

APPLICABILITY OF SPECIFIC ACOUSTIC EMISSION FOR THE INVESTIGATION OF THE TRANSIENT PHASE OF CUTTING

ISTVÁN POLYÁK^{1*} AND ISTVÁN BIRÓ¹

¹ Department of Manufacturing Science and Engineering, University of Technology and Economics, Műgyetem rkp.3., Budapest, 1111, HUNGARY

In the metal chip formation zone, during the large-scale and high-speed shaping of the raw material, high-frequency but low-energy pressure waves are generated within the solid material. The entire set of these pressure waves can be detected in machining research through acoustic emission measurement. The magnitude and features of the acoustic emission mainly depend on the material of the workpiece and tool, the technological parameters, and tool wear. Exploiting this property, it has become widespread in the field of process monitoring. By relating the acoustic emission to the theoretical chip cross-section, we obtain a characteristic indicator proportional to the chip formation process. Examining the specific acoustic emission as a function of the theoretical chip cross-section allows us to clearly observe and measure the transient phase of the cutting process, i.e., when the tool edge enters and exits the cutting zone. The range of small chip thickness is considered to be the range of theoretical chip thicknesses that are equal to or smaller than the tool edge radius. In this range, the statistical behavior of the specific acoustic emission differs from that observed at larger theoretical chip thicknesses, indicating a change in chip formation quality—referred to as process transition or instability. Cutting in this unstable range is undesirable and can deteriorate the finish of the machined surface. This study presents the measurement technique for the specific acoustic emission, the development of related process indicators, and their application to monitor the transient stage of cutting.

Keywords: chip forming, face grooving, thin chip removal, specific acoustic emission

1. Introduction

In recent years, alongside achieving adequate manufacturing quality, sustainability has gained increasing importance. Among various machining methods, material removal by cutting remains dominant [1]. With the advent of Industry 4.0 and the significant growth in data processing capabilities, precise, real-time process monitoring has become feasible. This is particularly important in precision and micro-machining, where process stability strongly influences machining quality. Instabilities in cutting processes can induce vibrations, which degrade the quality of the machined surface. Consequently, machining in unstable regimes is undesirable, as it leads to deterioration of surface quality [2]. Stable material removal cannot be maintained if machining conditions are not steady but are instead subject to transitional states. Tool entry into and exit from the workpiece typically induce such transient conditions in chip formation. Until a stable chip formation state is reached, the machined surface is shaped by deformation processes of varying extent and quality. Transient phases in cutting processes are inherent to all machining technologies; however, their effects are most pronounced

in milling. During milling, the cutting edges periodically enter and leave the workpiece, continuously affecting process stability. With respect to stringent quality requirements, the transient behavior of cutting is especially critical in micro-milling.

The most frequently employed process indicators for analyzing machining include [3]:

- cutting force,
- vibration,
- temperature, and
- acoustic emission (AE).

In addition, sensor fusion for measuring these quantities is commonly applied [4]. The present study exclusively investigates the applicability of acoustic emission among the aforementioned indicators.

Acoustic emission refers to elastic stress waves that propagate through solid materials and originate from energy release during deformation processes. In machining, the primary sources of AE are plastic deformation during chip formation and deformation induced by friction between the tool and the workpiece. The magnitude of AE depends on the intensity of deformation, thus on machining parameters, as well as on tool–workpiece friction. Owing to this latter factor, AE has become widely used in tool wear monitoring [5]. By

