium level, second experimental set), Depth of Cut = 0.25 mm. These conditions yield minimum cutting force (~180 N), lowest vibration amplitude (<13 N), and best surface finish (Ra ≈ 1.0–1.2 μm).

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