euspen's 25th International Conference & Exhibition, Zaragoza, ES, June 2025
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Acoustic emission-based approach for monitoring the stand-off distance during abrasive waterjet cutting processes

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Abstract
Monitoring waterjet cutting processes presents significant challenges, particularly in measuring the stand-off distance (SOD), a critical parameter for cutting quality that has not previously been measurable in a non-contact manner. This study introduces a novel approach using acoustic emission (AE) signals for real-time, non-contact SOD monitoring. Experiments on aluminium and steel demonstrated a clear correlation between the power spectral density (PSD) of AE signals and SOD, with increasing SOD resulting in decreased median PSD values (analyzed using Welch's method).

acoustic emission (AE), distance monitoring, frequency analysis, abrasive waterjet cutting, signal processing

1. Introduction

Abrasive waterjet cutting (AWJC) is an advanced machining process widely utilized in various industrial manufacturing applications. This method offers numerous advantages, particularly its ability to cut a broad range of materials with minimal thermal impact, making it especially suitable for innovative and heat-sensitive materials. The process operates by eroding the material through a high-pressure jet of water enriched with abrasive particles [1]. Several parameters influence the effectiveness and quality of AWJC, including traverse speed, water pressure, the quantity and characteristics of abrasive particles and other factors. Among these, the stand-off distance (SOD) defined as the distance between the cutting nozzle and the workpiece, is especially critical. Variations in SOD can significantly impact cutting accuracy, surface finish, and overall process efficiency, highlighting the necessity of precise monitoring to optimize abrasive waterjet (AWJ) performance.

This study explores the feasibility and potential of acoustic emission (AE) signals for accurately tracking SOD variations and establishing a correlation between AE features; specifically, the power spectral density (PSD) values and SOD. The overall objective is to develop a reliable, real-time monitoring method to enhance the control and optimisation of AWJC processes, thereby improving accuracy, efficiency, and quality in industrial applications.

In the following sections, a summary of the state of the art in AWJ monitoring is presented, along with the basis for sensor selection and the measurement principle. Investigations into the measurement process and the functionality of the signal processing method are also discussed. Finally, a brief summary of the results and the conclusion is provided.

2. Overview of State-of-the-Art abrasive waterjet monitoring

The monitoring of AWJC has significantly advanced in recent years, with a strong focus on optimizing key parameters and maintaining consistent cutting quality. Traditional monitoring methods, such as surface roughness evaluation and material deformation analysis, typically rely on post-cutting measurements and thus limit their applicability in real-time process adjustments. While machine-integrated methods that track parameters like water pressure, abrasive flow rate, and nozzle wear are becoming more prevalent for real-time monitoring, they often require high-precision equipment or are limited to laboratory environments, making them less feasible for broad industrial use.

Among these studies, emerging technologies, particularly energy-related sensing methods like AE monitoring, align with the growing trend of real-time monitoring in AWJC.

Axinte et al. [2] developed an energy-based tracking system using AE sensors at the nozzle and workpiece to monitor jet energy levels, detect anomalies, and optimize parameters like nozzle feed speed through root mean square (RMS) signal analysis. Popan et al. [3] also introduced an AE-based monitoring method for AWJC processes, targeting system malfunctions such as abrasive flow interruptions, nozzle clogging, and water pressure fluctuations. Their approach employs mathematical regression models to predict AE signal characteristics, considering parameters like water pressure, abrasive mass flow rate, feed rate, and material thickness.

Furthermore, several studies have explored the frequency-domain characteristics of vibration and AE signals to establish correlations between signal behaviour and process parameters. Kinik et al. [4] investigated the relationship between traverse speed and vibration amplitude, demonstrating that variations in speed influence oscillation intensity and surface topography. Their findings, specifically for stainless steel AISI 304, confirmed that lower traverse speeds reduce vibration amplitudes and improve surface quality, whereas higher speeds result in insufficient material erosion, leading to poorer cut quality.