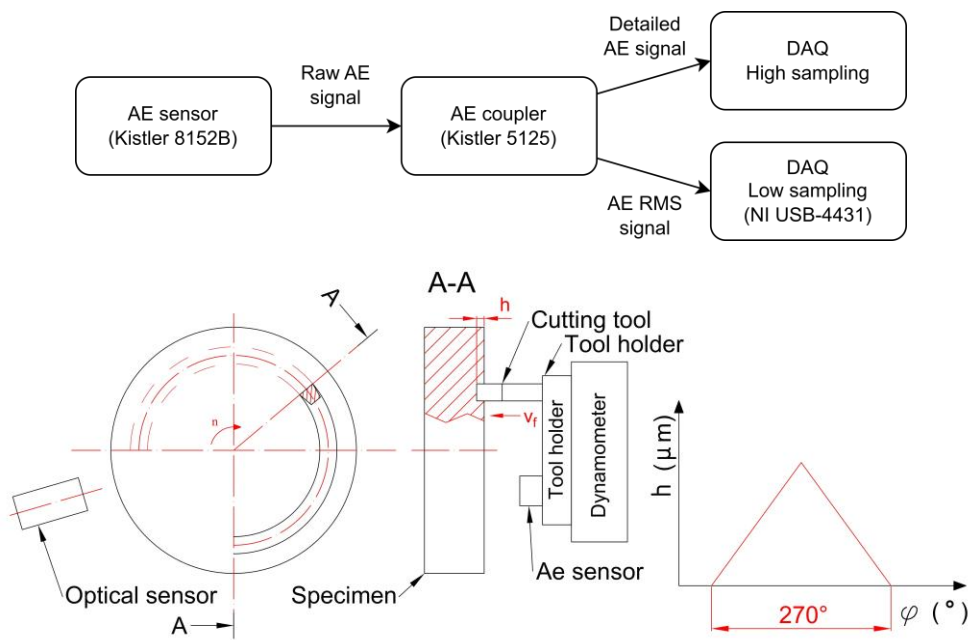


Figure 1: A typical measurement setup for AE in machining (above), Experimental setup (below)

normalizing AE to the theoretical chip cross-section ($h \cdot b$), a proportionality-based indicator of the chip formation process is obtained:

$$ae(h) = \frac{AE(h)}{h \cdot b} \quad (1).$$

When examined as a function of relative sharpness (h/r_β), specific processing parameters allow the transient phase of cutting, such as tool entry and exit, to be distinctly observed and quantitatively characterized [6].

In the transient regime, the statistical behavior of specific acoustic emission differs significantly from that observed under steady-state cutting conditions. Due to this property, it can serve as an indicator for detecting changes in the quality of the chip formation process, i.e., for analyzing process transitions [7]. The present study introduces the methodology for measuring specific acoustic emission, the derivation of processed indicators, and their applicability to the transient phase of cutting.

2. Experimental design

During machining, acoustic emission propagating in the solid material can be detected using an AE sensor that works on the piezoelectric principle. A typical measurement setup is shown in Figure 1. When ultrasonic frequency pressure waves pass through, electric charges proportional to the wave's amplitude are generated on the surface of the piezoelectric crystal. In practice, AE waves that mainly travel along a primary direction, perpendicular to the contact surface, are best suited for measurement.

AE sensors often incorporate a built-in charge amplifier. The raw AE voltage signals, amplified to a manageable voltage level, are conditioned by a coupler module. This conditioning typically includes additional

amplification and band-pass filtering. The filter bandwidth (typically 100 kHz to 1 MHz) depends on the sensor's frequency response characteristics. The filtered signal is commonly referred to as the *detailed AE signal*.

Furthermore, the coupler can generate, in an analog manner, the root mean square (RMS) value of the detailed AE signal by means of an integrator. The integration time constant is on the order of a few milliseconds. The resulting signal is referred to in the literature as *AE RMS*. Its magnitude is proportional to the energy content of the acoustic emission and indicates the AE trend. The pre-processed signals provided by the coupler can be directly measured and sampled. Due to its high-frequency nature, the detailed AE signal requires a specialized data acquisition system capable of recording at sampling rates exceeding 2 MS/s (MegaSamples per second). In practice, digital oscilloscopes are also frequently used; however, their applicability is limited by the restricted number of data points, which depends on internal memory size. In contrast, AE RMS measurement requires only approximately 10 kS/s, depending on the integration time constant. Since AE RMS maintains the trends of the AE, this parameter is therefore examined in this research.