Additionally, Pahuja et al. [5] analyzed AE and vibration signals during AWJ machining of Titanium, CFRP, and hybrid Ti/CFRP stacks, identifying dominant frequency variations at different traverse speeds and pressures. Their study demonstrated a strong correlation between PSD variations and process parameters, highlighting that AE signals are more reliable than accelerometer signals at high traverse speeds, where excessive mechanical vibrations can distort accelerometer data.

more of these parameters can result in process inconsistencies and negatively impact part quality.

To monitor these fluctuations, AE sensors were used to capture high-frequency signals generated during the cutting process. These signals are a result of mechanical interactions such as material deformation, abrasive particle impact, and the cutting action itself. These high-frequency acoustic signals provide valuable information about the dynamics of the waterjet cutting process and can be correlated with the SOD.

Moreover, AE sensors are more robust for the rough AWJC

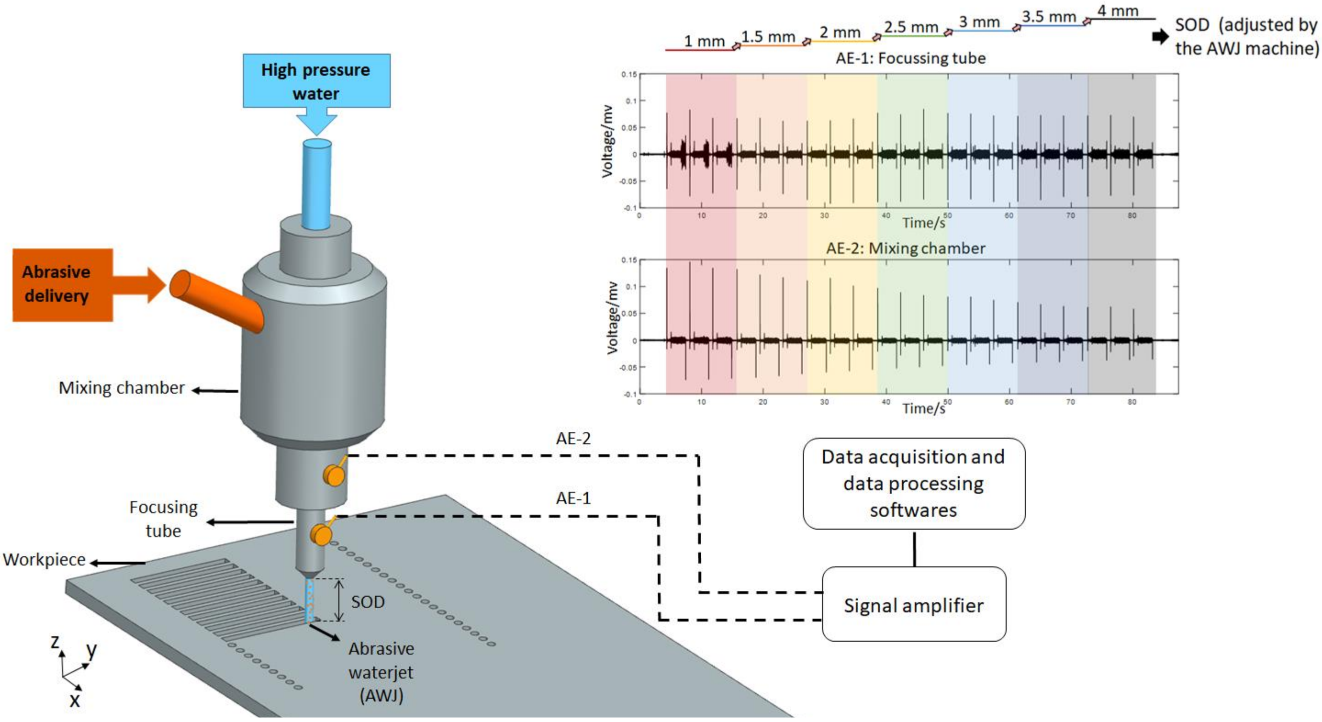

Figure 1. Schematic representation of the AWJC process and the measurement setup for monitoring the SOD variation using AE sensors

Previous studies have indicated that variations in SOD can directly impact cutting performance, including the precision of cuts and surface quality [6]. Given the significant impact of these variations, this work demonstrates how AE signals and their characteristics in the frequency domain, when analyzed alongside other key process parameters such as water pressure, abrasive flow rate, and nozzle wear, can provide valuable insights into SOD fluctuations and enable more effective monitoring of AWJC processes.

3. Measurement Principles, Sensor Selection and Data Processing

3.1. Basis for measurement principle, sensor selection and placement

The selection of sensors and planning of measurements were conducted based on the functionality and working principles of the AWJC, which is a multi-step process that involves the flow of energy through various stages.

The energy from the jet is influenced by parameters such as pump pressure, SOD, and abrasive flow, and is subsequently converted into erosion energy at the workpiece. However, variations in energy distribution caused by fluctuations in one or

environment where tactile and optical sensors might interfere with the cutting process.

For the measurement setups in this study (

Figure **1**), two AE sensors (SONOTEC T10) were attached close to the cutting area to detect the effects of the distance to the workpiece.

AE-1: Positioned at the focusing tube, mounted using wax and a holder.

AE-2: Positioned beneath the mixing chamber, mounted using wax and water-resistant adhesive tape.

The idea is to capture the acoustic emission as close to the process as possible, while utilizing simple methods for mechanical attachment. The sensor positioning was also determined for recording different process information. The sensor located on the focusing tube captures signals related to energy interactions and jet dynamics near the jet's origin, providing information influenced by input energy and jet trajectory. The sensor beneath the mixing chamber monitors disturbances caused by the abrasive mixing process or transitions along the jet path. Together, these sensors provide comprehensive monitoring of energy variations throughout the

AWJC process, which is particularly advantageous for detecting the SOD.

3.2. Welch Analysis for Data Processing

Welch analysis is a robust signal processing technique widely used for estimating the power spectral density (PSD) of signals. This method involves dividing the signal into overlapping segments, applying a window function to each segment, and computing the periodograms. By averaging the periodograms of these segments, Welch analysis significantly reduces the variance of the PSD estimates, making it particularly effective in noisy environments [7].

The measurements were designed to keep all influencing parameters constant, allowing the SOD to be the only variable parameter. For this purpose, the water pressure was set to 3700 bar, the abrasive flow rate to 320 g/min, and the feed rates were selected to achieve a medium-quality cut. These were 1200 mm/min for aluminium sheets and 400 mm/min for steel sheets, based on the machine-specific and material-specific data stored in the machine interface.

During the measurements, linear cuts with a length of 30 mm were made at two different positions on the sheets, with SODs ranging from 1 to 4 mm (steps of 0.5 mm). To compensate for