Since the sensor's sensitivity depends on the incidence angle of the incoming waves, careful consideration is required when selecting its position and orientation. Determining the orientation of the sensor's main axis requires prior knowledge of the dominant AE source. During the transient phase of machining, both the cutting and feed directions may serve as appropriate orientations, as the specific force components characterizing the forming load are of comparable magnitude in this regime [8]. The sensor should be placed as close as possible to the expected origin of acoustic emission to minimize the dissipation of the pressure waves during propagation. The optimal mounting

Table 1: Experiment design and parameter values

$v_c=119$ (m/min)		$f=0,106$ (mm/1)	
No.	f (mm/1)	No.	v_c (m/min)
1	0,061	6	59
2	0,081	7	84
3	0,106	3	119
4	0,106	4	119
5	0,139	8	168

location depends on the machining technology employed. In general, the sensor should be affixed to the stationary component closest to the emission source. For milling and drilling processes, this is typically the fixture, whereas in turning operations, attachment to the tool is common practice [9].

For determining the specific acoustic emission, the other required parameter is the theoretical chip cross-section. In most studies, this parameter is not measured directly. Instead, it is typically calculated indirectly, based on the theoretical values set on the machine tool. Only a limited number of chip formation configurations allow direct, measurement-based determination of the chip cross-section. These are technologies that can be regarded as free-cutting operations. One such example is planning, where achieving modern cutting speeds poses a significant challenge. In addition, certain turning configurations enable post-process measurement of the removed layer cross-section. Examples include radial turning, as well as the face-grooving turning arrangement (see *Figure 1*) applied in this study. In these experiments, the deformed layer cross-section can be accurately determined afterwards through surface profile measurements.

The experiments were conducted in the ultra-precision and micro-machining laboratory at the Department of Manufacturing Science and Technology of Budapest University of Technology, using a Hembrug Mikrotorn 50 precision lathe. The specimen used for the experiment was S960QL, a high-strength structural steel. The cutting tool employed was type 10EAL2.5FA. The insert had an edge radius of $r_\beta = 20 \mu\text{m}$. An acoustic emission sensor (Kistler 8152B221) was mounted on the tool holder to monitor the cutting process. To accurately determine the rotation period of the test specimen, an optical sensor (Omron E3F-DS10B4) was employed. This configuration enabled correlation of the profile measurements obtained after machining using a Mitutoyo SJ 400 device, with the in-process measurements acquired taken during cutting.

A total of eight grooves were created on the test specimen, each using distinct technological parameters. The experimental parameters are summarized in *Table 1*. According to the experimental design, it is possible to examine the effects of cutting speed and feed per revolution independently, with each factor varying across four levels.

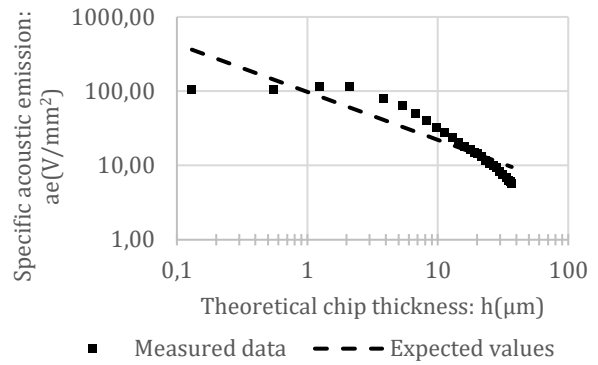


Figure 2: Measured and calculated expected values for experiment No. 3, tool entry

3. Results and discussion

3.1. Evaluation

The evaluation was performed using the LabVIEW software environment. The theoretical chip cross-section was derived from the profile measurement data, while the theoretical chip thickness was defined as the average distance from the face surface of the prepared specimen. The theoretical chip width was identified as the local minimum value within the profile measurement data. The specific acoustic emission values were calculated based on *Equation 1* presented previously before. Data from each experimental setup (groove) were analyzed separately, with a focus on the tool edge entry and exit. The specific acoustic emission values were investigated as a function of the theoretical chip thickness, examining deviations from the exponential mathematical model used to represent the deviation from stable cutting conditions.