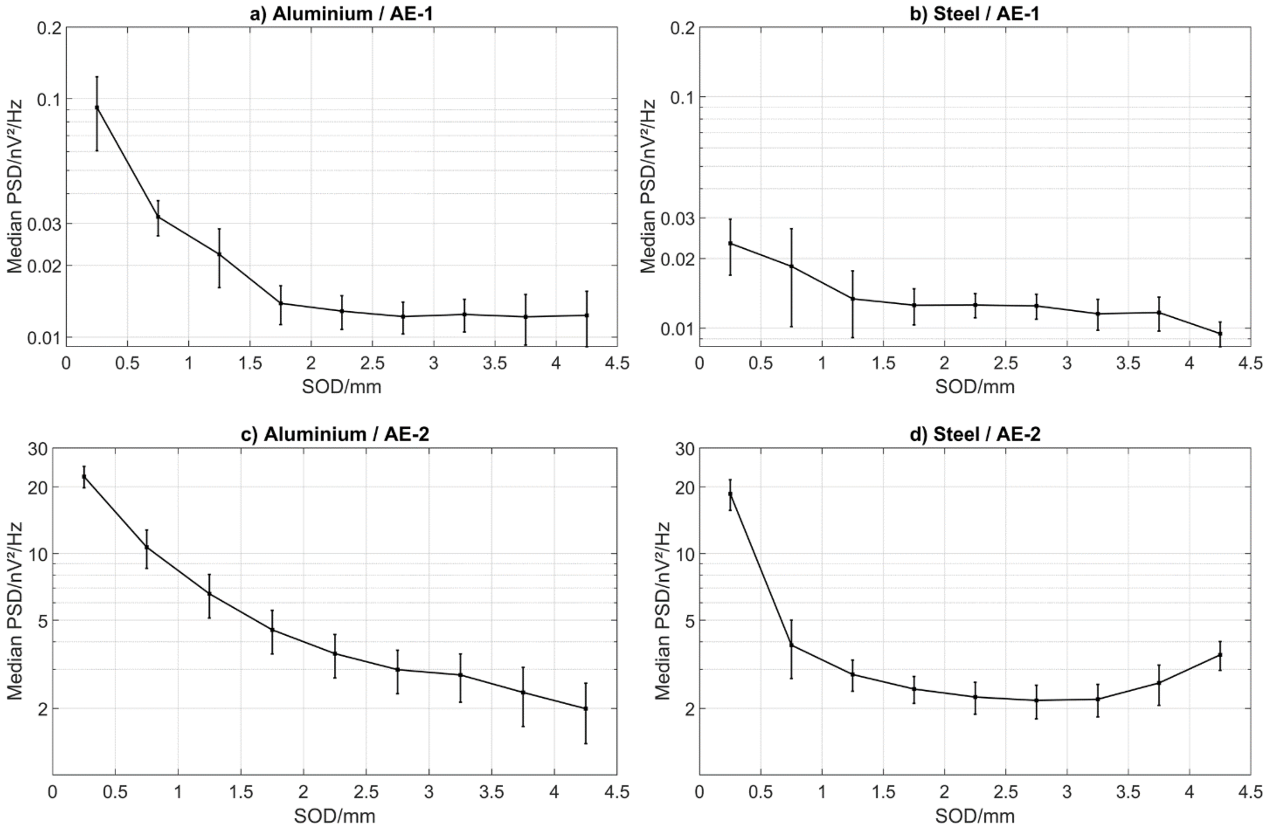

Figure 2. Representation of PSD values as a function of actual SOD for two frequency ranges: 70-80 kHz at the focusing tube (a, b) and 35-45 kHz beneath the mixing chamber (c, d); based on measurements from three cut sheets each, made of aluminium (a, c) and steel (b, d)
Error bars indicate the variability of PSD values within each SOD class, estimated using half of the interquartile range

In AWJC, where AE data are influenced by high dynamic variability, Welch analysis enables the identification of frequency bands associated with fluctuating process parameters such as the SOD. By averaging over multiple segments, the method ensures more reliable and robust spectral estimates, which are critical for monitoring and optimizing cutting processes.

4. Development of the Experimental setup and data processing

4.1. Experimental investigations and measurement setup

The experiments were conducted to monitor the cutting process of aluminium and construction steel sheets with a thickness of 2.5 mm using an STM 1020 PremiumCut 3D waterjet cutting machine. The machine has a 5-axis cutting head and allows an inner table working area of 2002 mm x 1002 mm, a feed rate of 0-40 m/min, a maximum workpiece load of 800 kg/m^2, positioning accuracy of ±0.025 mm/m and repeatability of ± 0.025 mm/m at 20°C. The focusing tube size has an internal diameter of 0.8 mm.

SOD deviations caused by sheet curvature or potential inaccuracies in the SOD control of the waterjet system, the distance from the predefined contour on the sheet was recorded using a triangulation sensor (optoNCDT ILD2300-50).

The sampling frequencies of the AE sensors and the triangulation sensor were 192 kHz and 300 Hz, respectively.

4.2. Signal acquisition and data processing

The data measured by the triangulation sensor and AE sensors were recorded using a 9874-2-2 HBM signal amplifier and subsequently transferred to a computer in a format compatible with MATLAB software for further analysis.

The first step involved preprocessing the distance data recorded by the triangulation sensor to reduce noise. Relevant data segments corresponding to the positions of the cutting contours were then extracted. The actual SODs during the measurements were determined by comparing the processed data with the adjusted SODs set by the AWJ machine.

Similarly, the data collected from each AE sensor for the cutting contours were extracted and noise was reduced during preprocessing. The analysis of AE data was performed using

Welch's method provided in MATLAB. This analysis used time windows of 40960 samples (corresponding to approximately 0.2 seconds) with a 50 % overlap. The resulting PSD values were averaged over 10 kHz-wide bands and analyzed within the 0 to 96 kHz frequency range.

Significant frequency bands of 70-80 kHz for AE-1 and 35-45 kHz for AE-2 were identified and utilized for further evaluation in relation to SODs. These frequency bands provided crucial insights into the correlation between AE signals and variations in the SOD during the cutting process.

Different statistical analyses were used to evaluate the PSD values in relation to the SOD to determine the most meaningful parameter for examining the relationship between the PSD values and the change in the SOD.

5. Results

Following the classification of the actual SODs in classes ranging from 0 to 4.5 mm (steps of 0.5 mm), a statistical analysis of the data distribution revealed a clearer relationship between the PSD values and the SOD.

Among the parameters examined, the median was identified as the most effective for categorizing PSD values based on the SOD, as it demonstrates greater robustness against outliers compared to other parameters.

The corresponding results for both workpiece materials are illustrated in Figure 2. The interquartile range (IQR/2) is employed as a robust measure of variability and uncertainty around the median PSD values within each SOD class. This method was selected due to the limited number of measurements available per material and per SOD class.

The results indicate that as the SOD increases, the PSD values consistently decrease, while the variability within the interquartile ranges increases. This trend is more pronounced for aluminium, where a clear correlation is observed. For steel, the trend is noticeable up to a SOD of 3.5 mm with AE-1 and 2.5 mm for AE-2, beyond which the relationship becomes less distinct. The increased variability in the data from AE-1 at the focusing tube may be due to reflections of the jet, which introduce additional disturbance and lead to greater data scatter.

6. Conclusions

This paper presents a comprehensive approach to monitoring SOD during AWJC processes by leveraging AE signal analysis of two AE sensors, one mounted on the AWJ focusing tube and the other beneath the mixing chamber. Through the study of PSD values, a notable relationship between these values specially the PSD values obtained from the data of the AE sensor beneath the mixing chamber and the SOD was identified for two distinct materials, aluminium and steel. The findings indicate that as the SOD increases, the median of PSD values decreases.

This relationship is particularly evident in aluminium, where a continuous decrease is observed with greater distances. A similar, albeit limited, trend was found for steel, with the pattern only persisting up to 2.5 mm of distance.

This study establishes, a clear correlation between specific frequency bands and SOD at varying machine positions for these materials. These insights enable the non-invasive monitoring and control of the SOD through acoustic signals, leading to improved cutting quality, reduced material loss, and greater overall process efficiency. The findings reveal the most significant effects at lower SODs (around 2 mm and below), which correspond to the typical cutting range. This is particularly relevant, as accurate monitoring within this range can help prevent collisions that may cause damage to the focusing tube or the workpiece.

Future research could focus on investigating additional sensor positions and testing the validity of these findings under a wider range of process conditions. Further refinement of the frequency bands may enhance the robustness of the monitoring system, offering a more reliable method for real-time SOD control and more efficient AWJC operations.

4. Acknowledgment

Supported by:

Federal Ministry for Economic Affairs and Climate Action

on the basis of a decision by the German Bundestag

This Project is supported by the Federal Ministry for Economic Affairs and Climate Action (BMWK) on the basis of a decision by the German Bundestag.

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