$$AE_i(h_i) = \log(ae_i(h_i)) \quad (2),$$

$$H_i = \log(h_i) \quad (3),$$

$$AE_i(H_i) = B \cdot H_i + C \quad (4),$$

$$ae_i^e(h_i) = 10^{AE_i(H_i)} \quad (5),$$

$$\varepsilon = \frac{ae_i^e(h_i) - ae_i(h_i)}{ae_i^e(h_i)} \quad (6).$$

To facilitate the analysis, the $ae(h)$ data were linearized through logarithmic transformation (*Equations 2 and 3*). An approximate function (expected value) was then derived using linear regression (*Equation 4*). An example of the model fitting is illustrated in *Figure 2*. After raising the data to the tenth power and returning to normal values (*Equation 5*), we analyzed the relative error between the measured values and the expected value (*Equation 6*) based on the relative sharpness of the tool.

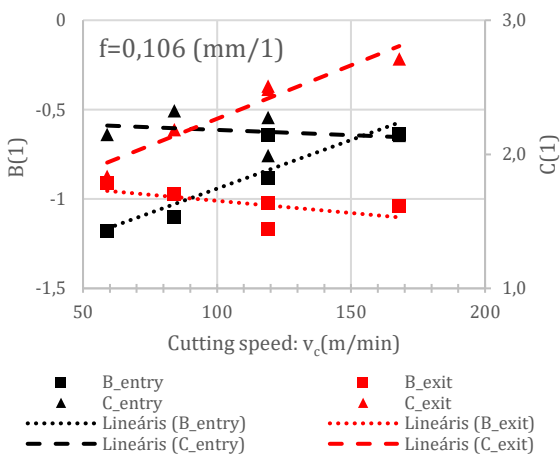
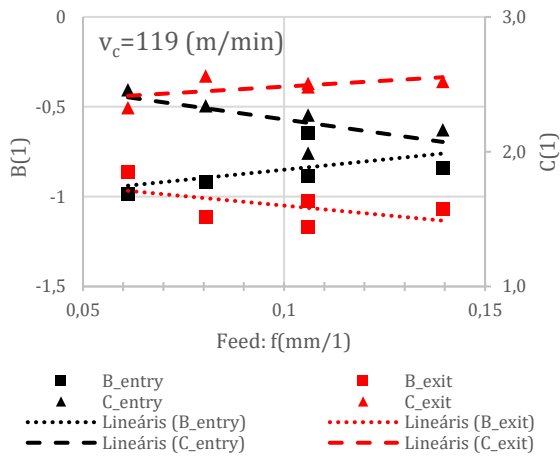


Figure 3: The coefficients obtained from the linear fit

3.2. Results

The coefficients obtained from the linear regression are depicted in Figure 3. The diagrams clearly demonstrate that as the feed per revolution and the cutting speed increase, the coefficient trends at tool entry and exit diverge in opposite directions (see trend lines in different colors). The influence of varying cutting speed and feed is evident for both factors. Additional experiments are required to investigate the extent and the underlying causes of this phenomenon; however, this topic is beyond the scope of the current discussion.

The values illustrating the deviations from the exponential mathematical model (Equation 6), based on the relative sharpness during chip formation, are shown in Figures 4 and 5. In all four cases, the deviation from the model within the examined range of relative sharpness changes direction multiple times. The mathematical model used to approximate the expected values tends to overestimate the measured values near the extreme ends of the examined h/r_β range, while it underestimates them in the middle range. Furthermore, the model requires correction for this range.

This phenomenon suggests that the model does not adequately represent the actual physical process at very low relative sharpness, leading to limited and unreliable

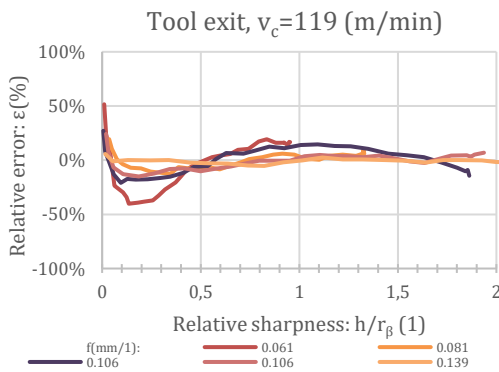
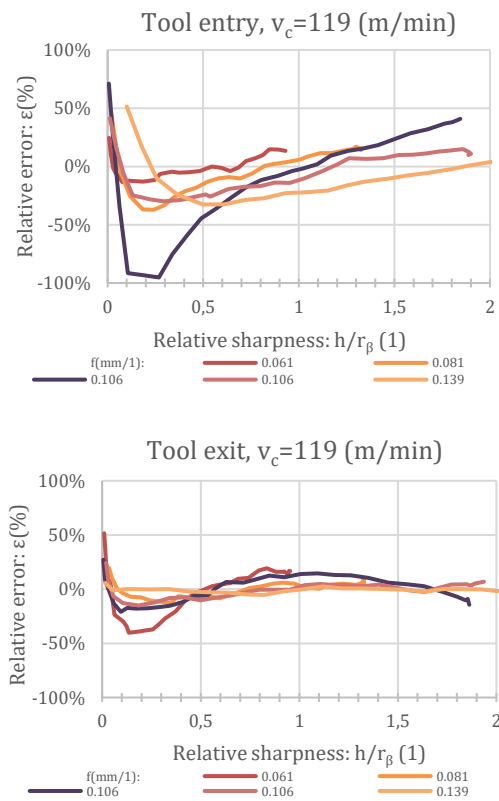


Figure 4: Relative error from exponential model ($v_c=119(\text{m/min})$)

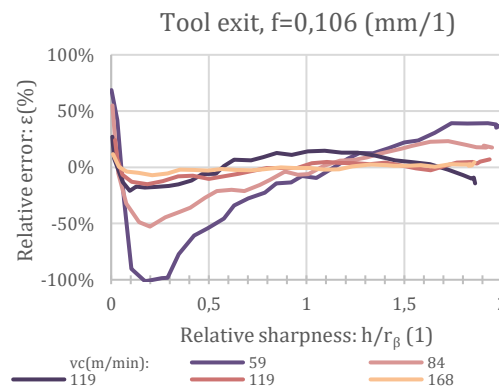
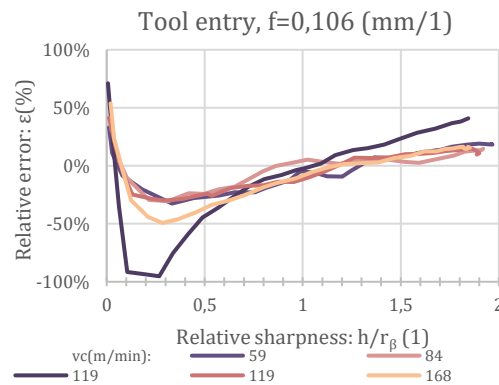


Figure 5: Relative error from exponential model ($f=0,106(\text{mm}/1)$)

predictive capability in this range. Also, this behavior can indicate that the chip formation mechanism is changing in this region. This phenomenon can also be related to the value of specific cutting force [10]; thus, specific acoustic emission may be employed in a similar manner to characterize the transient phase of the cutting process.

4. Conclusion

This study presents a methodology for using specific acoustic emission (AE) as an indicator of transient cutting phases, particularly during tool entry and exit. By normalizing AE with respect to the theoretical chip cross-section, this method enables a clear distinction between steady-state and transient chip formation, as the mathematical model used to approximate the expected values tends to overestimate the measured values near the extreme ends of the examined h/r_β range, while it underestimates them in the middle range. This finding indicates that qualitative changes occur in the chip formation mechanisms under these conditions, similar to the specific cutting force. Therefore, specific acoustic emission can be utilized in a similar way to characterize the transient phase of the cutting process. Additionally, cutting speed and feed per revolution were observed to influence the AE response differently at entry and exit, indicating a complex interaction between machining parameters and transient behaviors. In summary, the findings confirm that specific AE can effectively detect and characterize process instabilities. This approach shows significant potential for integration into real-time monitoring systems within Industry 4.0, contributing to improved machining quality and sustainability.

SYMBOLS

A (mm ²)	theoretical chip cross-section
h (mm)	theoretical chip thickness
b (mm)	theoretical chip width
r_β (μm)	edge radius
h/r_β (1)	relative thickness
AE (V)	measured acoustic emission
ae (V/mm ²)	specific acoustic emission
B, C (1)	constants for linear fit
ε (%)	relative error

Acknowledgements

The project supported by the Doctoral Excellence Fellowship Program (DCEP) is funded by the National Research Development and Innovation Fund of the Ministry of Culture and Innovation and the Budapest University of Technology and Economics, under a grant agreement with the National Research, Development and Innovation Office and partly supported by the National Research, Development and Innovation Office in the

frame of the grant SNN146940 (Basic Investigation of the Applicability of Artificial Intelligence Based Predictive Models to Improve the Quality of Production with Advanced Machining Processes).

REFERENCES

- [1] Shokrani, A.; Arrazola, P.J.; Biermann, D.; Mativenga, P.; Jawahir, I.S.: Sustainable machining: Recent technological advances. *CIRP Ann.*, 2024, **73**(2), 483–508, DOI: 10.1016/j.cirp.2024.06.001
- [2] Wojciechowski, S.: Estimation of minimum uncut chip thickness during precision and micro-machining processes of various materials—A critical review, *Materials*, 2022, **15**(1), 59, DOI: 10.3390/ma15010059
- [3] Sun, W.; Zhang, D.; Luo, M.: Machining process monitoring and application: a review, *J. Adv. Manuf. Sci. Technol.*, 2021, **1**(2), 2021001, DOI: 10.51393/j.jamst.2021001
- [4] Xu, Q.; Dong, J.; Peng, K.; Fu, X.; Wang, H.: Mechanism and data fusion driven multi-indicator soft sensor framework for industrial processes, *ISA Trans.*, 2025, DOI: 10.1016/j.isatra.2025.07.062
- [5] Maia, L.H.A.; Abrão, A.M.; Vasconcelos, W.L.; Júnior, J.L.; Fernandes, G.H.N.; Machado, Á.R.: Enhancing machining efficiency: Real-time monitoring of tool wear with acoustic emission and STFT techniques, *Lubricants*, 2024, **12**(11), 380, DOI: 10.3390/lubricants12110380
- [6] Rahman, M.A.; Rahman, M.; Mia, M.; Gupta, M.K.; Sen, B.; Ahmed, A.: Investigation of the specific cutting energy and its effect in shearing dominant precision micro cutting, *J. Mater. Process. Technol.*, 2020, **283**, 116688, DOI: 10.1016/j.jmatprotec.2020.116688
- [7] Polyák, I.; Biró, I. A Characterisation of the specific cutting force under the conditions of fine chip-removal with the help of acoustic emission and microhardness measurement, *31st Int. Conf. Mech. Eng. (OGÉT)*, 2023, 400–404 (in Hungarian)
- [8] Pálmai, Z.; Kunderák, J.; Felhő, C.; Makkai, T.: Investigation of the transient change of the cutting force during the milling of C45 and X5CrNi18-10 steel taking into account the dynamics of the electro-mechanical measuring system, *Int. J. Adv. Manuf. Technol.*, 2024, **133**(1-2), 163–182, DOI: 10.1007/s00170-024-13640-6
- [9] Bernardes, L.P.; Júnior, P.O.C.; Dotto, F.R.L.; Rodrigues, A.R.; Silva, M.M.: Damage detection in machining tools using acoustic emission, signal processing, and feature extraction, *Eng. Proc.*, 2023, **58**(1), 109, DOI: 10.3390/ecsa-10-16258
- [10] Biró, I.; Szalay, T.: Extension of empirical specific cutting force model for the process of fine chip-removing milling, *Int. J. Adv. Manuf. Technol.*, 2017, **88**(9-12), 2735–2743, DOI: 10.1007/s00170-016-8957-x